DEPOSITIONAL PATTERNS AND STRATAL RELATIONSHIPS ON THE DISTAL MARGINS OF A FORELAND BASIN: MIDDLE JURASSIC GYPSUM SPRING AND LOWER SUNDANCE FORMATIONS, BIGHORN BASIN, WY

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The following faculty members have examined the final copy of this thesis (or dissertation) for form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Earth, Environmental and Physical Science with a major in Geology.

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ABSTRACT

Depositional patterns and stratal relationships in the Middle Jurassic Gypsum Spring and lower Sundance Formations were influenced by a combination of paleotopographic highs and eustatic changes in the eastern Bighorn Basin. Most of these highs are of tectonic origin related to an island arc collision to the west and assumed to be reactivations of crustal weaknesses from earlier western North American orogenies. Although overall basin geometry was affected by the encroaching tectonic load, the study area is far enough away from the orogenic front that it behaves like a passive margin in a ramp setting in response to relative sea level changes. The Middle Jurassic section in the Bighorn Basin records three major transgressive-regressive cycles. Many of these contain high-order cycles identifiable by evidence of subaerial exposure in outcrop or by a geophysical log signature showing cyclic alternating peaks and troughs within a given lithologic unit.

Chert pebble lag deposits have been used by previous workers to locate regional unconformities in the Bighorn Basin and throughout the Western Cordillera. One of these unconformities, the J-2 surface, is particularly enigmatic. If these lag deposits do in fact mark the J-2 unconformity the surface in the Bighorn Basin is localized and only present in the vicinity of paleotopographic highs, the Black Mountain High being the most prominent. The chert pebbles were shed off of this high and deposited locally and sporadically across two lithofacies units. The combination of paleotopography, tectonics and eustatic changes all contributed to the stratigraphy of the Middle Jurassic section. A sequence stratigraphic model was developed to gain insight into the timing of these tectonic and eustatic events in relation to deposition.

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CHAPTER ONE

INTRODUCTION

The stratigraphy of the Middle Jurassic section in the Bighorn Basin has been a source of disagreement for decades. The type sections of the Piper and Gypsum Spring Formations are known to be incomplete (Parcell and Williams, 2005) which poses a problem in setting a marker bed for these formations. The lack of index fossils makes facies correlation within the basin difficult for long distances. Pipiringos and O'Sullivan (1978) have named several Jurassic unconformities named J-0 through J-5 present either in the Bighorn Basin or in nearby age equivalent formations. Many of these unconformities represent pulses of tectonism and/or flooding events related to three Middle Jurassic marine inundations. Several high-order sub-cylces have been noted in the basin, often supported by evidence of subaerial exposure. One of these exposure surfaces recently discovered contains dinosaur tracks preserved in the lower Sundance Formation marking a middle Jurassic unconformity (Kvale et al., 2001) named the J-2b surface. Previous workers have described chert beds as lag deposits throughout the basin to mark some of these unconformities (Pipiringos and O'Sullivan, 1978). However, these unconformities are often found at different stratigraphic locations causing confusion in correlation (Imlay, 1956; Pipiringos and O'Sullivan, 1978; Kvale et al., 2001; Parcell and Williams, 2005). It appears that workers tend to place the location of chert pebbles noted by others where it fits their models, rather than identifying exactly where previous workers placed them. The chert layers are only traceable locally and are believed to be the results of differential erosion in a setting with variable paleotopographic relief.

The purpose of this study is to investigate the various Middle Jurassic lithofacies units and their relationships to possible unconformities that bound or truncate them. By correlating the chert pebble lag deposits with respect to the lithologic units they are found in, pinchouts and stratigraphic variability are apparent. Geophysical logs are employed to increase the coverage area and to correlate outcrop data into the subsurface. The main objective is to develop a sequence stratigraphic model for the east side of the Bighorn Basin and attempt to relate stratal relationships to Jurassic tectonics and/or paleoclimatic changes whenever possible.

There are numerous criteria used to classify the members of the Gypsum Spring Formation of Wyoming and Piper Formation of Montana, creating confusion in the literature (Imlay, 1956; Pipiringos and O'Sullivan, 1978; Schmude, 2000; Kvale et al., 2001; Parcell and Williams, 2005). For simplification, I have split the section older than the Sundance Formation into four readily identifiable units based on color and lithology. From oldest to youngest the units are as follows: Basal Gypsum unit, Red Claystone A, Gray Limestone unit and Red Claystone B. Agreement on the Sundance Formation nomenclature consisting of the Canyon Springs, Stockade Beaver Shale and Hulett Members of the Middle Jurassic section is more common, and is used in this report. I present this nomenclature to establish a model for investigation of the local units on the east side of the Bighorn Basin without attempting a correlation to more regional stratigraphic markers.

CHAPTER 2

GEOLOGIC SETTING

2.1 Location

The study focuses on the Middle Jurassic section on the east side of the Bighorn Basin from near the town of Warren in southern Montana to Thermopolis in northern Wyoming at the southern margin of the basin (Figures 1-2). The Middle Jurassic contains the Gypsum Spring Formation and the informal lower Sundance member of the Sundance Formation. Some (Pipiringos & O'Sullivan, 1978; Imlay, 1980; Schmude, 2000) claim the upper member of the Piper Formation exists above the Gypsum Spring Formation in the Bighorn Basin but further studies are needed to prove this.

The Bighorn Basin is a younger, Laramide orogenic intermontane basin developed during the Cretaceous and Tertiary. It is bounded to the west by the Absoroka Mountains, to the northwest by the Beartooth Mountains and to the north by the Nye-Bowler lineament and the Pryor Mountians. It is bounded to the east by the Bighorn Mountains and to the south by the Owl Creek Mountains where the basin drains. The basin is oriented NW to SE and is approximately 190 km (120 mi) long by 100 km (60 mi) wide.

The Middle Jurassic section is exposed on the north, east and south margins closest to the Pryor, Bighorn and Owl Creek Mountain fronts where all stratigraphic sections were measured. The margins of the basin contain many anticlines and faults creating well-exposed outcroppings of the Middle Jurassic section. Several Paleozoic formations have been targeted for oil and gas exploration since the early 20th century.

Although the Middle Jurassic section does not produce in the Bighorn Basin, geophysical logs targeting deeper formations allow for investigation into the subsurface basinward. In the middle of the basin the Mesozoic section is at least 6100 m (20,000 ft) deep and no geophysical logs are present.

2.2 Tectonic History

Regionally, the Middle Jurassic strata of the Western Cordillera were deposited in a highly complex active tectonic region. As Pangea broke up during the Early Jurassic, the North American continent moved westward in response to the opening of the North Atlantic basin (DeCelles, 2004). A subduction zone developed off the west coast of North America, created an Andean-type arc complex (Brenner and Peterson, 1994) and began moving eastward. During the beginning of the Middle Jurassic, the study area was located in a nearly symmetrical intracratonic basin (Buscher, 2003). The magmatic arc migrated eastward until it collided with the western margin of the continent, which is related to the complex Nevadan orogeny (Buscher, 2003). In response to the encroaching tectonic load, a retro-arc foreland basin developed (Parcell and Williams, 2005) due to downwarping of the continent. DeCelles (2004) suggests the foreland basin developed due to a combination of crustal and upper mantle processes. The Twin Creek Trough subsided in eastern Idaho and Utah as the foreland basin developed (Figure 1).

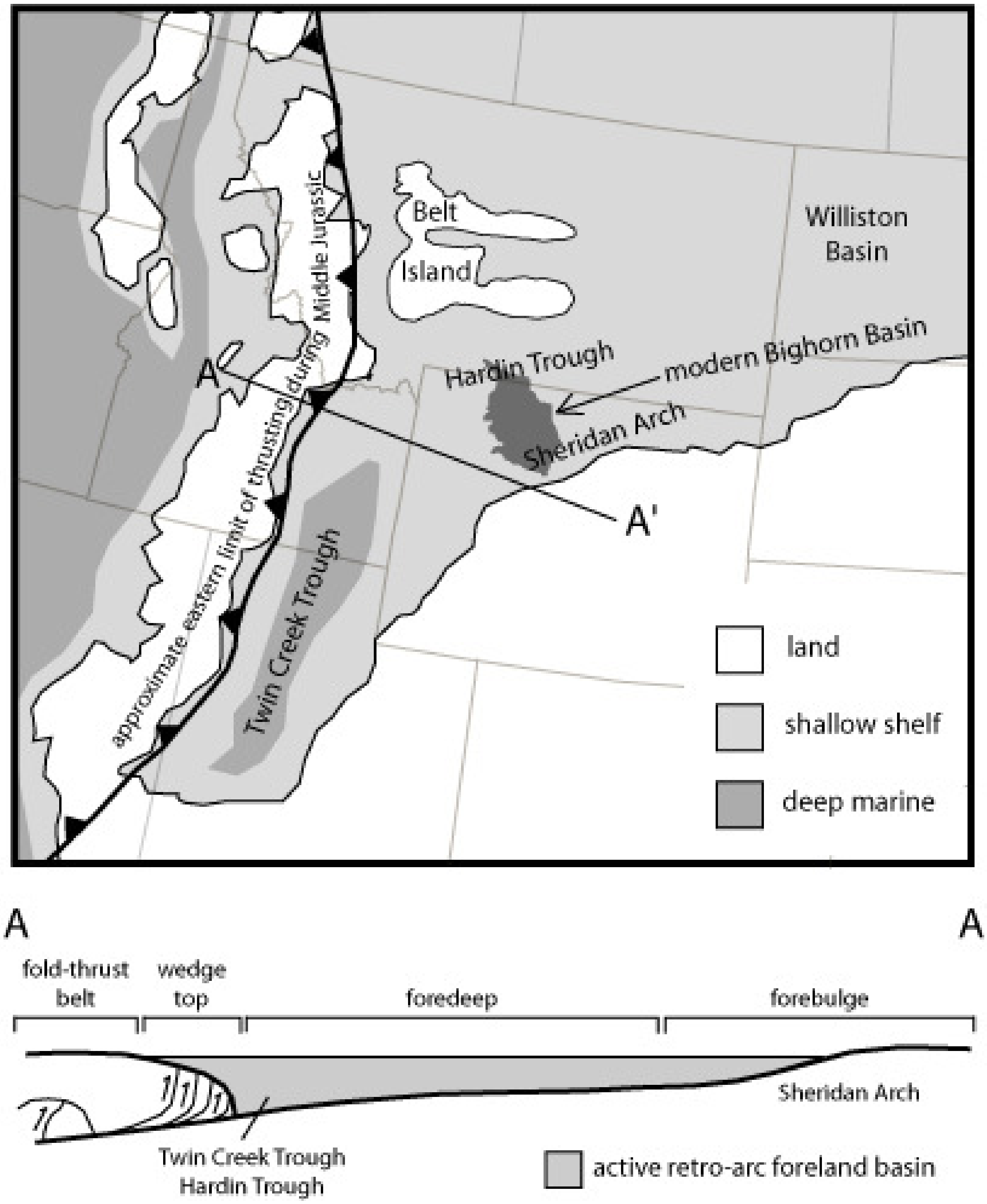

Figure 1: Top: Middle Jurassic paleogeographic reconstruction of the Wyoming Shelf area. Bottom: Cross-section from A to A' across the developing foreland basin. Notice that near the study area, the basin has only slight dip. Modified from (Parcell and Williams, 2005)

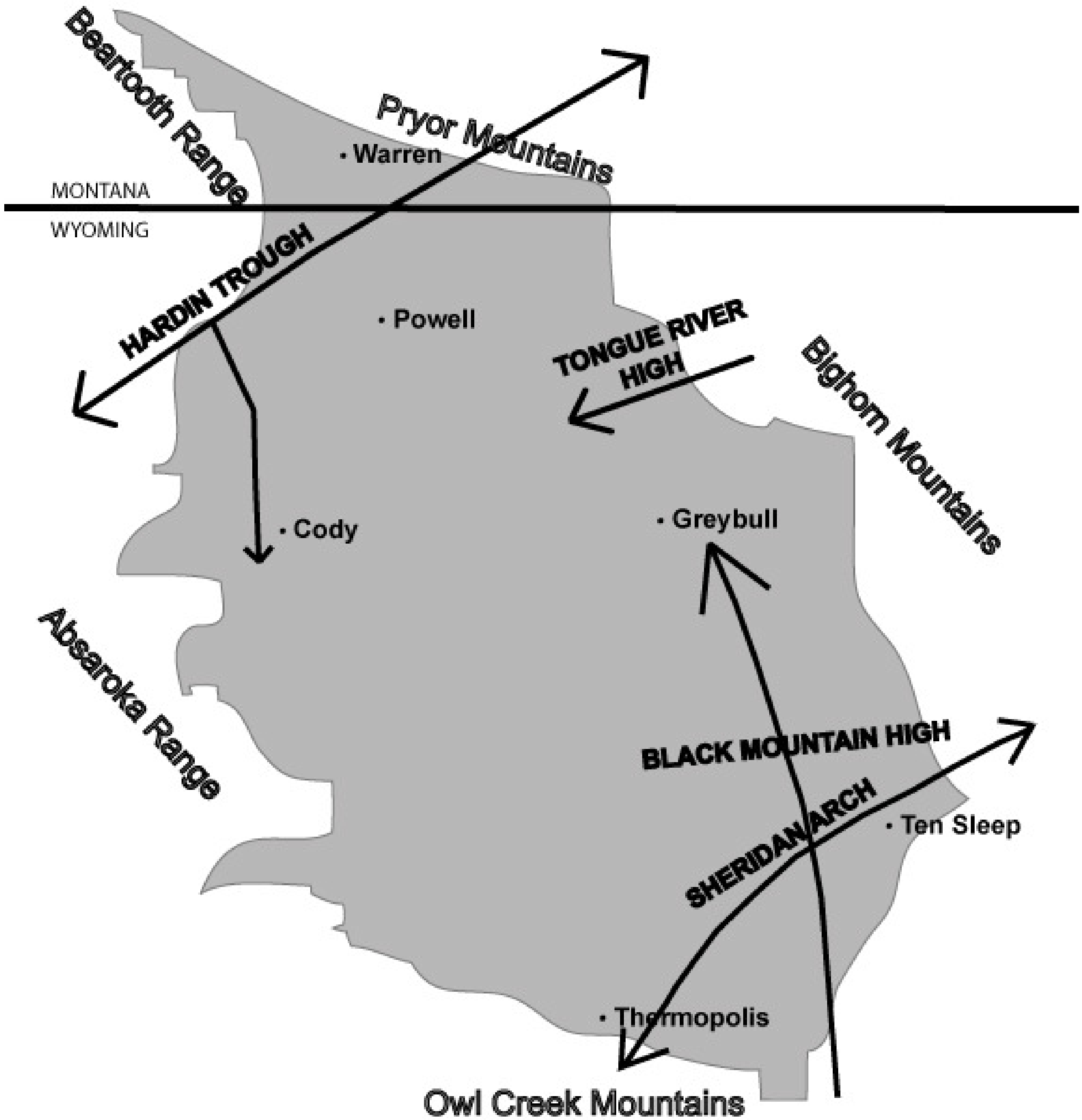

Figure 2: Outline of modern Bighorn Basin and surrounding mountain ranges. Middle Jurassic structural interpretations modified from (Schmude, 2000).

The North American continent was rotating clockwise and migrating north during the island-arc collision (DeCelles, 2004), creating complex stresses in many directions. These stresses caused non-homogenous structural responses in the study area that generally followed predetermined weaknesses from earlier western orogenies dating back to the Precambrian (DeCelles, 2004). Regionally, the Middle Jurassic strata display a change from a symmetrical intracratonic basin to a westward dipping foreland basin style (Buscher, 2003). However, the study area was far from the encroaching tectonic load, creating a slight regional westward dip.

Several structural features were tectonically active during the Middle Jurassic in response to the complex orogen to the west. The uplift or subsidence of these features affected depositional patterns and created localized unconformities in the study area.

Belt Island Complex

The Belt Island Complex (or Boulder High) in Southern Montana is an area believed to have been periodically uplifted and subsided throughout the Middle Jurassic (Peterson, 1954; Imlay, 1980; Schmude, 2000). It is located directly in the path of the transgressions and regressions of marine waters during the Middle Jurassic (Figure 1). It has been suggested that the Belt Island Complex created restricted marine conditions periodically throughout deposition of the Gypsum Spring Formation by creating a barrier that blocked circulation (Imlay, 1956; Peterson, 1957, Schmude, 2000).

Sheridan Arch

The Sheridan Arch is a large anticlinal uplift stretching across the study area in a lineament that runs from south of Thermopolis to north of Tensleep, WY and into the Powder River Basin (Figures 1-2). It was first recognized by Peterson (1954) when he noticed different ostracod assemblages on either side of the structure, suggesting it was a positive feature restricting circulation. It is clearly visible on cross-sections and isopachous maps of the Hulett Member of the Sundance Formation. Evidence suggests that the isopach thinning is not an indication that the Sheridan Arch was present at the time of deposition, but is evidence of an unconformity that eroded and beveled the top of the Middle Jurassic strata (Schmude, 2000). His model suggests that the Sheridan Arch was not a positive feature until its uplift in the Upper Jurassic and therefore had no effect during deposition of the Middle Jurassic sequence.

Black Mountain High

The Black Mountain High is a northwest plunging anticlinal feature in the southeastern portion of the study area mentioned by several previous workers (Pipiringos and O'Sullivan, 1978; Brenner and Peterson, 1994; Schmude, 2000). Schmude (2000) suggested it is a complex structure with alternating anticlines and synclines parallel to the trend of the overall structure. It stretches from the southern edge of the study area north near the town of Greybull, WY (Figure 2). This feature is a NW trending arm of a larger structure originally noted by Love (1939). It is believed to represent a pulse of tectonic uplift at the end of deposition of the Gypsum Spring Formation during late Bajocian to early Bathonian time. Many believe this tectonism to be the event that created the J-2 unconformity in the study area based on isopach thinning and subcrop data across the Black Mountain High (Pipiringos and O'Sullivan, 1978; Schmude, 2000).

Tongue River High

The Tongue River High is a structural feature trending westward from the Bighorn Mountains in between the town of Lovell and Greybull, WY (Figure 2). It is likely related to the Tongue River Lineament, a zone of basement weaknesses extending into the Bighorn Mountains to the east (Schmude, 2000). The structure likely caused isopach thins and possible basin restriction periodically during the Middle Jurassic.

Hardin Trough

The Hardin Trough was a depression that connected the Williston Basin to the northeast and the Twin Creek Trough to the southwest during the Jurassic (Peterson, 1957). The trough is a large feature trending NE but appears to clip only the northern tip of the study area (Figures 1-2). The Red Dome, MT outcrop from Imlay (1956) used in this study appears to be on the fringes of this trough. The Hardin Trough is more pronounced on the west side of the basin where the lower Sundance thickens drastically (Schmude, 2000).

2.3 Paleogeography

The Middle Jurassic section in the Bighorn Basin represents a series of marine inundations. The Middle Jurassic strata were deposited at or near sea level on the distal margins of a retro-arc foreland basin (Figure 1). This caused the area to respond to relative sea level changes as if it were a passive ramp margin setting. The paleotopographic relief was low causing transgressions to affect areas far inland. Differential tectonic uplift periodically altered the paleotopographic relief of the study area causing pinchouts and unconformities.

Hot, arid conditions existed throughout most of the Middle Jurassic. Studies of Jurassic equatorial currents suggest that this was an area that received little to no annual rainfall (Kocurek and Dott, 1983). The arid atmosphere combined with hypersaline marine waters throughout the deposition of the Gypsum Spring Formation prevented faunal diversity in the area. During deposition of the Sundance Formation, open marine waters inundated the land surface further than previous transgressions. Although abundant oysters and belemnites are found, faunal diversity remained relatively low, especially among index fossils.

CHAPTER THREE

METHODOLOGY

The foundation of the study is the six stratigraphic sections measured over three field seasons from 2010-2011. Stratigraphic thicknesses were measured for each section with a Jacob's staff and lithologies were recorded at each interval. Ideally, the base of the massive gypsum at the base of the Gypsum Spring Formation was the target for the bottom of each section measured. However, red shales and siltstones eroded from above or below often cover the contact. The section was measured from within 1-2 meters of the base of the gypsum to the contact with the Upper Jurassic glauconitic sands. A hand lens was used in the field to aid in describing the type, texture and mineralogy of each unit. Samples were collected to be analyzed in the lab under a binocular microscope and for thin section and XRD analysis.

Outcrop gamma ray data were taken at five of the outcrops during the last two field seasons for use in correlating lithologic units from outcrop to subsurface geophysical logs. For each data point a hole approximately 30 cm (1 ft) deep was dug at 0.5 m intervals. Readings of total gamma ray counts per second were taken by hand-held spectrometer (geoMetrics Model GR-310) at each 0.5 m interval. The data were loaded into Microsoft Excel and subsequently into SMT (now IHS) Kingdom Software v. 8.2 to simulate the character of a geophysical log. Kingdom Software is a seismic and geologic interpretation software mainly used in the exploration for petroleum. The type log from Grace Federal 1 is shown in Appendix E.

Figure 3: Measuring section with Jacob's staff. Jan War following with the spectrometer creating an outcrop gamma ray profile, BPSC outcrop.

In the lab the stratigraphic sections were drawn to scale using Canvas X software and lithofacies descriptions and sample numbers accurately labeled next to rock type (Appendix C). All samples were analyzed under a Meiji Techno EMZ-8TR binocular microscope and necessary adjustments were made to the lithologies on the stratigraphic sections. Samples needing further examination were prepared for thin section work (Appendix A) and XRD analysis.

Select samples were prepared and analyzed using a Rigaku Miniflex II XRD machine and Jade Software v. 9 to clarify unidentified minerals. I planned to use the XRD results to aid in correlating the carbonate units within the measured sections. However, the carbonate samples are nearly all calcite with few minor minerals existing in multiple samples and the use of the XRD for correlation purposes was abandoned.

Eighteen samples were prepared and sent to National Petrographic Service, Inc. in Houston to make thin sections. The samples were analyzed under a Meiji Mx 9300 polarizing petrographic microscope to determine texture, mineralogy, fossils and diagenetic features. Thin section pictures were taken with a SPOT Insight QE camera.

Depth-registered raster images of geophysical logs were purchased from MJ Systems and loaded into Kingdom. Log curves were digitized from the raster images containing gamma ray, resistivity or Laterologs. Gamma ray data was the main criteria for selecting well logs in order to correlate to outcrop GR data. Gamma ray and resistivity or Laterologs were also selected because they display lithologic changes in the gypsum, shales and carbonates of the lower units well.

The six measured stratigraphic sections were loaded into Kingdom as raster images and depth correlated. Nineteen stratigraphic sections published in (Imlay, 1956) were loaded into Kingdom in the same manner. Outcrop GR log curves created in Excel were loaded into Kingdom at the correct depth intervals to aid in correlation.

An extensive correlation from outcrop to subsurface was completed using 25 stratigraphic sections and 55 wells with geophysical logs. Cross-sections were made in several orientations to show erosional surfaces, and to identify thinning or pinchouts of the lithologic units to locate paleotopographic highs (Plates 8-11). Isopachous maps were generated to further support the cross-sections and to determine the timing of paleotectonic events (Plates 1-7). One thing to note is that the geophysical logs are registered to measured depth (MD) and not true vertical depth (TVD) meaning the thicknesses of lithologic units are actually true vertical thickness (TVT) instead of true stratigraphic thickness (TST). Wells having formation dipmeters are sparse (only three) in the study area. Regional dip calculations using the three-point method were unsuccessful due to numerous antiforms and synforms in the study area and too sparse well data. To overcome this problem, a ratio of the true vertical thickness (TVT) of each lithologic unit within a formation to the TVT of that formation was created for each well. For example, if Formation A contains Lithologic Unit 1, the ratio is the TVT of Lithologic Unit 1 divided by the TVT of Formation A. This results in a pseudo-isopachous map displaying the thickness of a unit as a percentage of the overall formation thickness. These percentages were gridded as isopachous maps in Kingdom and compared to the original isopachs. The only anomalous areas occurred at locations where a given lithologic unit was heavily eroded or missing, which was expected because it distorts the overall formation thickness. There were no anomalies in other parts of the study area so I assume that slight changes in formation dip do not have an intense effect on formation thicknesses and therefore the isopachs. The isopachous maps in this report are truly isochore maps, without the percentages applied.

A sequence stratigraphic model was developed using lithofacies descriptions and environments of deposition complimented with allostratigraphic analysis. Three transgressive-regressive cycles were noted, disregarding sequence hierarchy. The cycle boundaries were placed at unconformable surfaces or their assumed correlative conformities and maximum flooding surfaces were marked. A relative sea level curve was developed and displayed alongside the stratigraphic sections (Appendix C). Possible connections to changes in eustacy, tectonics or sediment influx were suggested when plausible.

CHAPTER FOUR

LITHOSTRATIGRAPHY

4.1 General Stratigraphy

The Middle Jurassic section in the study area lies unconformably on the Triassic Chugwater Group. This is an amalgamation of the J-0 and J-1 surfaces of Pipiringos and O'Sullivan (1978) which is said to be a regional unconformity, separating the Middle Jurassic lower Sundance Formation from the Upper Jurassic upper Sundance Formation. The section in the Bighorn Basin represents three cycles of relative sea level rise and fall. The Middle Jurassic section can be seen in Figure 3.

Gypsum Spring Formation

The type section for the Gypsum Spring Formation measured by Love (1939) in the Owl Creek Mountains is problematic for use because it is different from the Gypsum Spring section in the Bighorn Basin. It consists of a basal gypsum member, a middle red claystone member and an upper gray limestone member. Above the limestone member of the Gypsum Spring most everywhere in the study area lies a red claystone nearly identical lithologically to the other red claystone member below the limestone. There is an ongoing debate whether this upper red claystone is part of the Gypsum Spring Formation or extention of part of the Piper Formation of Montana. The Piper Formation at its type section in central Montana consists of a basal gypsum and red claystone member, a middle limestone member and an upper red claystone member. This is remarkably consistent with the Gypsum Spring section in Wyoming plus the upper red claystone. It may be that the Piper and the Gypsum Spring are in fact equivalent and that the Gypsum Spring type section is incomplete (Imlay, 1945; Parcell and Williams, 2005). However, many claim the J-2 unconformity lies at the top of the gray limestone member of the Gypsum Spring Formation and only the upper red claystone member of the Piper transgressed into the Bighorn Basin (Pipiringos and O'Sullivan, 1978; Imlay, 1980; Schmude, 2000). Additional work needs to be completed in Montana to resolve this dilemma as it is out of the scope of this project.

For simplification, I have split the section older than the Sundance Formation into four readily identifiable units based on color and lithology. From oldest to youngest the units are as follows: Basal Gypsum unit, Red Claystone A, Gray Limestone unit and Red Claystone B. I present this nomenclature to establish a model for investigation of the local units on the east side of the Bighorn Basin without attempting a correlation to more regional stratigraphic markers.

The age of the Gypsum Spring Formation is thought to be Early to Middle Bajocian based on fossil evidence presented by Imlay (1980). This would include the Basal Gypsum, Red Claystone A and the Gray Limestone units in this report. However, ammonite genera found on the west side of the basin suggest a late Bajocian age for the Gray Limestone unit (Kvale et al., 2001). It has been suggested that the Upper Member of the Piper Formation (Red Claystone B in this report) is Bathonian in age based on fossil evidence. This would place the J-2 unconformity between the Gray Limestone unit and Red Claystone B. At this time, further investigation is needed to support these claims.

Sundance Formation

The Sundance Formation is generally classified into two informal members called the lower and upper Sundance. In the Bighorn Basin, the lower Sundance consists of green and yellow marine sandstones, shales and limestones and is broken into three members- The Canyon Springs, Stockade Beaver Shale and Hulett Members. This brings about some inherent confusion because a member of a formation is generally not classified within another informal member. The reason for the informal lower and upper Sundance classification scheme is rooted in the fact that the lower Sundance incorporates the Middle Jurassic section, while the upper Sundance is Upper Jurassic, supposedly lying above a regional unconformity. The lower and upper Sundance are stratigraphic equivalents to the Rierdon and Swift Formations, respectively, of southern Montana (Imlay, 1956). Pipiringos and O'Sullivan (1978) place the J-4 unconformity at the top of the lower Sundance in Wyoming (Rierdon Formation in Montana). Kvale et al. (2001) places the J-3 at this boundary, but still agrees that the upper Sundance is Upper Jurassic. Although the lower and upper Sundance could probably both be elevated to formation status, the Sundance Formation is widespread with many different members and facies changes covering portions of several states. Elevating these to formation status could cause even more problems with people using it in distal locations where the ages are not the same.

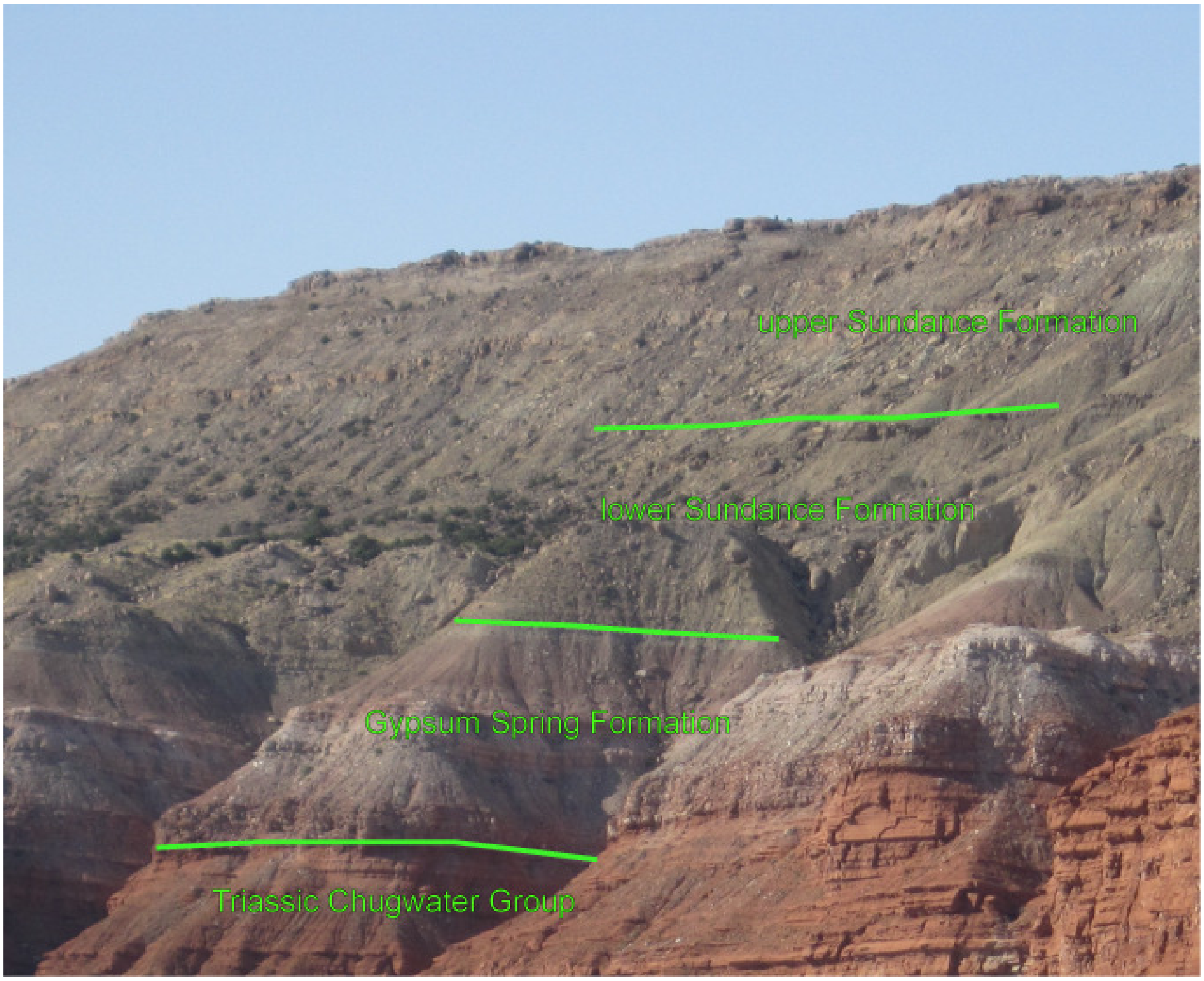

Figure 3: Photograph showing entire Middle Jurassic section from the base of the Gypsum Spring Formation to the top of the lower Sundance Formation, Bighorn National Forest, WY.

Nearly all previous workers agree with or at least tolerate the lower and upper Sundance labeling scheme, as well as the Canyon Springs, Stockade Beaver and Hulett Members of the lower Sundance in the Bighorn Basin. For the sake of clarity, this nomenclature is used in this report.

4.2 Basal Gypsum Unit

Lithology

The Middle Jurassic section in the Bighorn Basin lies on an amalgamation of the J-0 and J-1 unconformities Below this surface the entire Lower Jurassic section is missing. The Basal Gypsum unit is a widespread, thick gypsum layer containing thin red shale beds representing high-order cycles. The gypsum is up to 30 m (100 ft) thick and is remarkably consistent throughout the study area with the exception of the Crooked Creek Road outcrop near the Montana/Wyoming border where it is missing. In outcrop the gypsum interval appears as a brecciated, white massive gypsum with thin red shale beds (Figure 5). Although originally gypsum, anhydrite dominates this unit in the subsurface (Meyer, 1984). The current gypsum formed from the rehydration of the anhydrite as it was uplifted (Meyer, 1984). The gypsum may have developed this broken texture as rehydration weakened the integrity of the rock.

The J-1 unconformity is often covered by either the red siltstones of the underlying Chugwater Group or the weathered shales of Red Claystone A and considerable digging is often required to expose it. A chert breccia has been noted at the base of the Basal Gypsum unit (Pipiringos and O'Sullivan, 1978; Imlay, 1956, 1980;

Schmude, 2000) and was found at an outcrop east of the Between Potato Ridge and South Chugwater Bluff outcrop. Hand sample displays a hard chert with alternating wavy layers of white, gray and pink colors (Sample SCB 1). A thin section of this sample shows many small calcite inclusions and staining with Alizarin Red-S confirms this.

Outcrop Gamma Ray and Subsurface Geophysical Response

Although the Chugwater-Gypsum Spring contact is often covered and difficult to pinpoint in outcrop, it is the most recognizable surface in subsurface geophysical logs because of the sharp decrease in gamma ray response at the base of the gypsum (Appendix E). The broken or brecciated texture displayed in outcrop is not present in geophysical logs, so others have suggested it is a recent dissolution-collapse feature (Schmude, 2000). High-order shallowing upward cycles present within the unit are marked by alternating beds of red claystone, dolomite and gypsum (Meyer, 1984). These cycles are visible in the geophysical logs, but were not noted in outcrop in this study.

Environment of Deposition

The Basal Gypsum unit represents the first inundation of the sea during the Middle Jurassic into a broad basin stretching from eastern Idaho to eastern Montana. The gypsum is interpreted to have formed in a restricted marine environment under intense evaporitic conditions. The gypsum formed in shallow water (<10 m) periodically restricted from ocean currents.

Figure 5: Brecciated texture of gypsum covered with red shale in the Basal Gypsum unit of the Gypsum Spring Formation.

No high-order evaporates in the sequence are present in the basin, so periodic influx of marine waters must have kept the water saturated with respect to gypsum, but below the saturation point of high-order evaporites.

The gypsum is a widespread unit across the basin, which suggests that the water chemistry was similar throughout. Therefore, the controls on water chemistry must have been basin-wide, rather than restricted to changes in water chemistry related to lagoons. Meyer (1984) suggested the “Evaporative Drawdown Model” of (Maiklem, 1971) could explain the periodic inundations of marine water. The Belt Island Complex in northern Montana was probably uplifted to a positive topographic position, blocking circulation of marine waters while allowing a relatively weak source of water into the basin through channels cut into it. Others claim the Belt Island Complex was never completely submerged and was a submarine swell acting as a barrier to prevent currents from entering the basin (Peterson, 1954). Spring tides and storms could still provide a periodic source of marine water. Although the mechanism is unclear, west of the Belt Island Complex, no age equivalent evaporites are found (Peterson, 1972). This suggests that the Belt Island Complex did affect water chemistry in the basin and more open marine conditions existed west of this structure during the Middle Jurassic.

4.3 Red Claystone A

Lithology

The Basal Gypsum unit is overlain by Red Claystone A everywhere in the study area. This unit ranges in thickness from 0 to 12 m (40 ft) and consists of dark red claystones and shales and often containing thin gypsum or green shale lenses (Figure

6). The claystones range from a blocky to fissile texture. In outcrop, the claystones are generally highly weathered and often cover the basal gypsum with red shales.

Outcrop Gamma Ray and Subsurface Geophysical Response

The red claystones in geophysical logs and in outcrop are marked by a gradual increase upward in the gamma ray curve often with a sharp decrease from the occasional gypsum lens (Appendix E). The resistivity curve registers much lower than the underlying Basal Gypsum or the limestones above.

Environment of Deposition

Red claystone A has few indicators of environment of deposition other than the highly oxidized red sediment it contains. It is interpreted to be supratidal to terrestrial in origin due to the combination of thin gypsum layers and redbeds. The gypsum layers are interpreted to have formed in sabkha conditions due to a combination of capillary pumping and evaporation (Shinn, 1983). The redbeds making up the majority of the unit formed near the transition zone from supratidal to terrestrial conditions. The red beds are from the oxidation of iron within the deposits while exposed to the air (Potter, 1980). The absence of root casts and burrows suggests that the region was extremely arid, highly saline and unfavorable to plant or animal life.

The red beds of the Middle Jurassic sequence are thought to be partially reworked from adjacent exposed Triassic or Pennsylvanian-Permian red beds (Peterson, 1972). Many of the Middle Jurassic red claystones probably underwent in situ oxidation of iron during deposition in the hot, hyperarid climate (Doyle, 1984).

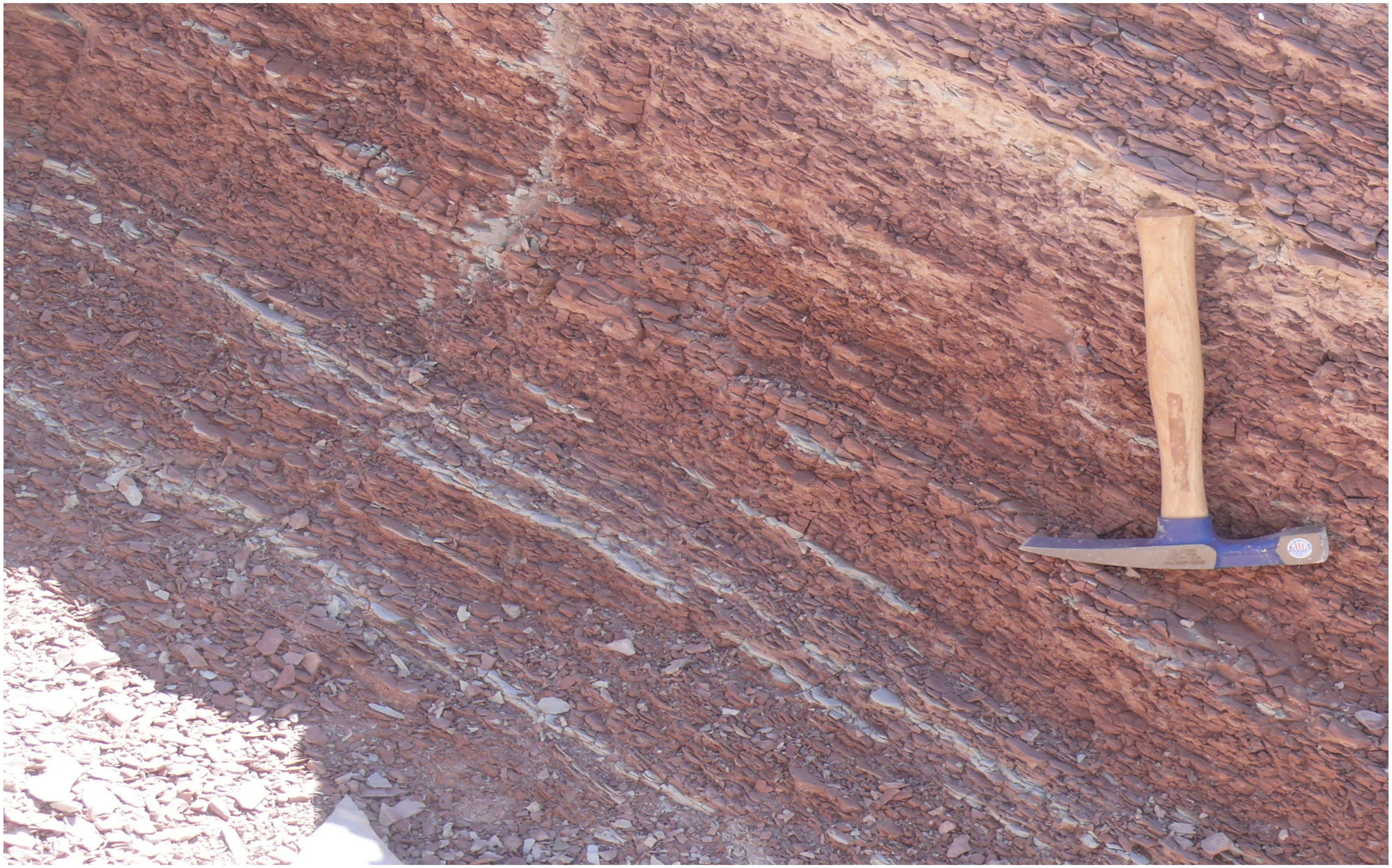

Figure 6: Alternating red and gray blocky claystones of Red Claystone A. Hammer length is 30 cm.

4.4 Gray Limestone Unit

Lithology

The Gray Limestone unit lies above Red Claystone A consisting mainly of gray or green mudstones (Figure 7) and wackestones that are often dolomitic. The carbonates alternate with beds of gray and green calcareous shales. Red shales occur frequently in the upper part of the unit and are commonly associated with the presence of thin gypsum layers. The unit ranges in thickness from 25 m (80 ft) to 0 m where it has been removed in the southeastern portion of the study area. At the West Sheep Mountain Canyon outcrop, algal heads are present on bedding planes within the mudstones and others have been noted on the west side of the Bighorn Basin (Williams, 2004; Parcell and Williams, 2005). West of the study area, the limestones contain more packstones, grainstones and wackestones with fewer mudstones. The Gray Limestone unit in outcrop and in the subsurface generally displays three high-order cycles on the east side of the basin identifiable by three limestone beds alternating with shales.

The upper limestone layers of the unit often contain chert nodules that many believe are the source of the chert pebble lag deposits said to mark unconformities within the basin (Pipiringos and O'Sullivan, 1978, O'Sullivan and Pipiringos, 1997; Schmude 2000). However, the chert bedded in the formation do not have the polished, subangular texture described by Pipiringos & O'Sullivan (1978). Schmude (2000) claims that the J-2 unconformity exists at the top of the “Cherty Limestone” of the Gypsum Spring Formation as evidenced by the chert pebble lag present. Discrepancy between workers on the placement of the top of this limestone member has caused confusion in the literature in the past. The fact that this top either marks an unconformity or simply a change in lithology has significant stratigraphic importance and is explained later in this report.

Outcrop Gamma Ray and Subsurface Geophysical Response

The high-order cycles of the Gray Limestone unit are easily identifiable in geophysical logs but more difficult in outcrop gamma ray profiles. The carbonate mudstones show up as a sharp gamma ray decrease followed by a sharp increase from the presence of the interbedded shales (Appendix E). The resistivity curves react inversely, sharply increasing with every gamma ray decrease.

In the type log (Appendix E) the Gray Limestone unit displays three cycles. This is similar everywhere except in the southeastern portion where the top of the unit has been eroded.

Environment of Deposition

The Gray Limestone unit represents a maximum flooding surface within the second Middle Jurassic transgressive-regressive cycle. The environment of deposition is interpreted to be subtidal to intertidal. Some of the mudstones were deposited in shallow water below wave base (Parcell and Williams, 2005) on the west side of the basin. Further eastward, the lack of dessication cracks and the presence of mud suggest a lower intertidal environment (Parcell and Williams, 2005).

Figure 7: Resistant gray mudstones of the Gray Limestone unit, Gypsum Spring Formation.

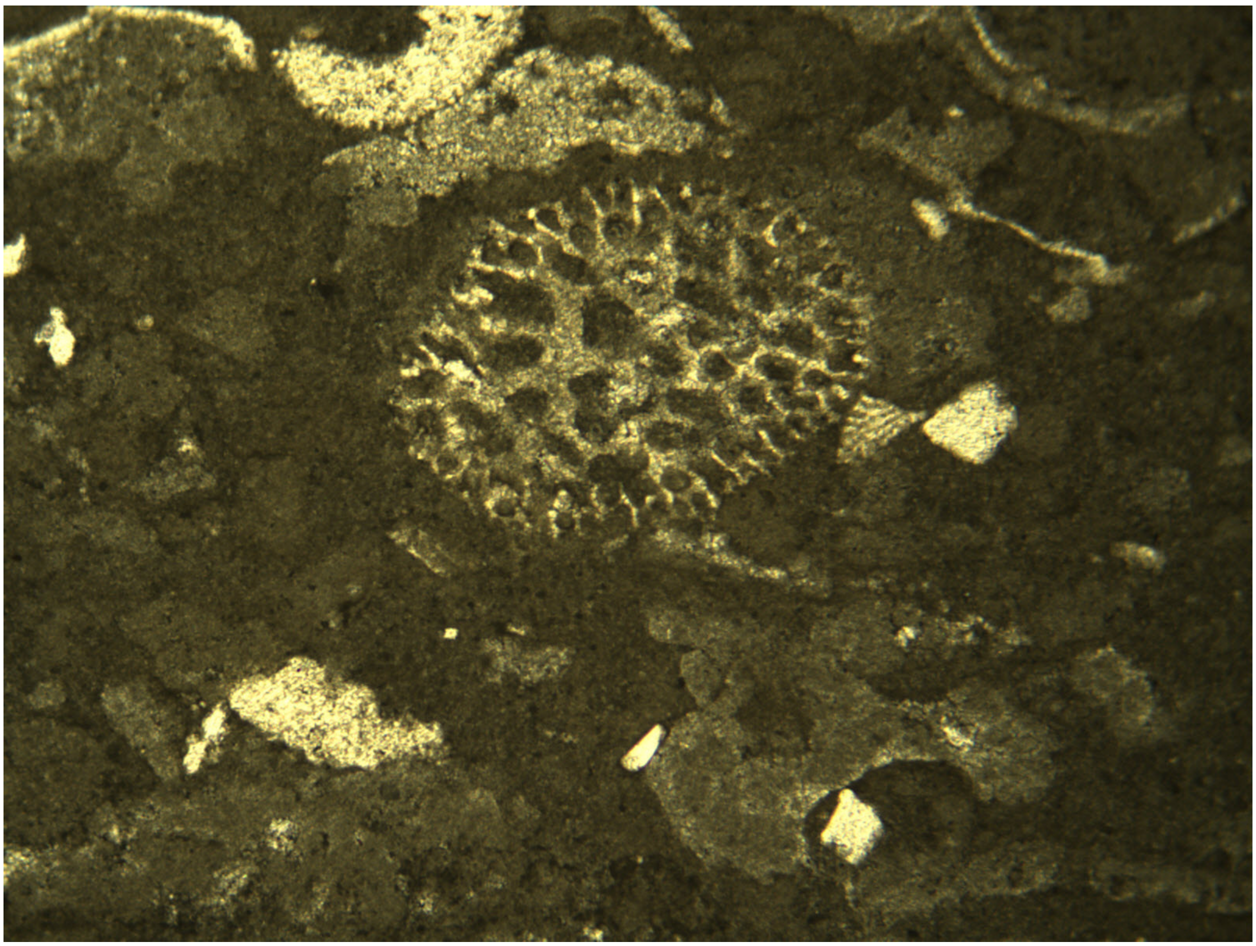

Figure 8: Green calcareous algae in Thin Section WSMC 2 from the Gray Limestone unit. PPL, 10X magnification.

The presence of calcareous algae (Figure 8), pelecypods, and a possible ostracod in a wackestone (Sample WSMC 2) supports a lower to upper intertidal or even supratidal environment on the eastern side of the basin (Burke, personal communication).

A dinosaur tracksite was found near the town of Shell near the base of the Gray Limestone unit by Kvale et al. (2001). They were found in a layer of "Fenestral fabric…hemispheroidal stromatolites and oncolites, and laminated micritic mudstones," (Kvale et al., 2001, p. 247). Fenestrae and sheet cracks were found in many of the mudstone samples within the Gray Limestone in this study. These features form as gas escape structures in tidal flats (Shinn, 1983). This evidence suggests that periodically during Gray Limestone unit deposition, tidal flat or sabkha conditions existed on the east side of the Bighorn Basin, especially near paleotopographic highs. The grain-supported limestones to the west of the study area suggest an increasing energy regime to the west, probably due to increasing water depth basinward.

There are three distinct high-order cycles within the Gray Limestone unit identifiable in outcrop and by well log signatures, except where the unit has been eroded in the southeastern section of the study area. These periodic inundations probably did not account for more than a few meters of change in water depth. However, the generally flat paleotopography of the study area would have allowed minor water depth changes to affect lithologies over a large area.

4.5 Red Claystone B

Lithology

Red Claystone B consists of dark red claystones, with lenses of limestone, dolomite and gypsum. The lithology is very similar to Red Claystone A, which causes some confusion with regional correlation. Claystone B in outcrop appears as red weathered shales (Figure 9). It ranges from 0 to 23 m (75 ft), thins from N to S and pinches out onto the Black Mountain High in the southern part of the study area.

Previous workers (Pipiringos and O'Sullivan, 1978; Imlay, 1980; Schmude, 2000) claim that the Red Claystone B in this report is equivalent to the Upper Member of the Piper Formation in southern Montana, which consists mainly of red shales and minor gypsum. In their models, the Piper transgressed southward onto the newly uplifted Black Mountain High, which was eroded to form the J-2 unconformity. This surface is interpreted as separating the top of the Gypsum Spring Formation from the overlying Upper Member of the Piper Formation. However, as previously mentioned, the placement of the tops of certain lithologic units are in disagreement or unclear. At this point the data in this study do not prove which model is correct.

At the top of Claystone B at 8 outcrops used in the study area, a chert pebble lag separates the dark red claystones from the overlying oolites of the Canyon Springs Member of the lower Sundance. This chert lag deposit and the abrupt change from regressive to transgressive deposits marks an unconformity and the end of the second transgressive-regressive cycle in the Middle Jurassic. However, this unconformity appears to only be present on the east side of the basin. Meyer (1984) claims no evidence of an unconformity other than a change in lithology exists on the west side of the Bighorn Basin, so it may be a localized surface. The cherts are believed to be derived from the Gray Limestone unit of the Gypsum Spring Formation and reworked as the sea transgressed during deposition of the overlying Canyon Springs Member. It could be that the east side of the Bighorn Basin was more prone to tectonic uplift due to the orientation of older crustal weaknesses where Middle Jurassic faults developed. Chert present at the base of the overlying Canyon Springs Member in several sections in the southeastern portion of the study area could have been shed off of the Black Mountain High and reworked on the east side of the basin due to wave action.

A white dolomitic limestone that is here placed in the Red Claystone B is marked as the top of the Gray Limestone unit by Pipiringos and O'Sullivan (1978) and Imlay (1980). Chert pebbles were found at the top of this layer and are assumed to represent the J-2 unconformity. Sample SHV X55 of this mudstone from the South Hyattville outcrop has a thin layer of chert at the top, where an irregular surface separates it from the mudstone below (Figure 10). However, the chert pebbles said to represent the J-2 surface are larger and were derived from the Gray Limestone unit below.

A layer of cauliflower chert is sometimes found in the Red Claystone B and even near the top of the Gray Limestone Unit. This chert is generally red to pink and off-white in color and has the typical cauliflower texture. Close examinations show that the chert appears to have replaced gypsum and has taken the shape of the gypsum lathes. At the BPSC and South of Hyattville outcrops, the chert is found just below the white dolomitic limestone that at BPSC contains the chert pebble lag believed to be sourced from the Gray Limestone unit below.

Outcrop Gamma Ray and Subsurface Geophysical Response

In the subsurface and in outcrop, Red Claystone B is identified by a gradual increase in the gamma ray curve above the drastic decrease from the carbonates below (Appendix E). This obviously changes depending on where the top of the Gray Limestone unit is placed. There is occasionally a sharp decrease from gypsum, limestone or dolomite lenses. The resistivity curve is relatively flat and registers much lower than the underlying carbonate mudstones or oolitic limestones above.

Environment of Deposition

Claystone B lacks good indicators of environment of deposition. It is interpreted to be supratidal to terrestrial in origin due to its red color. Schmude (2000) interprets it as subtidal restricted marine in origin, but the gypsum layers are very thin (<5 cm) and the cauliflower chert nodules represent silica replacing anhydrite or gypsum in sabkha conditions (Shinn, 1983). The red color of the shales further suggests exposure to dry arid conditions (Potter, 1980). It is believed to represent the regression of the second inundation during the Middle Jurassic after maximum transgression during Gray Limestone deposition. A white dolomitic limestone that is correlateable from Sykes Mountain to Northwest of Hyattville shows slight evidence of subaerial exposure. A thin section (Sample SHV 55) shows megaquartz replacing gypsum blades, likely indicating sabkha conditions for this relatively short interval.

Figure 9: Weathered shales of Red Claystone B with pieces from Gray Limestone unit in float.

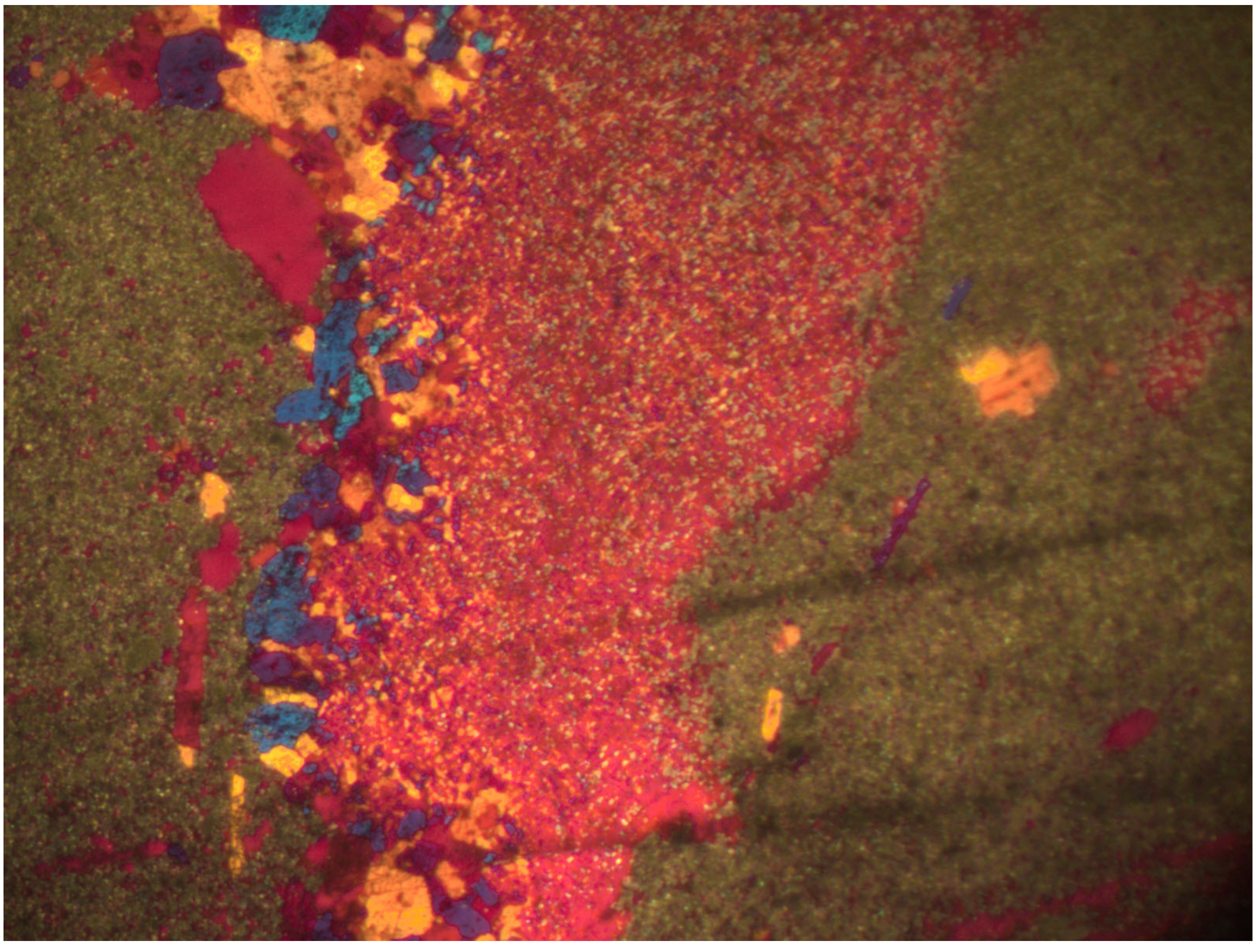

Figure 10: Thin Section SHV X55 showing the calcareous mudstone (brown) – chert and megaquartz (varicolored) irregular interface. Chert infilling is perpendicular to bedding direction. XPL, 4X magnification.

The cauliflower chert layer found below the white dolomitic limestone is interpreted to have formed in supratidal to terrestrial sabkha conditions. Its proximity to the very different angular chert pebbles in two outcrops that are thought to represent J-2 erosion by Pipiringos and O'Sullivan (1978) is perplexing. If they are related to each other in some way, it could have important implications on stratal relations and the sequence stratigraphic model, but it is unclear at this time.

4.6 Canyon Springs Member

Lithology

The Canyon Springs Member is mainly composed of yellow to green marine sandstones or limestones that are commonly oolitic (Figure 11). It is up to 12 m (40 ft) thick and pinches out on a nearly circular paleohigh in the southeastern portion of the study area. It is recognizable in outcrop by the abrupt change in lithology from the red shales of Claystone B to its green or yellow sands and oolites. The ooids are commonly stained with hematite or algal coated (Figure 12) and interspersed with sparry calcite cement, quartz sand and shells. Thin sections show deformation of the ooids, calcite cement and a few broken bivalve shells (Figure 12). The deformation is the same in all directions and was probably due to post cementation compaction, rather than due to tectonic stress. Chert pebbles possibly representing an unconformity at the base of this member have been noted in eight sections by Imlay (1956) and the author. However, some of these may represent an amalgamation of the J-2 and a later unconformity. A dinosaur tracksite was found within the Canyon Springs Member by Kvale et al. (2001)

near the town of Shell, WY (now the Red Gulch Dinosaur Tracksite). He found thousands of small tridactyl tracks (10-15 cm in length) on a mudstone layer traceable locally. The North Sheep Mountain outcrop (Sample NSM 2-111) contains alternating layers of mudstone and very thin microbial laminations and could represent this surface. A thin section shows chert and megaquartz adjacent to lime mudstone separated by an irregular surface (Figure 10), probably representating meteoric influence.

The Canyon Springs Member is thought to be Callovian in age based on fossil evidence provided by Imlay (1956). However, a bentonite layer 10 cm above the layer containing the Red Gulch Dinosaur Tracks was age dated to 165.2+/-3.8 x 10^6 years, making it Bathonian in age (Kvale et al., 2001). A wackestone infilling many of the dinosaur tracks and overlying the exposure surface also contains Middle to Late Bathonian age dinoflagellates (Kvale et al., 2001), which seems to corroborate this claim at least on the east side of the basin.

Outcrop Gamma Ray and Subsurface Geophysical Response

The Canyon Springs Member is readily identifiable in the subsurface by a sharp drop in the gamma gay curve and a substantial increase in the resistivity curve (Appendix E). The shape of the curve is often “boxy” rather than resembling a peak due to the consistent lithology of the member that stands in stark contrast to the units above and below.

Figure 11: Bench-forming oolitic grainstones of the Canyon Springs Member, lower Sundance Formation. North Sheep Mountain, Wyoming.

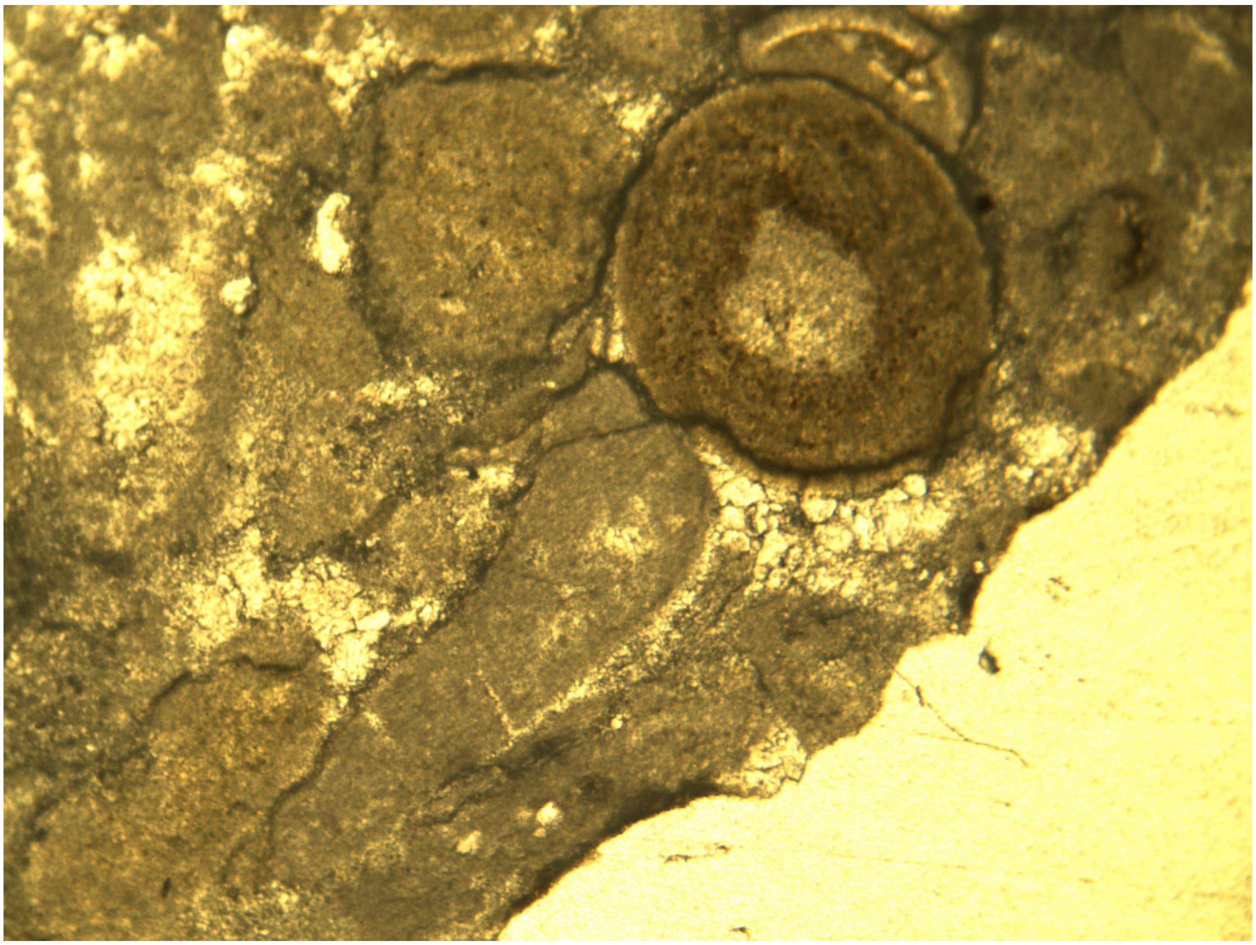

Figure 12: Thin Section BPSC 8 showing algal coated ooid in the Canyon Springs Member, lower Sundance Formation. PPL, 10X magnification.

Environment of Deposition

The Canyon Springs Member is a transgressive deposit marking the beginning of the third marine inundation during the Middle Jurassic. It is interpreted to be a transgressive deposit onlapping the gentle slope of the basin. The oolites formed on shoals or beaches that moved landward as the sea transgressed. The low faunal diversity within the member is likely due to high salinity, hindering organism growth and supporting ooid formation with increased carbonate precipitation (Scholle and Ulmer-Scholle, 2003). Well preserved algal-coated grains could indicate exclusion of herbivorous marine life in this environment.

A dinosaur tracksite found in a mudstone deposit within the member contains desiccation features and is interpreted to be a tidal flat to terrestrial deposit on a paleohigh. Schmude (2000) believes this is the northern terminus of the Black Mountain High. This is interpreted as an unconformity (J-3a) representing a minor regressive phase within the Canyon Springs Member (Kvale et al., 2001). It must have been a relatively short-lived event because of the thinness of the layer. It has been suggested that similar sites could exist on Middle Jurassic paleohighs in other areas such as the Tongue River High, the Belt Island Complex or other locations on the Black Mountain High, (Schmude, 2000) but none were found in this study.

4.7 Stockade Beaver Shale Member

Lithology

The Stockade Beaver Shale Member of the lower Sundance consists mainly of greenish-yellow calcareous shales within the study area. In outcrop, the unit weathers easily and is almost always covered to some extent (Figure 13). The oyster species *Gryphea nebrascensis* is abundant in this member except for at the South of Hyattville outcrop where one belemnite (squid) was the only fossil found. Belemnites are common in the upper part of the member, and appear to be in the same beds as the oysters in some instances. However, they are never found in abundance together and could just be collected during recent erosion of the incompetent shales.

The Stockade Beaver Shale conformably overlies the Canyon Springs Member. The contact is often sharp due to the change in lithology. The Hulett Member of the lower Sundance conformably overlies the Stockade Beaver Shale and is often hard to recognize in outcrop. The contact is gradational and often the only change is an increase in sand and a slightly yellower color.

Outcrop Gamma Ray and Subsurface Geophysical Response

In geophysical logs the gamma ray curve generally increases rapidly above the sandstones and oolites of the Canyon Springs Member (Appendix E). In most logs, this unit registers the highest gamma ray response due to the increase in marine shales deposited in deeper water. It generally becomes sandier upsection as it grades into the Hulett Member above.

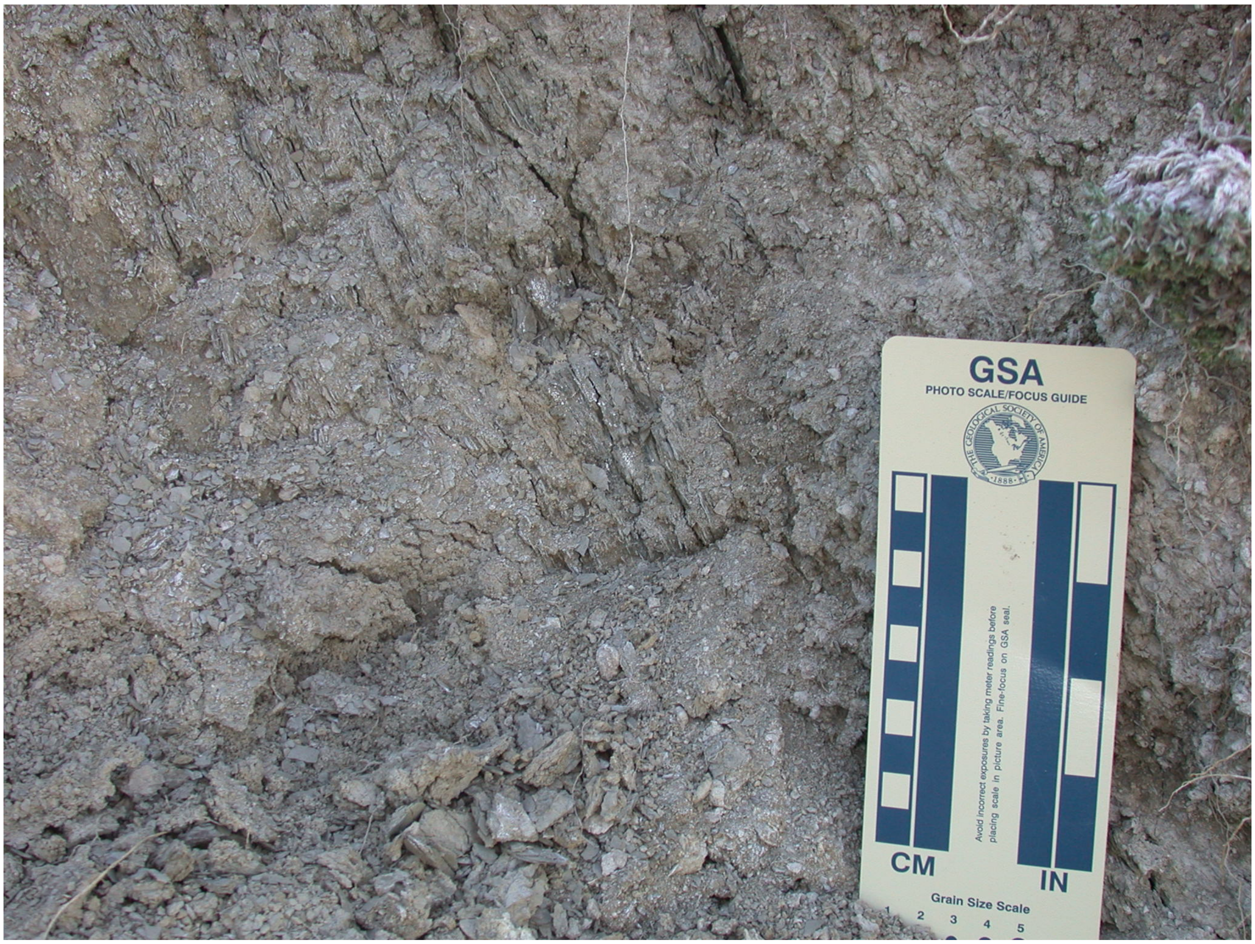

Figure 13: Green calcareous marine shales of the Stockade Beaver Shale Member, lower Sundance Formation.

In outcrop gamma ray profiles, extreme spikes sometimes occur at seemingly random positions within the member. XRD results of the shales have given no obvious indicators of the cause of the high gamma ray counts other than typical clay minerals containing potassium. These high gamma spikes are not traceable between outcrop or wells and appear to be erratic. The Morrison Formation overlies the upper Sundance and often is more resistant than the lower Sundance creating small ridges on the landscape. The Upper Jurassic Morrison Formation is the most mined source of uranium in the United States and runoff from these highs into ephemeral streams could be causing trace amounts of uranium compounds in the shales.

Environment of Deposition

The Stockade Beaver Shale Member was deposited in shallow open marine conditions and represents the furthest transgression of any Middle Jurassic sea. The member represents the maximum flooding surface of the sequence beginning with deposition of the Canyon Springs Member. The calcareous green shales and the presence of the oyster *Gryphea nebrascensis* and belemnites indicate open marine conditions. Oysters commonly appear several meters above the base of the member. As the sea transgressed water conditions could have been unfavorable for oysters for some time or it simply took time for them to reach the basin. Oysters are generally associated with higher water temperatures than belemnites, commonly thought to be directly proportional to water depth (Peterson, 1954). The appearance of belemnites in the upper part of the member suggests that conditions became more open marine with increasing water depth. The relative amount of oysters to belemnites in the upper section could be an indicator of small-scale changes in relative sea level. However, water temperature is not always controlled by depth alone. Peterson (1957) suggested that marine waters coming from the north and circulating in the basin would be colder than waters circulating from equal or lower latitudes. A change in the circulation patterns of marine waters could have some control over the relative abundance of oysters and belemnites. Overall the appearance of belemnites increases upsection probably indicating northward continental drift (Peterson, 1988). In reality, water depth, circulation and continental drift probably all contributed to the changing fossil assemblage in varying degrees of intensity and determining the dominant factor is out of the scope of this study.

4.8 Hulett Member

Lithology

The Hulett Member of the lower Sundance consists of a range of lithologies and facies. Greenish-yellow sandstones (Figure 14), sandy shales, mudstones, oolitic packstones, grainstones and paper thin limestones are all found within the member. The presence of minor amounts of glauconite are often present in the sandstones, but are small in comparison to the marine sands of the upper Sundance. It ranges in thickness from 0 m north of the Montana border to 23 m (75 ft) in the southeastern portion, and thins over the axis of the Sheridan Arch. In outcrop, it is often difficult to identify the Hulett Member due to the nature of the covered shales and can only be identified by a drastic increase in sandiness in relation to the calcareous greenish-yellow shales of the Stockade Beaver Shale Member below.

Outcrop Gamma Ray and Subsurface Geophysical Response

In the subsurface it is easily recognizable by a decrease in the gamma ray curve from the presence of quartz and calcite and a corresponding increase in the resistivity curve (Appendix E). At the top of the member there is a significant gamma ray kick along with a decrease in the resistivity that marks the top of the member. This is in turn marks the top of the Middle Jurassic section within the Bighorn Basin.

Environment of Deposition

The sandstones, and oolitic packstones and grainstones of the Hulett Member probably formed in shallow intertidal to subtidal zones during the last Middle Jurassic regression represented in the Bighorn Basin. The oolitic packstones and grainstones formed around the paleotopographic highs due to shoaling in higher energy environments. The paper thin limestone facies found at the Crooked Creek Road and North Sheep Mountain outcrops is thought to represent a restricted lagoonal deposit caused by uplift of the Tongue River High (Schmude, 2000). This facies is said to contain fossils of the fish (*Hulettia americana*), though none were found at either outcrop in this study.

At the northernmost outcrop, the Hulett Member is not present (Plates 7, 9). This location was probably on the margins of the Hardin Trough. This depression contained deeper water so the higher energy facies are not present. Facies similar to the Stockade Beaver Shale Member here are probably time correlative to the packstones and grainstones of the Hulett Member elsewhere.

Figure 14: Bench-forming calcareous sandstones of the Hulett Member, lower Sundance Formation.

CHAPTER 5

CORRELATION

Outcrop to subsurface correlations were completed using geophysical well logs and stratigraphic sections. Tops were set for each of the six lithologic units and they were correlated throughout the study area. Isopach maps for each of the lithologic units are shown in (Plates 1-7). A north to south representative cross-section was compiled (Plates 10-11) displaying the overall thinning of the Gypsum Spring Formation onto the Black Mountain High. A west to east cross-section (Plate 9) was made across a portion of the Black Mountain High that was still a positive topographic feature during deposition of the Canyon Springs Member of the lower Sundance Formation. The top of the Hulett Member was chosen as the datum and all stratigraphic sections and geophysical logs were hung from this formation top. This is a widespread transgressive surface implied to represent rapid transgression at the end of the Middle Jurassic and therefore is close to a timeline.

5.1 Gypsum Spring Formation

The Gypsum Spring Formation lies unconformably on rocks of the Triassic Chugwater Group. This surface is an amalgamation of the J-0 and J-1 unconformities of Pipiringos and O'Sullivan (1978) and is traceable throughout the study area. A basal chert breccia was noted by Pipiringos and O'Sullivan (1978) at this contact and was found at an outcrop east of the BPSC outcrop (Between Potato Ridge and South Chugwater Bluff) in this study. In every location except for the Crooked Creek Road outcrop, the Basal Gypsum unit lies on this surface. The contact with the overlying Red Claystone A is sharp but conformable and can be traced throughout the study area (Plates 9-11). Similar to the Chugwater-Gypsum Spring contact, this is easily recognized in geophysical logs but often covered in outcrop.

Deposition of the Basal Gypsum unit and Red Claystone A were unaffected by the uplift of the Black Mountain High as is shown by the relatively unchanging thicknesses from north to south until the southernmost portion of the study area where the Gray Limestone unit was completely removed and Red Claystone A is thinned due to erosion (Plates 1-2, 9-11). The isopach map for the Basal Gypsum member (Plate 1) shows very slight thickness changes representing the paleotopography of the basin of deposition. As the sea transgressed, marine waters filled the depressions left by J-1 erosion. The Gray Limestone unit lies directly on the Triassic Chugwater beds at Crooked Creek Road where a paleotopographic high existed that precluded deposition of the gypsum and claystones (Plate 10). It was not very extensive as can be seen on the isopach map (Plates 4-5). Red Claystone A at the West Sheep Mountain Canyon outcrop thickens drastically. It is possible that the top of Red Claystone A is lower than marked and the characteristic carbonates of the bottom of the Gray Limestone unit are missing. The outcrop GR curve shows a decrease about one meter down, which could be an increase in calcite as the claystones gradually progress into the Gray Limestone unit.

The Gray Limestone unit of the Gypsum Spring Formation shows erosional thinning from north to south and is missing completely at three locations in the south (Plates 3, 9-10). The line of truncation is arched and trends northwest, representing the most intensely uplifted area in the study area. However, this unit was deposited before uplift of the Black Mountain High. The carbonate mudstones in the lower part of the unit are correlatable across the study area and no significant thinning occurs except in the south.

The much disputed J-2 unconformity is said to be a major Jurassic unconformity that is recognized from Arizona to Canada along the Western Cordillera. A chert pebble lag is said to represent subaerial exposure after a pulse of tectonic uplift (Pipiringos and O'Sullivan, 1978). The problem with the J-2 unconformity is that no one can agree on where to place it. Pipiringos and O'Sullivan (1978), Imlay (1980) and Schmude (2000) claim that the J-2 surface marks the top of the limestone unit of the Gypsum Spring Formation. They state that the upper member of the Piper Formation of Montana is present above this unconformity in the Bighorn Basin because it transgressed southward onto a tectonically uplifted platform called the Black Mountain High. However, the literature shows that all three papers place the chert pebble lag in different places in the stratigraphic record.

One item of considerable importance is that along the east side of the basin, Imlay (1956) breaks the Gypsum Spring Formation into eight lithologic units that can be correlated from Sykes Mountain, WY to Northwest of Hyattville (Imlay, 1956, p. 578). He writes, "[units] 1 and 2 are equivalent to the lower member of the Piper Formation as exposed in the Pryor Mountains, 3-5 are probably equivalent to the middle member of the Piper Formation, and 6-8 equivalent to the upper member," (Imlay, 1956, p. 579). Pipiringos & O'Sullivan (1978) and Schmude (2000) place the top of the Gypsum Spring Formation at the top of the Gray Limestone member of this report. This coincides with the top of the original (Love, 1939) type section which is known to be incomplete. Both Pipiringos and O'Sullivan (1978) and Schmude (2000) claim that the J-2 unconformity separates the "Cherty Limestone" member of the Gypsum Spring Formation from the red claystones of the Upper Member of the Piper Formation and that a chert pebble lag marks the boundary. However, the blocky chert horizon at outcrops at Sykes Mountain and Northwest of Hyattville is noted at the top of lithologic unit 7 (Imlay, 1956, p. 578) - a thin layer of dolomitic limestone within the red claystones. This means Imlay placed this chert in the upper member of the Piper Formation of Pipiringos & O'Sullivan (1978) and Schmude (2000) or Red Claystone B of this study, and not at the top of the Gray Limestone member. Pipiringos & O'Sullivan (1978) and Schmude (2000) must have included the dolomitic limestone as part of the Gray Limestone unit, thus placing the chert at a different stratigraphic horizon than Imlay.

To further complicate matters, several years later Imlay (1980) changed his interpretation to agree with Pipiringos and O'Sullivan (1978) by placing the top of the Gypsum Spring Formation at lithologic unit 7 (Imlay, 1956, p. 578) and included only unit 8 in the Piper Formation. Imlay (1980) also claims that an unconformity at the base of the Piper Formation is "further substantiated by the presence of dark-gray wind-polished chert pebbles at the base of 86 feet (26 m) of dark-red claystone that underlies the Sundance Formation near the east end of Sykes Mountain", (Imlay, 1980, p. 84). However, at Sykes Mountain, 26 m from the top of what Imlay (1980) called the "Piper Formation" would place the chert pebbles exactly at the top of lithologic unit 5 (Imlay, 1956, p. 578). This stratigraphic position is not at the top of the dense, white dolomitic limestone later claimed as the top of the Gypsum Spring Formation.

A poster by O'Sullivan and Pipiringos (1997) placed a chert pebble conglomerate found at an outcrop northwest of Hyattville (Imlay, 1956, p. 578) at the base of their Piper Formation, therefore marking the J-2 unconformity. However, Kvale et al. (2001) noted that this chert was actually found at the base of the Canyon Springs Member of the Sundance, and found no evidence in the field of a chert pebble lag at the base of the Piper Formation of Pipiringos and O'Sullivan (1978).

It appears that even when certain workers think they are in agreement, further investigation proves otherwise. This lack of agreement concerning the tops of lithologic units is a definite cause of confusion within the literature over the last few decades. Three outcrops (North Sheep Mountain, and Imlay's Spence Dome and Northwest of Hyattville) display a similar problem. The placement of the top of the Gray Limestone unit can be manipulated in several ways that have drastically different effects on the sequence stratigraphic model. Outcrops BPSC and North Sheep Mountain were the only locations in this study where a chert layer was present at the top of the Gray Limestone unit (Appendix C). However, at North Sheep Mountain, the chert appears bedded, rather than a residual deposit representing an unconformity. At the other three locations where chert is present within the Gray Limestone, it lies below the top of the limestone and is considered here to be chert eroding in place from the limestone it was formed in.

This unconformity appears to be more localized than claimed by Pipiringos and O'Sullivan (1978). If the chert pebbles do mark an unconformity, it definitely exists in the southern half of the study area where affected by uplift of the Black Mountain High. However, Meyer (1984) and others note that in western half of the Bighorn Basin, the top of what he called the lower Gypsum Spring is conformable with the base of the upper Gypsum Spring. Meyer's lower Gypsum Spring includes the Basal Gypsum unit, Red Claystone A and Gray Limestone unit of this report. The paleotopographic relief in the area was not high and it appears that the unconformity was localized on the highs. If this is in fact the J-2 regional unconformity, uplift and erosion must not have been as significant as in other places throughout the Western Cordillera. This is not unreasonable considering the complex tectonic regime occurring to the west. Differential stresses could have focused the brunt of tectonic force away from the basin, sparing it from intense uplift and erosion.

Red Claystone B faces the same problems as previously mentioned simply because its thickness depends on the placement of the top of the Gray Limestone unit. However, the overall trend of this unit is clearly displayed in cross-section (Plate 10-11) and on the isopach map (Plate 4). The unit thins to the south and pinches out on a northwesterly plunging anticline. This isopach displays the true overall shape of the Black Mountain High well.

The truncation line of Red Claystone B runs in a wavy, semi-circular pattern from east of Thermopolis to south of Tensleep. This line is similar to where Schmude (2000) places the truncation line of his equivalent Piper Formation. However, Imlay (1980) states that the line runs approximately from Banner, Wyoming across the Bighorn Mountains to Hyattville, which is considerably farther north. Imlay must be using a different geophysical log signature for the base of the overlying Sundance Formation.

5.2 Lower Sundance Formation

Canyon Springs Member

The Canyon Springs Member of the lower Sundance Formation generally thins from north to south but is missing in several outcrops across the study area (Plates 5, 9-11). These locations were probably paleotopographic highs that precluded deposition of the oolitic limestones or they simply were not preserved. The largest of these is seen on the cross-section from B to B' (Plate 9) and clearly visible on the isopach map (Plate 5). This is interpreted to be a structural or erosional remnant of the Black Mountain High. The hard mudstones in the lower part of the Gray Limestone unit were probably more resistant to weathering than the upper part and remained a positive feature for some time after uplift. The Canyon Springs Member pinches out around this paleohigh. Significant thinning of the underlying Red Claystone B occurs at the West Sheep Mountain Canyon outcrop away from the main structure of the Black Mountain High to the south (Plate 4). There is no Canyon Springs present here and it is possible that another, smaller paleohigh existed that was still present during Sundance transgression.

The Canyon Springs Member is over 10 m (30 ft) thick in places in the north of the study area. This variation in thickness is likely due to undulating paleotopographic relief related to erosion of Red Claystone B. Chert pebbles were found at the contact in several locations that are thought to represent this erosion, probably sourced from the south where the Gray Limestone Member was still exposed, or reworked from earlier residual deposits as the sea transgressed.

North of the truncation line of Red Claystone B the Canyon Springs Member unconformably overlies it where present. This is evidenced by chert pebbles found at the Crooked Creek Road outcrop and were noted at several outcrops by Imlay (1956). However, on the west side of the Bighorn Basin Meyer (1984), Doyle (1984) and Williams (2004) did not locate any chert at this contact. An abrupt change in lithology does not necessarily indicate an unconformity, so this could possibly be the basinward correlative conformity of this surface. However, this is beyond the scope of this project. It can be said that overall the east side of the Bighorn Basin was once again more affected by erosion than the west suggesting land was to the east.

South of the truncation of Red Claystone B, the Canyon Springs Member overlies progressively older lithologic units due to uplift and erosion on the Black Mountain High. Progressing southeast, it uncomformably overlies the Gray Limestone unit, Red Claystone A and finally the Basal Gypsum unit (Plates 9-11) near the southern margin of the Bighorn Basin. It is obvious that although the Black Mountain High was no longer tectonically active, it was still a prominent structural feature that affected deposition.

Stockade Beaver Shale Member

The Stockade Beaver Shale Member conformably overlies the Canyon Springs Member everywhere that the Canyon Springs is present. The Stockade Beaver Shale Member thins from north to south in the study area (Plate 10-11). At the northernmost outcrop it is over 40 m (140 ft) thick and gradually thins to about 20 m (70 ft) just north of Greybull, WY. The member rapidly thins south and east of this location in a line that curves around to the north (Plate 6). This thinning is mainly caused by the Black

Mountain High, that was still a prominent structure affecting accommodation space. The Tongue River High of Schmude (2000) is seen trending southwest from the basin margin and creating a nose that terminates west of the North Sheep Mountain outcrop. This is the first time the Tongue River High has had a noticeable effect on deposition during the Middle Jurassic. This structure was uplifted along a zone of basement weakness called the Tongue River Lineament (Schmude, 2000). A cross-section through both of these structures reveals the drastic thinning from the North Sheep Mountain outcrop south to the Nupec Lamb Federal 1-2 well (Plate 9).

The shales of the Stockade Beaver often grade into the limestones and sandstones of the overlying Hulett Member. This is especially pronounced over the Black Mountain High where it is often difficult in well logs to discern the contact because of the coarsening upwards sequence.

The oyster fossils (*Ostrea nebrascensis*) typical of the Stockade Beaver Shale are missing at the South Hyattville outcrop. Directly to the south the member thins to less than 2 m (6.5 ft) (Plate 6). *Ostrea nebrascensis* is an indicator of open marine conditions (Peterson, 1954) and the water depth was probably too shallow for this species to survive at this location.

Hulett Member

The Hulett Member of the lower Sundance Formation has intermittent thickness changes throughout the study area (Plates 9-10). The Red Dome, MT outcrop, as described by Imlay (1956), is the only location where the unit is missing, but this is likely a facies change into shale similar to the underlying Stockade Beaver Shale Member.

This probably represents deepening to the north related to the Hardin Trough (Figures 1-2). This facies change was noted in the deeper portions of the Hardin Trough by Schmude (2000).

Near the town of Lovell, WY the Hulett Member has an undulating series of isopach thicks and thins (Plate 7) that is thought to be related to the Tongue River High (Schmude, 2000). He mentions “papery silty limestones” containing fossil fish in the area that were deposited in lagoons restricted by these highs. Very thin bedded limestones were found at the Crooked Creek Road and North Sheep Mountain outcrops in this study. No fish fossils were found but the beds are probably equivalent. Both outcrops are in areas of isopach thins possibly representing the shoaling mentioned by Schmude (2000).

The Hulett member thins drastically in a line running from north of Ten Sleep, WY to east of Thermopolis. This thinning demarcates the axis of the NE-SW trending Sheridan Arch (Plate 7). Peterson (1954) discovered two different ostracod fauna on either side of the structure and for years the Sheridan Arch was thought to be a positive feature during lower Sundance deposition (Peterson, 1957; Imlay, 1980). Later studies of Schmude (2000) seem to prove otherwise. The Stockade Beaver Shale Member shows no linear isopach thinning over the axis of the Sheridan Arch (Plate 6) so it is assumed not to be present until at least Hulett Member deposition. The timing of deposition in relation to uplift of the Sheridan Arch remains unclear. Bevelling of the top of the Hulett Member and lack of isopach thinning in the overlying Redwater Shale Member of the upper Sundance were noted by Schmude (2000). This would indicate that the Hulett Member was eroded after deposition by uplift of the Sheridan Arch causing the J-4 unconformity. Although the Hulett clearly thins over this high, no evidence of beveling of the top of the member or clear evidence of an unconformity was found in this study.

Most workers place the J-4 unconformity at the top of the Hulett Member (Pipiringos and O'Sullivan, 1978; Schmude, 2000) separating it from the glauconitic marine sandstones of the upper Sundance Formation. Kvale et al. (2001) disagrees and claims the J-3 unconformity separates Middle and Upper Jurassic and places the J-4 surface further into the upper Sundance. However, no apparent traces of an unconformity were identified in the field so the discussion remains uncertain.

CHAPTER 6

SEQUENCE STRATIGRAPHIC MODEL

The Middle Jurassic units were deposited on the distal margins of a foreland basin. The slight dip caused a geologic setting that responded to relative sea level changes like a ramp margin. For this reason, the transgressive-regressive cycle model proposed by Embry and Johannsen (1992) was used to develop the sequence stratigraphic model. There are no Transgressive, Highstand or Lowstand Systems Tracts as in the Exxon-Vail models in this setting. There are only the transgressive and regressive stages marked by their sequence boundaries and maximum flooding surfaces.

6.1 Pre-Middle Jurassic Cycles

Continental Lower Jurassic deposits in many places in Wyoming, Idaho and Utah lie unconformably on tilted older rocks ranging from Triassic to Precambrian. Pipiringos and O'Sullivan (1978) referred to this oldest Jurassic unconformity as the J-0 surface. Eolian erg deposits such as the Nugget Sandstone and equivalent Glen Canyon Sandstones were deposited during the Lower Continental Stage of Brenner and Peterson (1994). This sequence is not present in the Bighorn Basin and the Middle Jurassic Gypsum Spring Formation lies unconformably on the J-1 surface of Pipiringos and O'Sullivan (1978), which truncates the J-0 surface in the basin. A chert or limestone breccia sitting on the J-1 unconformity has been mentioned by several workers and was identified at an outcrop slightly northeast of the BPSC outcrop

(Sample SCB 1). Brenner and Peterson (1994) state that the J-1 unconformity separating the Lower and Middle Jurassic was created by sea level dropping faster than basin subsidence, thus eliminating accommodation space. However, in the Bighorn Basin there are no Lower Jurassic rocks, meaning accommodation space could have been non-existent.

6.2 First T-R Cycle

The first Jurassic record in the study area is the Basal Gypsum unit of the Middle Jurassic Gypsum Spring Formation. This early Bajocian unit marks the first of three transgressions during the Middle Jurassic, with each progressively reaching further inland. This first transgressive stage coincides with the First Marine Cycle of Brenner and Peterson (1994). This thick massive gypsum lies unconformably on the Triassic Chugwater formation except at the Crooked Creek Road outcrop where a paleotopographic high remained above sea level for the duration of the first cycle (Plate 10). This marine inundation transgressed from the west and filled paleotopographic lows and created a restricted marine environment with high rates of evaporation depositing a thick sequence of massive gypsum. The Belt Island Complex in western Montana was probably uplifted at this time and acted as a barrier restricting circulation within the basin. Spring tides and storms or alternatively channels replenished the restricted basin with marine waters oversaturated with respect to gypsum. High-order cycles within the Basal Gypsum are marked in geophysical logs by alternating beds of gypsum and red shales.

Gypsum deposits eventually filled all accommodation space within the study area and the supratidal to terrestrial deposits of Red Claystone A prograded over the Basal Gypsum unit under sabkha conditions across the area (Williams, 2004). This represents the regressive stage as relative sea level fell.

6.3 Second T-R Cycle

As relative sea level rose again the sea transgressed onto the continent and deposited the carbonates and shales of the Gray Limestone unit of the Gypsum Spring Formation. The alternating limestone, shale and minor gypsum layers represent high-order cycles within the unit. In the study area, the carbonates are mostly mudstones, some with fenestrae, sheetcracks and interbedded gypsum deposited in sabkha conditions. To the west of the study area, the carbonates exhibit higher energy conditions, suggesting land was to the east. This fits the model because the sea transgressed from the west.

Considerable disagreement exists regarding the boundary of this sequence based on the placement of the J-2 unconformity in relation to the top of the Gray Limestone unit. Many believe that the J-2 is at the top of the Gray Limestone and marks erosion after uplift of the Black Mountain High (Pipiringos and O'Sullivan, 1978; Imlay, 1980; Schmude, 2000). Evidence of a localized unconformity was found in the study area, but cannot be found on the west side of the Bighorn Basin (Meyer, 1984; Doyle, 1984; Williams, 2004). This study finds that the unconformity is a localized feature on paleotopographic highs in the study area that either partially or entirely erodes two, one or no lithologic units. This was primarily due to tectonic uplift. Small scale eustatic changes likely created an area around the highs where chert eroding from these highs was deposited at various stratigraphic levels within the Gray Limestone and Claystone B (Figure 15). The chert could have been reworked many times over as the shoreline moved in and out.

It is important to note that the first and second marine cycles in this report are both included as the "First Marine Cycle" of Brenner and Peterson (1994). They were attempting to tie the cycles to the J-0 through J-5 erosional surfaces of Pipiringos and O'Sullivan (1978) who claimed the Piper Formation (Red Claystone B here) was a transgressive deposit in the marine cycle above the J-2 unconformity. However, there is no mention of strata in between the Gypsum Spring and lower Sundance Formation in Wyoming in the Wilson diagram of Brenner and Peterson (1994, p. 220). This leaves out an entire lithologic unit in the model. Clear evidence of transgressive-regressive cycles was noted in this report regardless of whether or not they are bounded by unconformities.

A

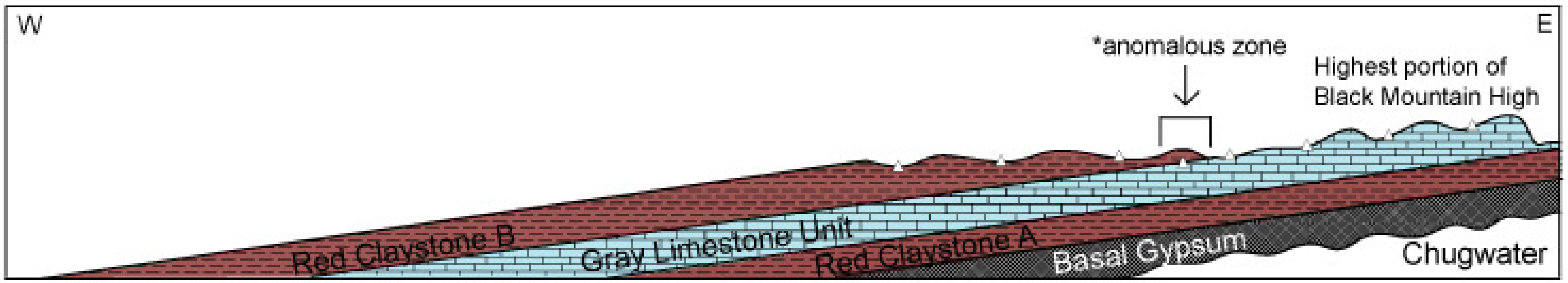

Diagram of chert pebble locations during uplift of Black Mountain High

B

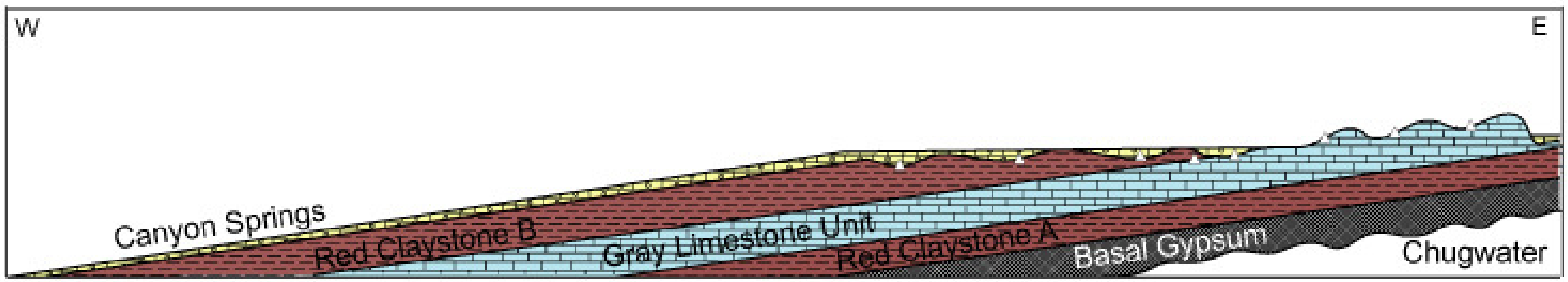

Diagram of chert pebble locations during Canyon Springs Member transgression.

Figure 15: A) Diagram explaining the distribution of chert pebbles across two lithologic units. B) Same as (A) but showing transgression of the Canyon Springs Member of the lower Sundance Formation.

6.4 Third T-R Cycle

The Canyon Springs Member represents transgression of the most extensive marine inundation during the Middle Jurassic. This coincides with the Third Marine Cycle of Brenner and Peterson (1994). The limestones, oolites and sandstones onlapped the continent from NW to SE. The Canyon Springs Member overlies Red Claystone B from beyond the northern edge of the study area to the zero line of that unit (Plate 4). The Canyon Springs Member pinches out around a nearly circular paleotopographic high interpreted to be an erosional remnant of the Black Mountain High (Plates 5, 9). The Red Gulch Dinosaur Tracksite contains hundreds of tridactyl tracks near the town of Shell, Wyoming. This is the J2b unconformity of Kvale et al. (2001) and is traceable for tens of kilometers north or south. These tracks were found in a tidal flat or sabkha deposit representing a minor regressive phase during the overall transgressive stage (Kvale et al., 2001). This surface is believed to be located on a paleotopographic high and is probably conformable basinward.

As relative sea level continued to rise, the green calcareous shales of the Stockade Beaver Shale Member were deposited in an offshore shallow marine environment. This member contains the maximum flooding surface of the Third Cycle, which is recognized as the highest gamma ray reading in geophysical logs. Open marine conditions appeared in the study area for the first time in the Middle Jurassic and are marked by the presence of oysters and belemnites. A subcycle within the Stockade Beaver Shale was noted by the presence of a “mud-cracked oolitic grainstone” by Kvale et al. (2001, p. 237). Oolitic grainstones found at West Sheep Mountain Canyon and North Sheep Mountain could be equivalent. The oolite at North

Sheep Mountain contains microbial laminations, which could indicate tidal flat conditions. This surface could be the J2b unconformity and is only present on the east side of the basin (Kvale et al., 2001).

When relative sea level dropped, the marine shales of the Stockade Beaver Shale Member gave way to the carbonate packstones, oolitic grainstones and quartz sandstones of the Hulett Member. Higher energy regimes dominated due to shallower water. This shallowing upwards sequence marks the regression of the third marine cycle and is said to be capped by a regional unconformity separating the Middle Jurassic lower Sundance Formation from the glauconitic marine sandstones of the Upper Jurassic upper Sundance. The Hulett Member thins across the Sheridan Arch leading previous workers (Peterson, 1954; Kilibarda and Loope, 1997) to consider the structure to be a positive feature during the Middle Jurassic. However, the upper Hulett Member is reported to show beveling over the Sheridan Arch, probably due to uplift and erosion related to the J-4 unconformity (Schmude, 2000). This thinning was confirmed with cross-sections and isopach data (Plates 7,11) in this study but no clear evidence of an unconformity was found in outcrop. However, this is still enough evidence to suggest the Sheridan Arch was not a positive feature during the Middle Jurassic.

A cross-bedded oolite believed to be eolian in origin was discovered by Kilibarda and Loope (1997) in the northeast side of the basin near Little Sheep Mountain. This oolite is thought to represent an island in the Sundance Sea where ooids formed in the leeward subtidal zone were blown onto the island where they formed cross-bedded dunes. Oolitic packstones and grainstones were found in the Hulett Member at several outcrops in the study area, but none showed evidence of eolian deposition. However, this localized surface is the J2c unconformity of Kvale et al. (2001) and represents a subcycle within the overall regressive stage.

CHAPTER SEVEN

CONCLUSION

The stratigraphy of the Middle Jurassic section in the Bighorn Basin continues to be perplexing due to incomplete type sections and poor faunal diversity. Disagreement among workers has created various interpretations of the sequence stratigraphic model. This study was undertaken to shed light on recent developments and points of disagreement in the literature. The presence of chert pebbles in the basin are thought to be residual deposits marking unconformities. These unconformities are localized around numerous paleohighs uplifted in response to orogenic collisions to the west. If the J-2 surface is in fact traceable throughout the Western Cordillera, tectonic stresses in the Bighorn Basin must have been less intense than elsewhere on the western margin of North America. These differential stress regimes seem to be apparent at several scales, evidenced by the lack of erosional unconformities on the west side of the basin.

Tectonics and eustatic changes affected the sequence stratigraphic record at different times during the Middle Jurassic. The slight paleodip westward from the study area created low topographic relief and a geologic setting that responded to relative sea level change like a ramp margin setting. Subsidence, or uplift and subsequent erosion created paleohighs that affected depositional patterns and stratal relationships at various times throughout the Middle Jurassic. A paleohigh just north of the Montana border precluded deposition of the Basal Gypsum and Red Claystone A lithofacies units until transgression during deposition of the Gray Limestone unit. The most prominent structure affecting Middle Jurassic deposition was the Black Mountain High, a plunging anticline trending northwest from south of the Bighorn Basin to near the town of Greybull, WY. This feature was uplifted and eroded from the top of the Gray Limestone unit down into the Basal Gypsum unit in the southernmost part of the study area. The Tongue River High noted by Schmude (2000) occluded accommodation space during Stockade Beaver Shale Member deposition in the lower Sundance Formation. It appears that this feature affected Hulett Member deposition as well by creating restricted lagoonal limestone facies in the vicinity of Lovell, WY. The Sheridan Arch was long thought to be a positive feature during the Middle Jurassic. Isopach data proves that this structure had no effect on deposition until Hulett Member time. It is unclear at this time whether it simply lessened accomodation space or that uplift and erosion of the Hulett Member occurred after the end of Middle Jurassic deposition.

A sequence stratigraphic model records the three marine inundations during the Middle Jurassic, along with numerous high-order cycles indicated by surfaces displaying evidence of subaerial exposure. The first marine transgression is recorded by the Basal Gypsum unit of the Gypsum Spring Formation as restricted marine conditions deposited thick gypsum layers in paleolows. Regression of the first marine inundation deposited the prograding supratidal to terrestrial Red Claystone A unit. The transgressive stage of the second cycle is represented by the carbonate mudstone and wackestones of the Gray Limestone unit. The regressive stage of this cycle is represented by the supratidal to terrestrial deposits of Red Claystone B. Uplift of the Black Mountain High is thought to have occurred after Gray Limestone deposition and likely continued into Red Claystone B time. This uplift is marked by a residual chert pebble lag deposit in the vicinity of this high. The beginning of the third cycle in several areas is marked by a chert pebble lag at the base of the oolitic Canyon Springs Member of the lower Sundance Formation. A minor regressive phase during deposition of this member is marked by a mudstone found north of Sheep Mountain, WY. This surface displays evidence of subaerial exposure and is thought to be the same surface on which Kvale et al. (2001) found tridactyl dinosaur footprints near Shell, WY. Each of the three major marine inundations was further reaching than the last, and maximum flooding during the Middle Jurassic occurred during deposition of the Stockade Beaver Shale Member of the lower Sundance Formation. These green fossiliferous carbonate shales grade into the overlying packstones and grainstones of the Hulett member that were deposited as relative sea level fell at the end of the Middle Jurassic. No evidence of an erosional unconformity representing the J-3 or J-4 surface was found in outcrop, but is assumed based on fossil evidence recorded by Peterson (1954) and Imlay (1956) and the drastic change in lithology.

CHAPTER 8

FUTURE WORK

Most importantly, Red Claystone B of this report needs to be compared to the upper member of the Piper Formation in Montana. If these two units are equivalent, then Red Claystone B is likely a transgressive deposit and the model proposed by Pipiringos and O'Sullivan (1978 is correct. Of course this assumes that the Basal Gypsum unit, Red Claystone B and Gray Limestone unit of the Gypsum Spring Formation of this report are not equivalent to the Piper Formation. A thorough investigation and correlation from central Montana southward into the Bighorn Basin could possibly resolve the stratigraphic problem. Chemostratigraphy through X-ray fluorescence is suggested as a possible tool for comparison. If Red Claystone B in Wyoming and the Piper Formation of Montana have a distinctive XRF signature, assumptions could be drawn on their similarities. X-ray fluorescence samples could also be taken above and below the supposed J-2 unconformity. In some locations the rocks above and below the chert pebble lags appear exactly the same in the field. If the XRF signature changes drastically above the lag deposit, then a definite environmental change after this surface could be inferred.

It will be necessary for more outcrop studies focusing on the chert pebbles thought to represent Jurassic unconformities. Often in the literature, chert found by other workers is placed in the wrong stratigraphic position. An examination of outcrops where chert pebbles are noted in the literature and a detailed record of what type of chert is present and its exact stratigraphic position could help clarify some of the incongruity. Collaboration among workers is also suggested so that problems stemming from misunderstanding the literature are resolved and prevented in the future.

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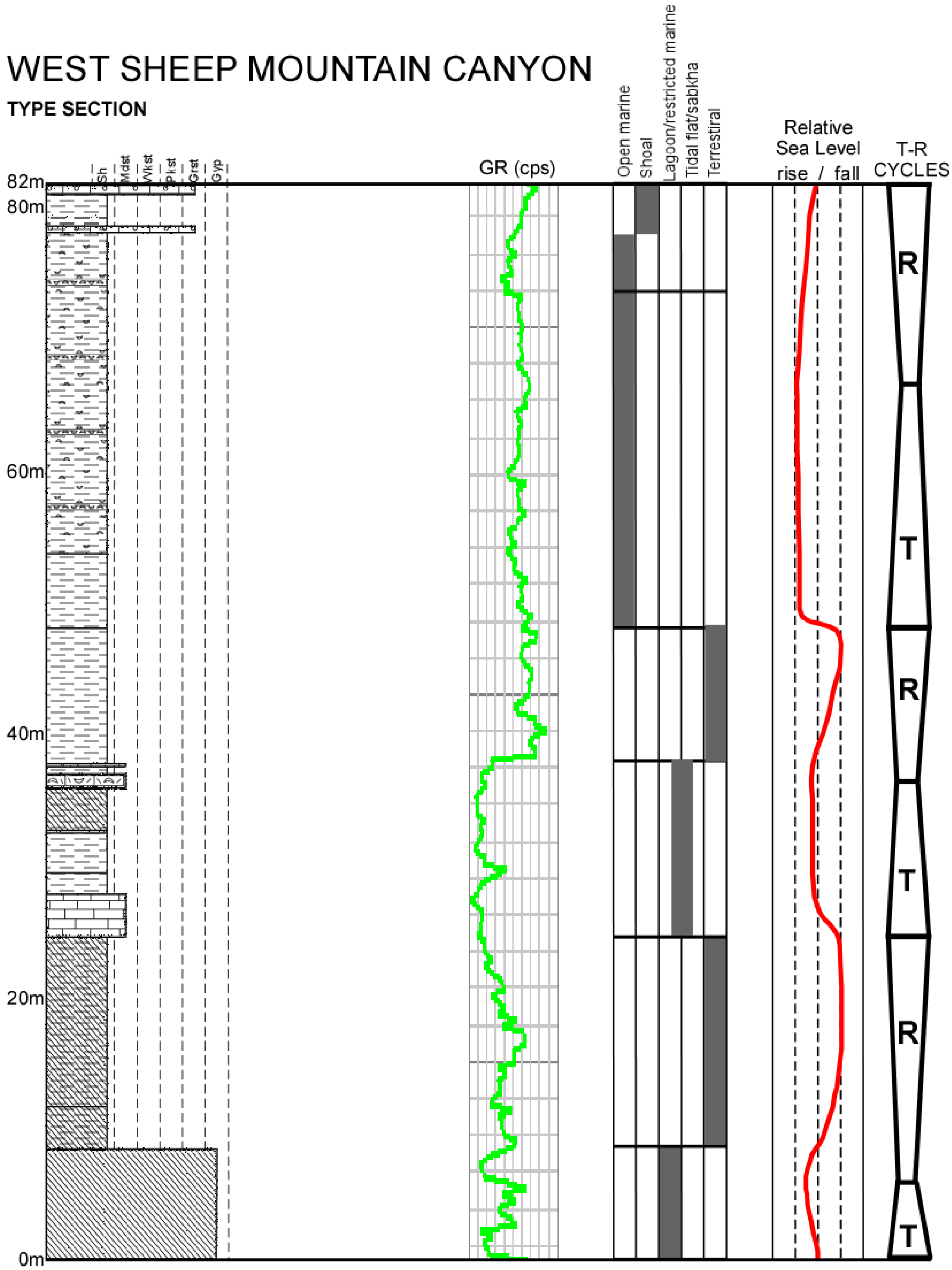
APPENDICES

Appendix A: Sample Descriptions		
Sample No.	Thin Section	Description
Between Potato Ridge and South Chugwater Bluff		
BPSC 2		Shale, red, hard, blocky, slightly platy
BPSC 3		Mudstone, medium-dark gray, dolomitic, sheet cracks, vertical fractures
BPSC 4		Mudstone, dark gray, possible raindrop impressions or gastropod trace fossil?, sheet cracks
BPSC 5		Shale, cauliflower chert with white and red coloring, some quartz crystals (shaped like Gyp lathe)
BPSC 6		Mudstone, dolomitic, white, massive, hard, blocky, chert in float
BPSC 7		Packstone-Grainstone, gray, reddish-brown ooids ~0.3 mm, skeletal grains (possible bivalve)
BPSC 8	X	Packstone-Grainstone, ooids ~0.3mm, some green ooids, some reddish-orange, white calcite cement
Crooked Creek Road		
CCR 1		Mudstone, brownish-gray, fenestrae ~0.1-1 mm, dense, hard, secondary replacement by calcite, 5-10 cm thick blocky laminations
CCR 2		Mudstone, brownish-dark gray, dolomitic, vugs, linear fractures replaced by calcite, stylolite
CCR 3		Wackestone, brownish-dark gray, vugs (only on exposed surface), bivalves, faint thin beds ~0.6 mm
North Sheep Mountain		
NSM 7		Shale, gray, non-calcareous, thin layer of gypsum
NSM 8		Mudstone, medium-dark gray, dolomitic, sheetcracks, stylolite
NSM 9		Shale, light brown, yellowish-gray, hard, fissile, calcareous

Appendix A continued		
Sample No.	Thin Section	Description
North Sheep Mountain continued		
NSM 11		Shale, yellow, calcareous
NSM 12		Shale, light brown, calcareous
NSM 13		Shale, grayish-orange-pink, calcareous
NSM 14		Shale, light brown, hard, blocky, slightly calcareous
NSM 15		Mudstone, dark-medium gray, vugs ~4 mm occluded by silica
NSM2 Cht	X	Chert, banded brown, black, red, white, some replacement of algal features
NSM2 111	X	Chert, black, brown, layered replacement of algal features
South Chugwater Bluff (*J-1 surface only)		
SCB 1	X	Chert, white with red specks, many calcite inclusions
South of Hyattville		
SHV X28		Mudstone, gray, calcareous, thin layers of dolomite
SHV X44		Mudstone, gray, dolomitic, thin bedded, vugs, sheetcracks
SHV X45		Mudstone, light gray-white, dolomitic, sheetcracks
SHV X52		Shale, gray, blocky, cauliflower chert
SHV 55	X	Mudstone, light gray-white, dolomitic layered, fenestrae, vugs

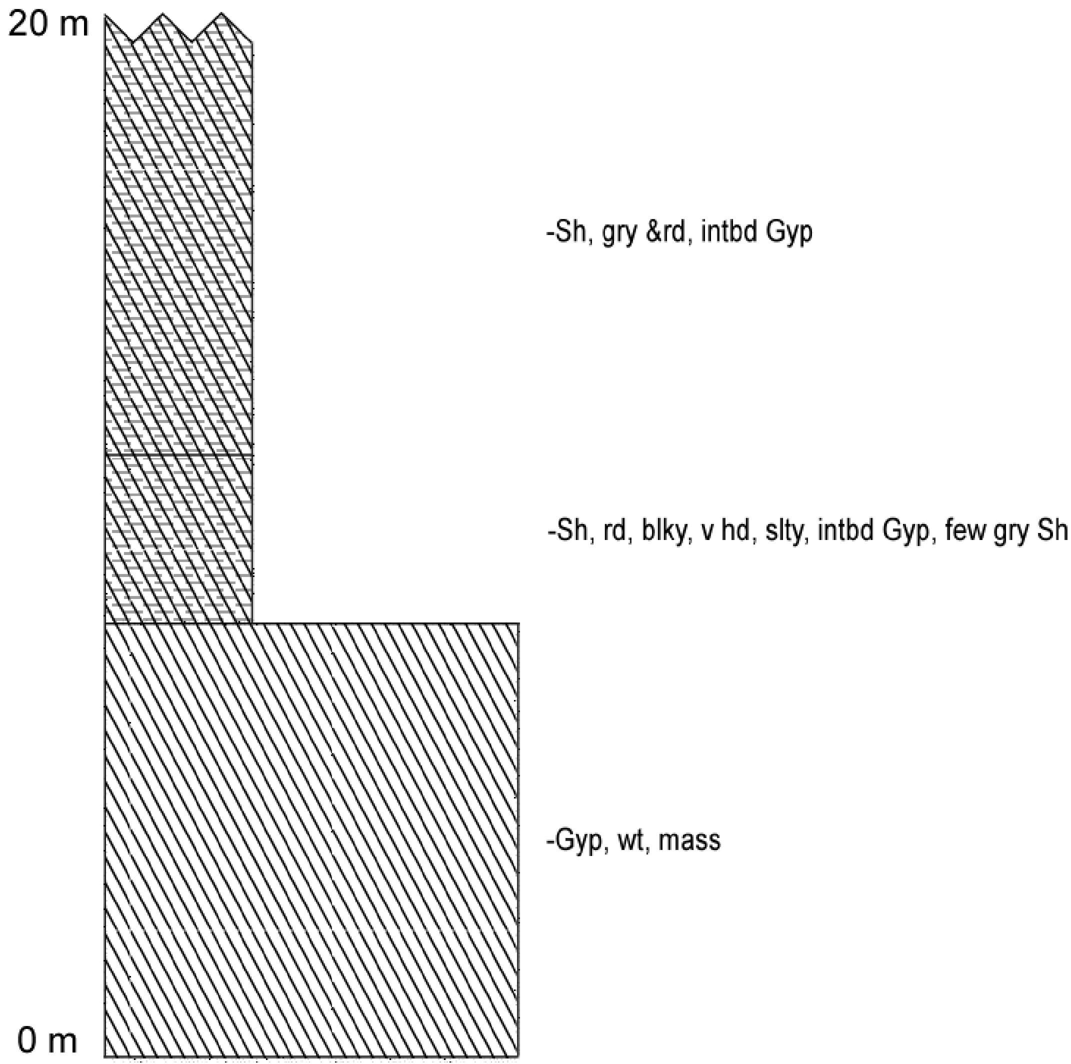
Appendix A continued		
Sample No.	Thin Section	Description
West Little Sheep Mountain continued		
WLSM 2		Mudstone, medium dark gray, vugs <3 mm, biomoldic porosity (shells), fenestrae
WLSM HG	X	Appears to be a green sandstone but XRD shows mostly analcime
WLSM 3	X	Chert, mosaic texture, chert replaced gypsum and limestone
WLSM 4		Mudstone, medium gray, sheet cracks, shells secondarily replaced by calcite, green staining on calcite
WLSM 6		Chert, nodular with dark and light banding
WLSM 7		Mudstone, greenish-yellow, silty, very thin bedded ~1-2 mm, platy
WLSM 8		Packstone-Grainstone, greenish-yellow, ooids, 0.2-0.5 mm, skeletal fragments, quartz grains, poorly sorted
WLSM 9		Mudstone, yellow, horizontal fractures, gastropods, bivalves
West Sheep Mountain Canyon		
WSMC 1		Mudstone, medium gray, dense, fenestrae 0.3-1.8 mm, sheet cracks, few vugs occluded by silica
WSMC 2	X	Mudstone, grayish-brown, skeletal fragments, algae, bivalves
WSMC 3		Mudstone, yellow-gray, very thin bedded 1.2 mm thick, trace fossils on bedding plane
WSMC 4		Mudstone, medium-dark gray, algal heads up to 3 cm
WSMC 5		Mudstone, grayish-brown, calcite filled fractures, bivalves
WSMC 6		Grainstone, greenish-yellow, ooids <0.5 mm (some with red staining), sparry calcite cement
WSMC 7		Grainstone, greenish-yellow, ooids, quartz grains ~0.1 mm, poorly sorted

Appendix B: Measured Outcrop Locations					
Well Name	**Latitude**	**Longitude**	**Middle Jurassic section**	**Middle Jurassic section**	**GR**
BPSC	44.4198	-107.7693	91 m	297 ft	X
Crooked Creek Road	45.0187	-108.4232	77 m	254 ft	
Imlay_01_Red Dome	45.2122	-108.8268	102 m	334 ft	
Imlay_09_Gypsum Creek Near Head	45.0493	-108.5049	79 m	258 ft	
Imlay_10_Gypsum Creek East	45.0049	-108.4217	100 m	327 ft	
Imlay_15_Sykes Mountain	44.9386	-108.2556	105 m	345 ft	
Imlay_16_Little Sheep Mountain	44.8060	-108.2664	103 m	338 ft	
Imlay_17_Spence Dome	44.6867	-108.2178	98 m	322 ft	
Imlay_18_NW of Shell	44.6352	-107.8103	87 m	284 ft	
Imlay_19_South of Shell	44.4198	-107.7693	101 m	332 ft	
Imlay_20_NW of Hyattville	44.3748	-107.6795	91 m	300 ft	
Imlay_21_Southeast of Hyattville	44.2104	-107.5412	66 m	216 ft	
Imlay_22_NW of Tensleep	44.1207	-107.5328	51 m	167 ft	
Imlay_23_NW of Tensleep	44.0644	-107.5050	58 m	189 ft	
Imlay_24_Otter Creek	43.8740	-107.3333	59 m	194 ft	
Imlay_25_NW of Big Trails	43.7802	-107.3459	53 m	174 ft	
Imlay_26_Redbank School	43.6847	-107.3335	44 m	145 ft	
Imlay_27_SW of Nowood	43.5490	-107.5020	51 m	168 ft	
Imlay_28_SE of Thermopolis	43.6097	-107.9508	53 m	173 ft	
Imlay_29_South of Thermopolis	43.6228	-108.2027	58 m	190 ft	
Imlay_30_West of Thermopolis	43.6434	-108.5068	86 m	282 ft	
North Sheep Mountain	44.6947	-108.2162	80 m	262 ft	X
South of Hyattville	44.2290	-107.5694	69 m	227 ft	X
West of Little Sheep Mountain	44.8006	-108.3021	105 m	344 ft	X
West of Sheep Mountain Canyon	44.5973	-108.1545	89 m	293 ft	X


WEST SHEEP MOUNTAIN CANYON
TYPE SECTION
Sh
Mdst
Wkst
Pkst
Grst
Gyp
82m
80m
60m
40m
20m
0m
GR (cps)
Open marine
Shoal
Lagoon/restricted marine
Tidal flat/sabkha
Terrestiral
Relative Sea Level
rise / fall
T-R CYCLES
R
T
R
T
R
T

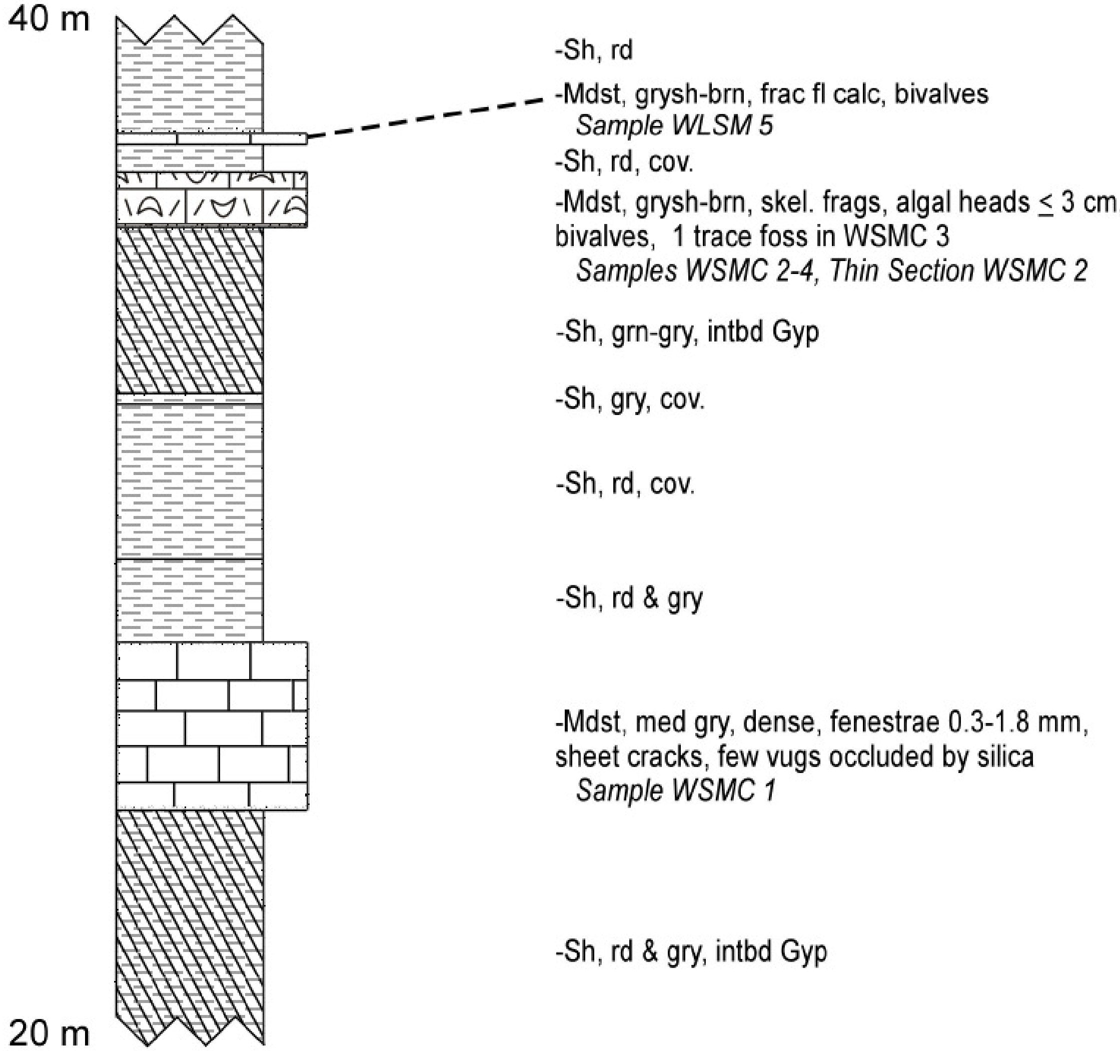
Appendix C-1 continued

WEST SHEEP MOUNTAIN CANYON
TYPE SECTION



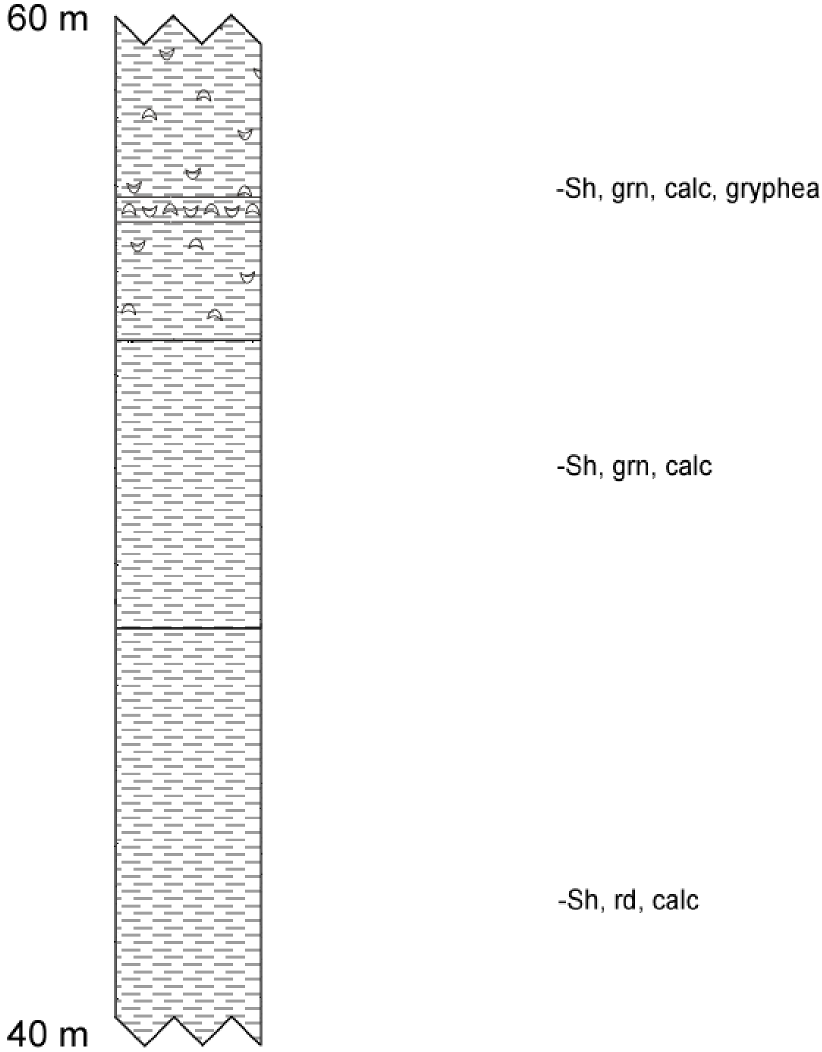
Appendix C-1 continued

WEST SHEEP MOUNTAIN CANYON
TYPE SECTION

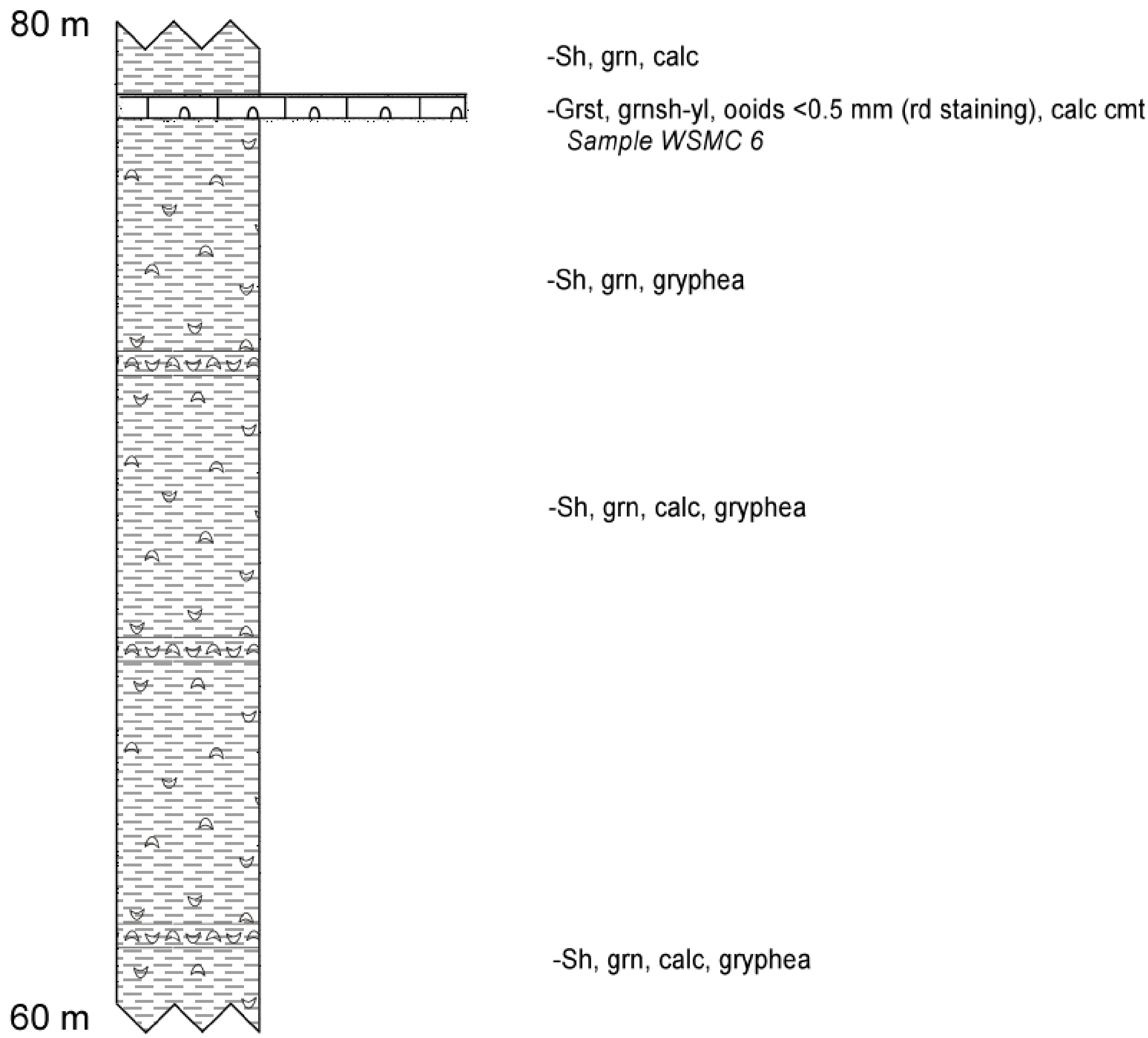


Appendix C-1 continued

WEST SHEEP MOUNTAIN CANYON
TYPE SECTION



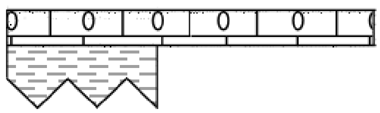
WEST SHEEP MOUNTAIN CANYON
TYPE SECTION



Appendix C-1 continued

WEST SHEEP MOUNTAIN CANYON
TYPE SECTION

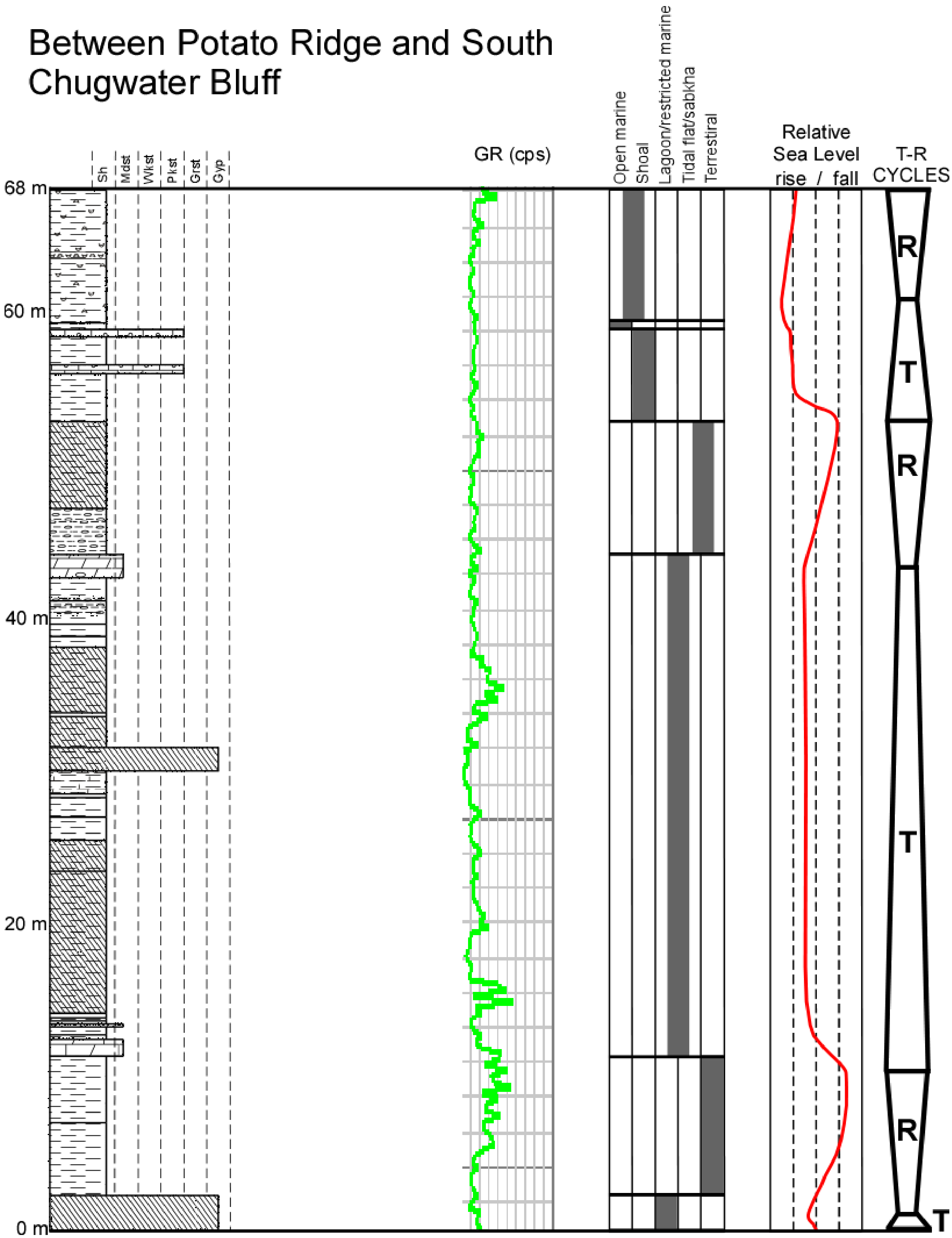
82 m



80 m

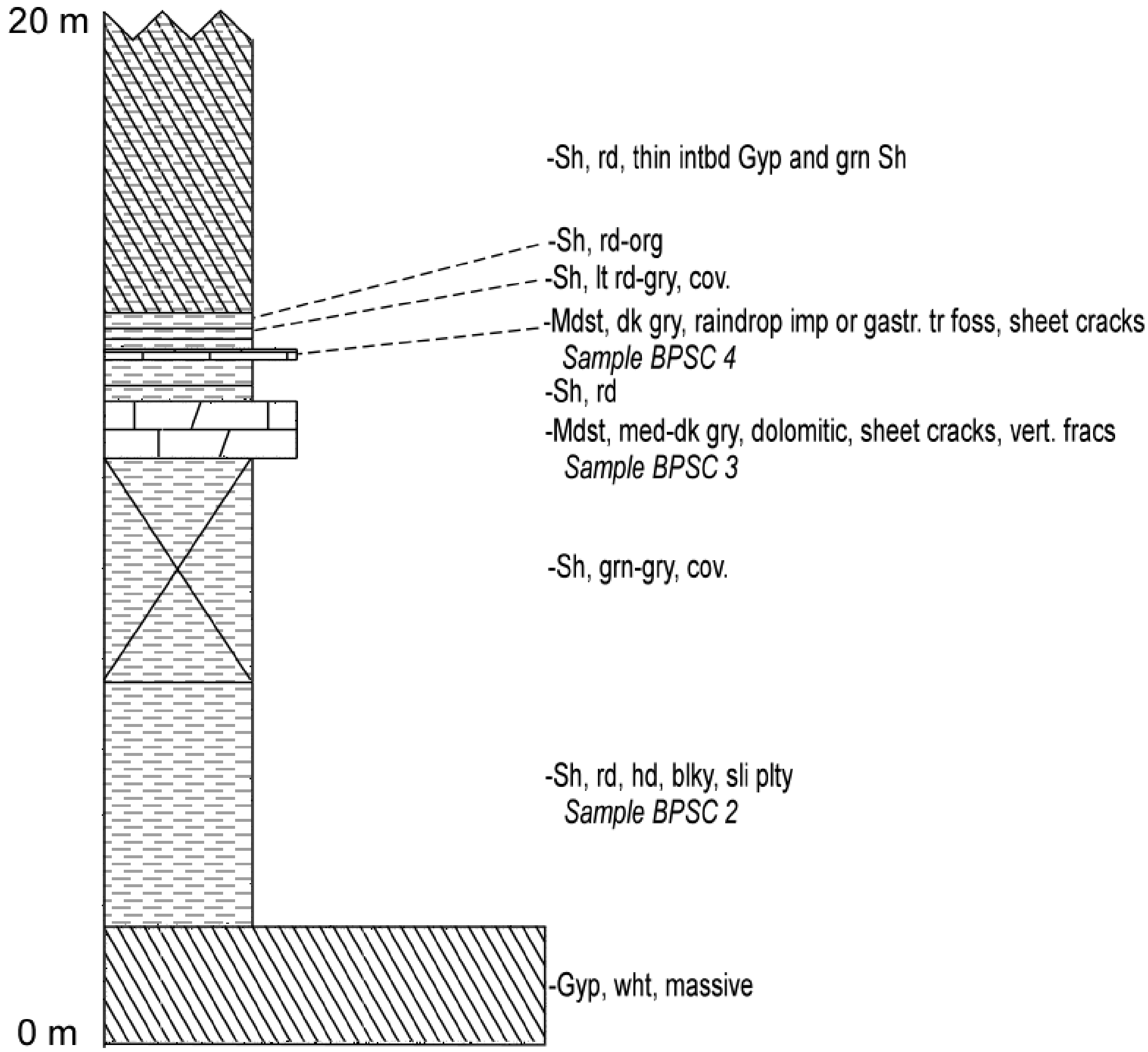
-Grst, grnsh-yl, ooids, qtz gr ~0.1 mm, prly srtd
Sample 7

-Sh, grn, calc

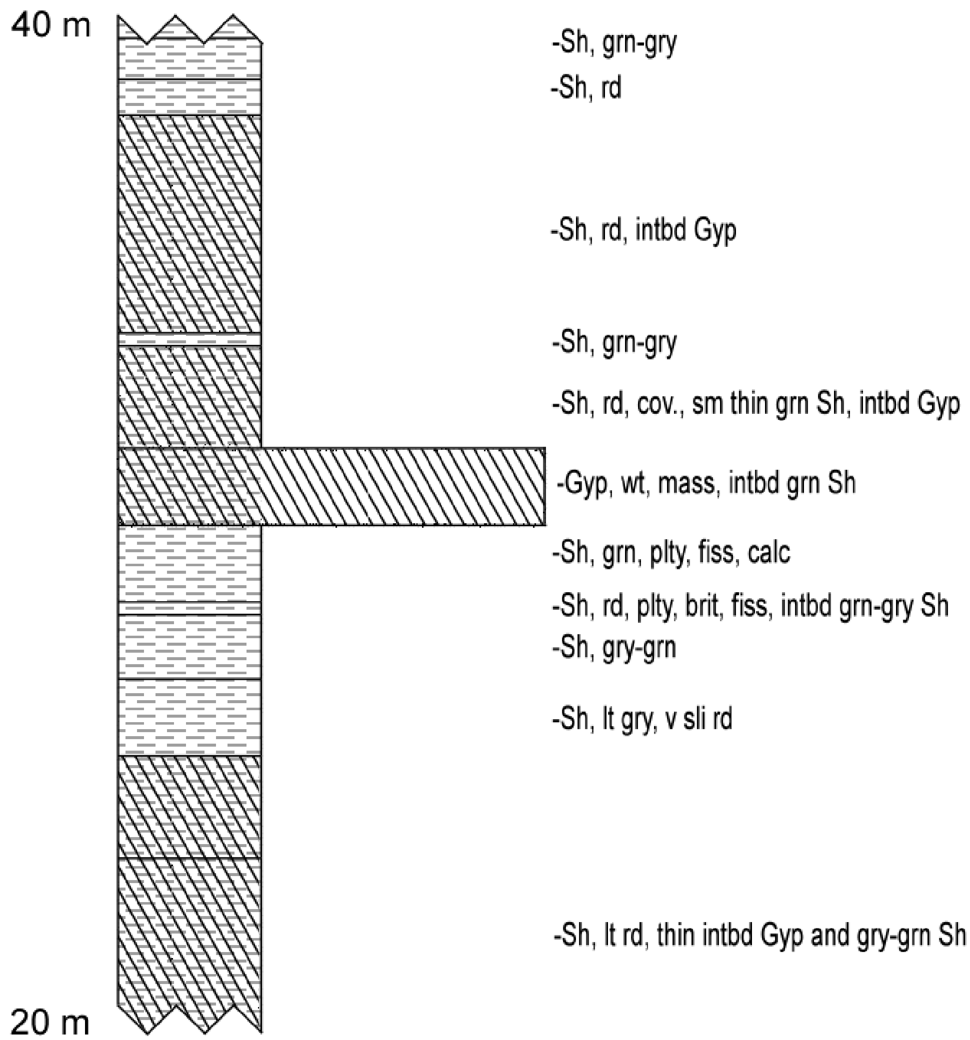

Between Potato Ridge and South Chugwater Bluff
Sh
Mdst
Wkst
Pkst
Grst
Gyp
GR (cps)
Open marine
Shoal
Lagoon/restricted marine
Tidal flat/sabkha
Terrestiral
Relative Sea Level
rise / fall
T-R CYCLES
68 m
60 m
40 m
20 m
0 m
R
T
R
T
R
T

Appendix C-2 continued

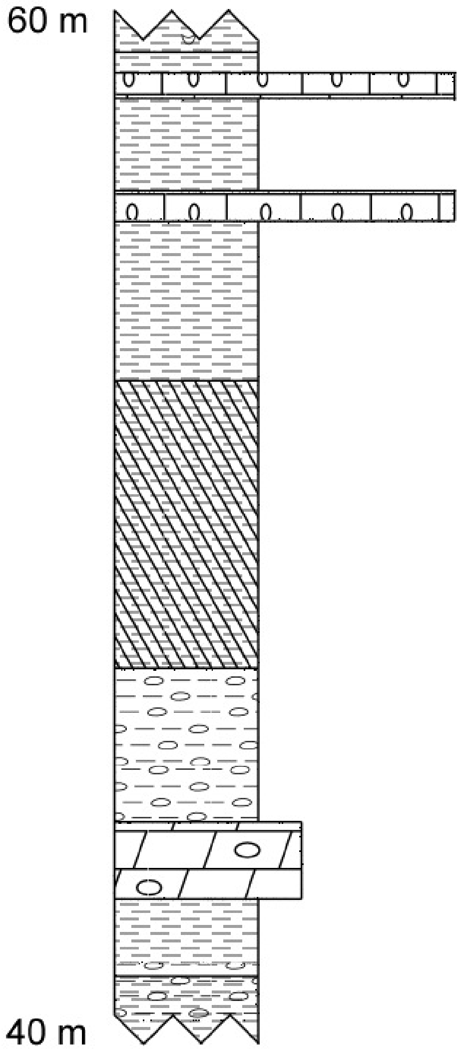
BETWEEN POTATO RIDGE AND SOUTH CHUGWATER BLUFF



BETWEEN POTATO RIDGE AND SOUTH CHUGWATER BLUFF



BETWEEN POTATO RIDGE AND SOUTH CHUGWATER BLUFF



-Sh, grn-gry, calc

-Pkst/Grst, ooids ~0.3mm, sm grn ooids, sm rdsh-org, wht calc cmt. *Sample BPSC 8, Thin Section BPSC 8*

-Sh, grn-gry

-Pkst-Grst, gry, rdsh brn ooids ~0.3mm, skel grains (bivalve)
Sample BPSC 7

-Sh, grn-gry

-Sh, rd, intbd Gyp

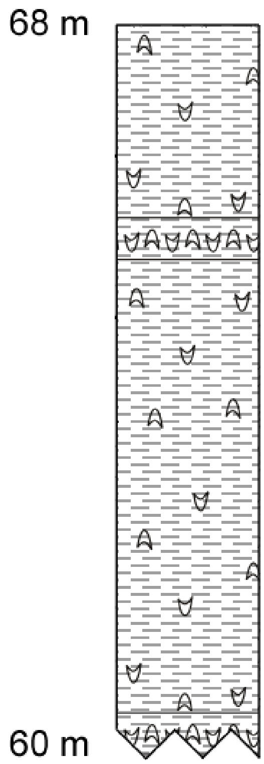
-Sh, grn-gry, Cht & Gyp in float

-Mdst, dolomitic, wht, mass, hd, blky, Cht in float
Sample BPSC 6

-Sh, Cht, ang w/ bands of grysh-wht, rdsh-org, yl-org in wht calc matrix

-Sh, caul. Cht, wht, rd staining, sm qtz xls (shaped like Gyp lathe)
Sample BPSC 5

BETWEEN POTATO RIDGE AND SOUTH CHUGWATER BLUFF

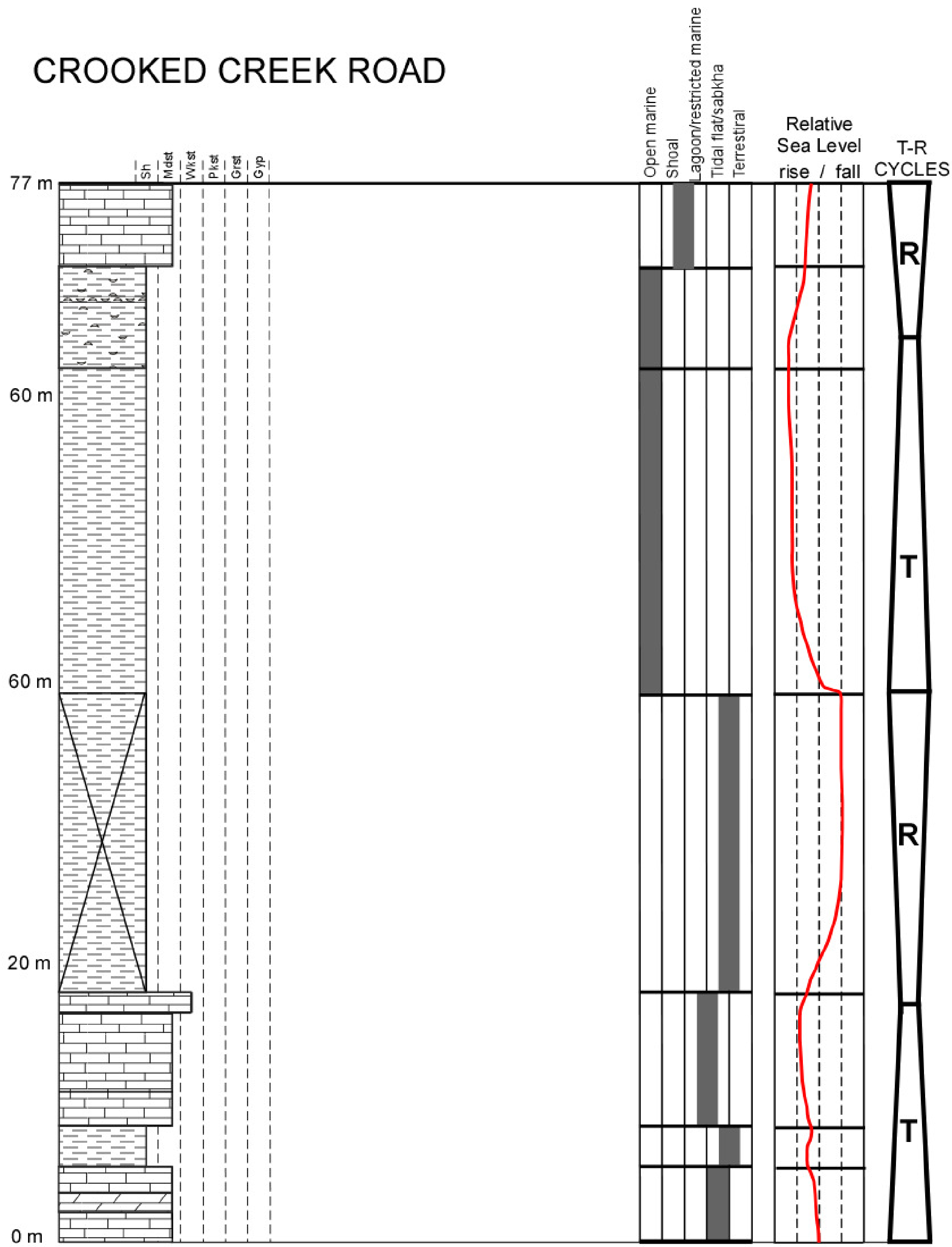


-Sh, grn-gry, gryphea

-Sh, grn-gry, gryphea

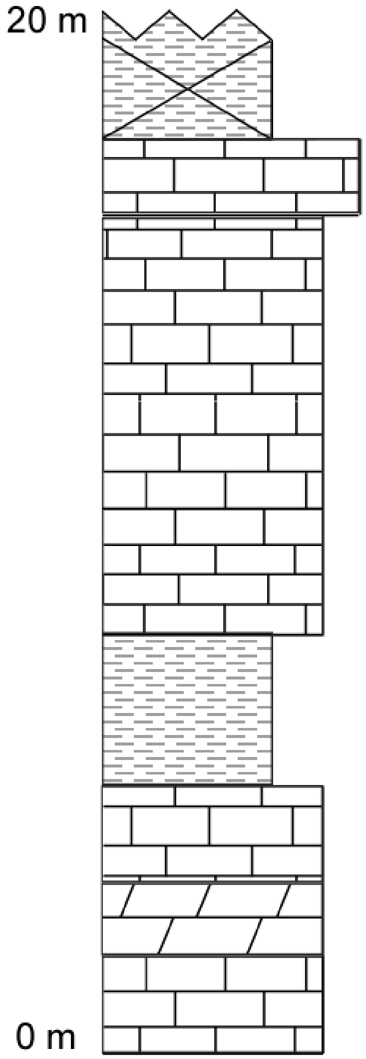
Appendix C-3

CROOKED CREEK ROAD



Appendix C-3 continued

CROOKED CREEK ROAD



-cov. Sh, rd

-Wkst, brnsh-dk gry, vugs (only on exposed surface), bivalves, faint thin beds ~0.6mm
Sample CCR 3

-Mdst, wt

-Mdst, rd

-Mdst, lt creamy, plty, u. surface grades into rd Mdst

-Sh, grysh-rd, calc, harder than below

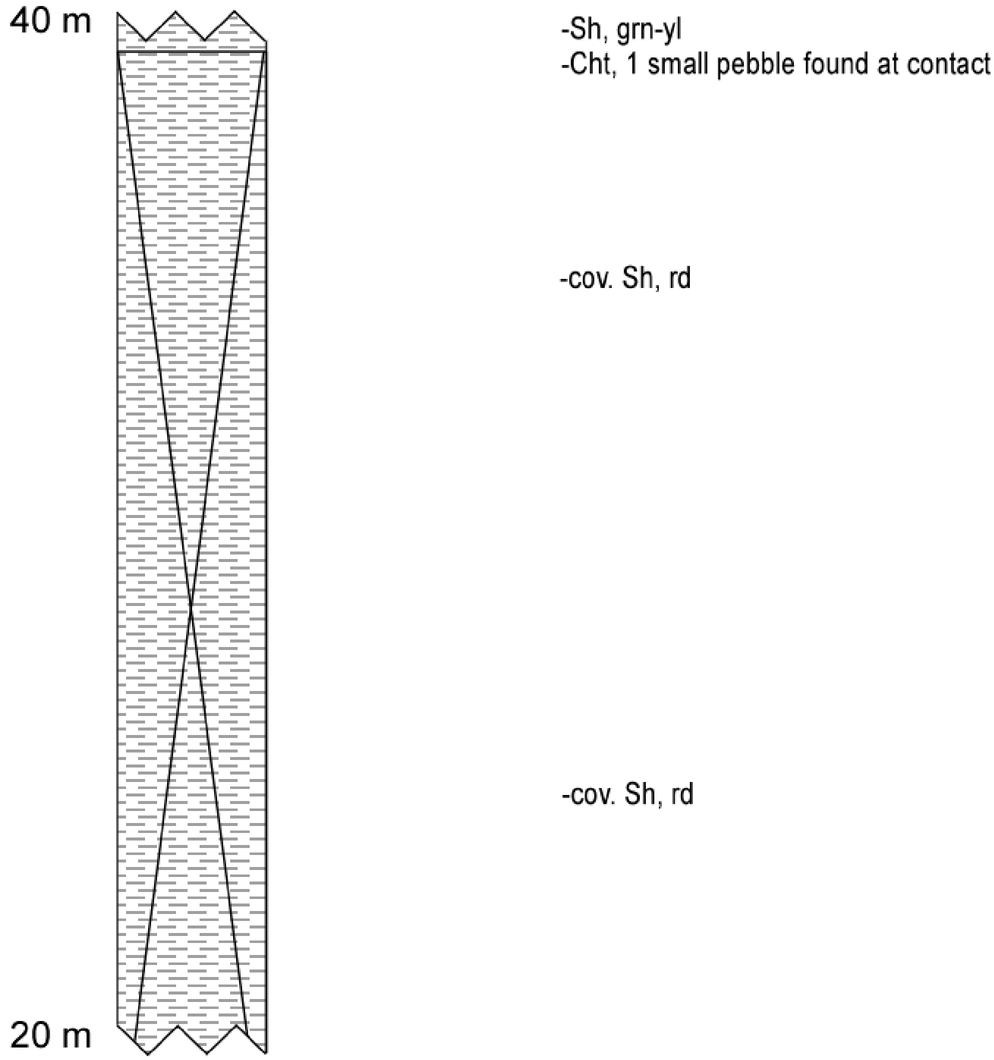
-Sh, rd, calc

-Mdst, lt gry, v hd

-Mdst, brnsh-dk gry, dolomitic, few vugs, linear fracs replaced by calc, stylolite
Sample CCR 2

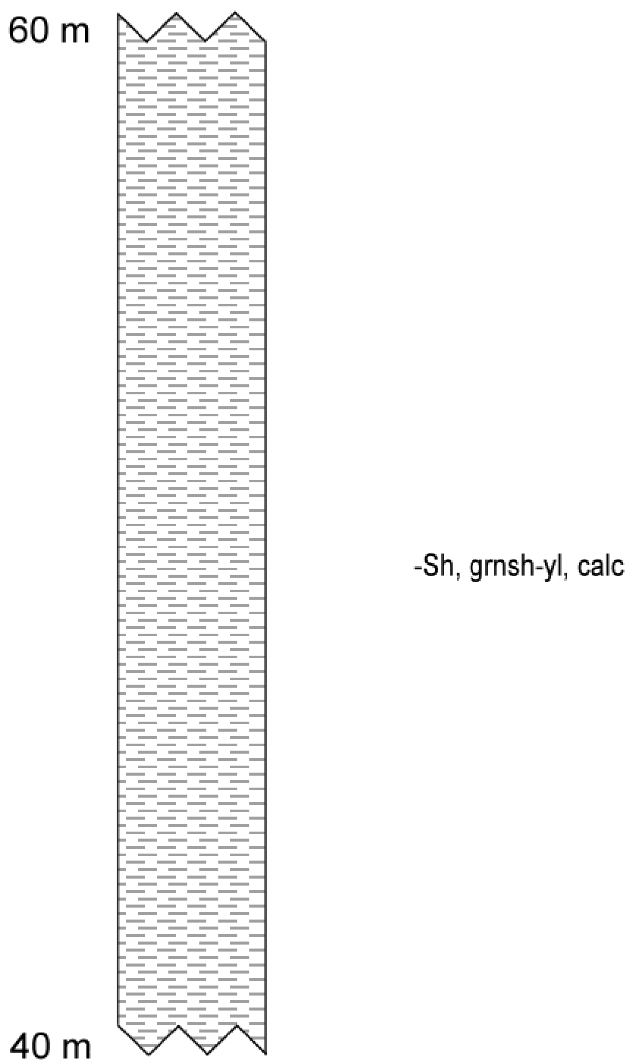
-Mdst, brnsh-gry, fenestrae ~0.1-1 mm, dense, hd, 2ndary repl. by calc, 5-10 cm thick blky laminations
Sample CCR 1

CROOKED CREEK ROAD



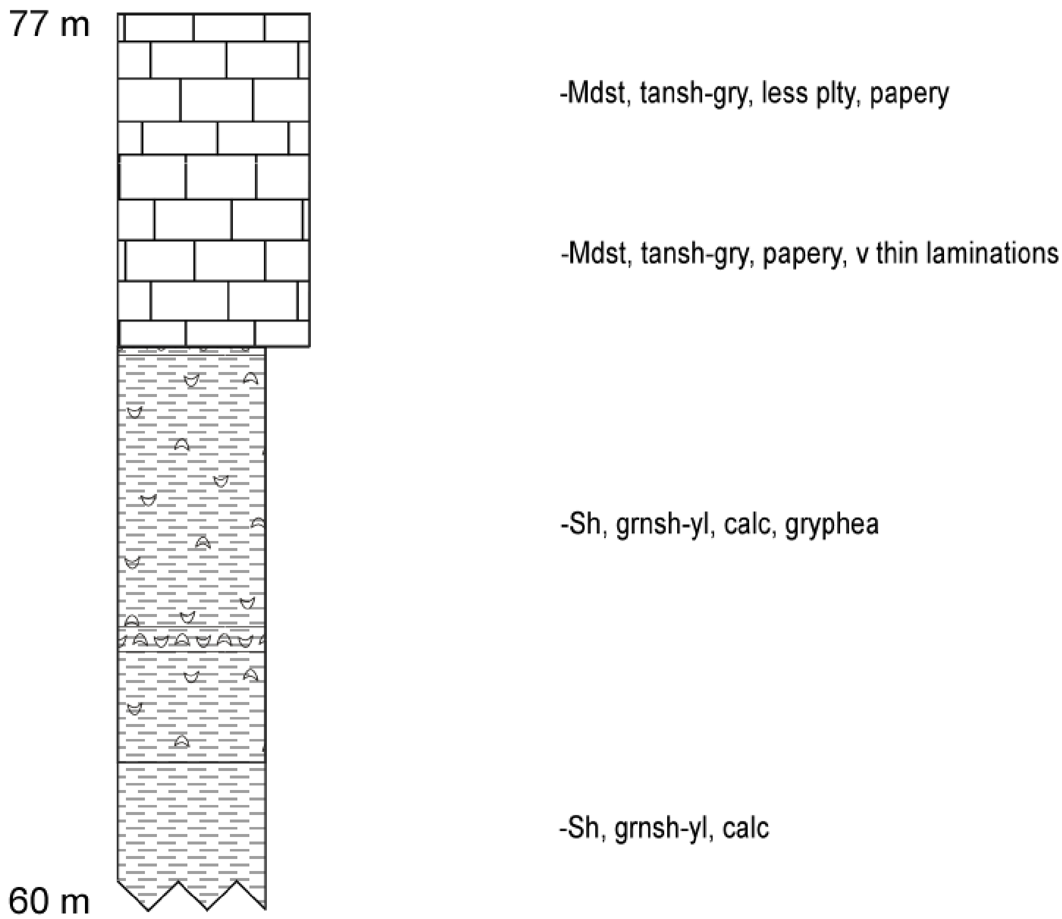
Appendix C-3 continued

CROOKED CREEK ROAD

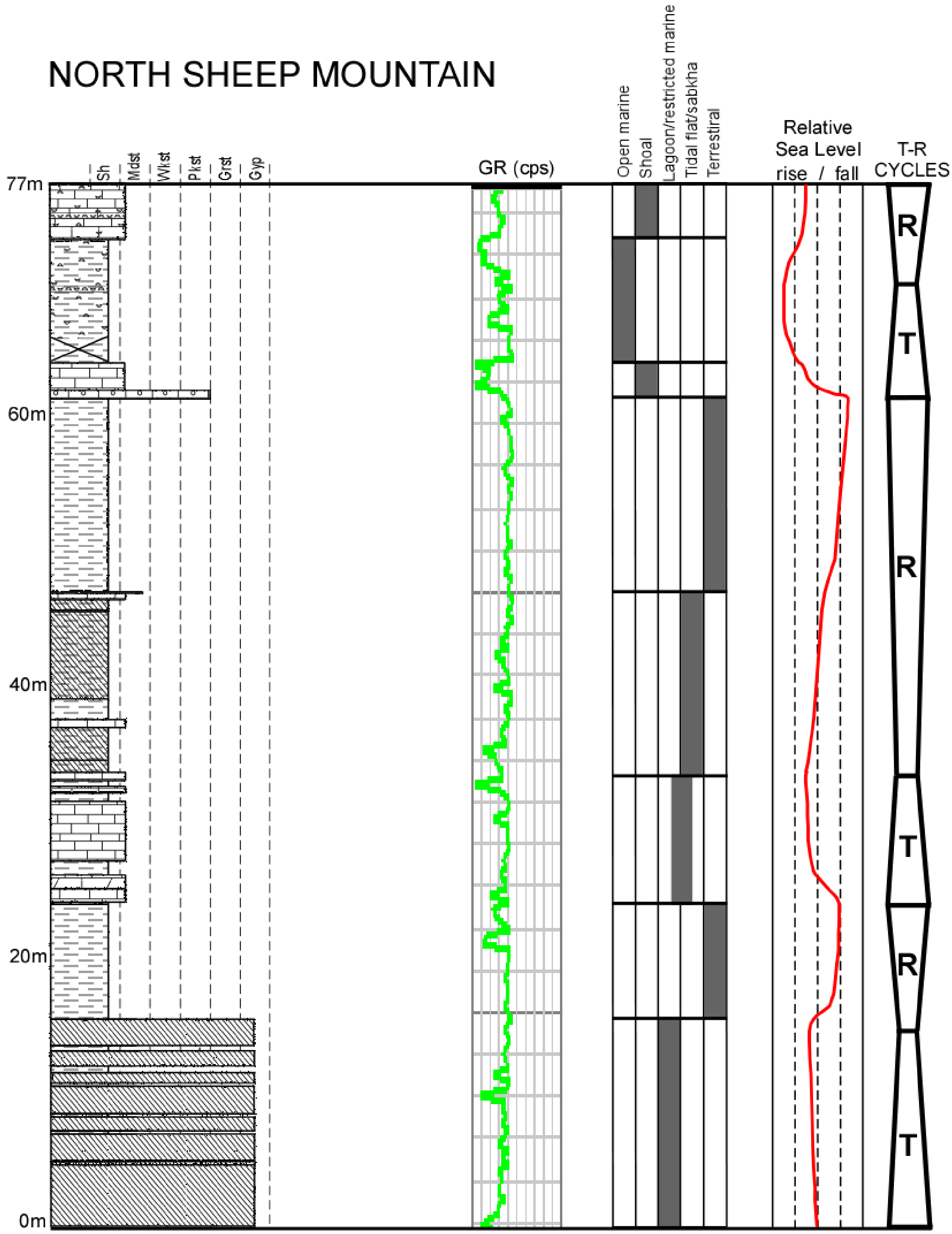


Appendix C-3 continued

CROOKED CREEK ROAD

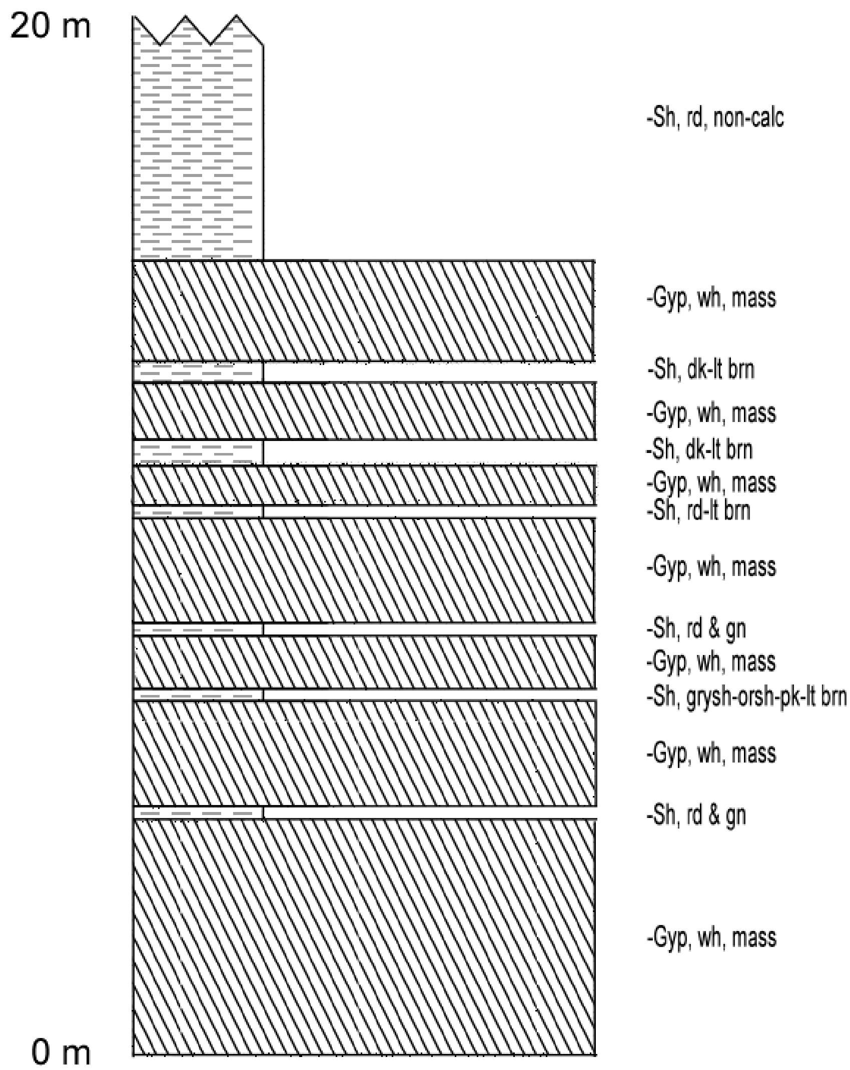


Appendix C-4


NORTH SHEEP MOUNTAIN
77m
60m
40m
20m
0m
Sh
Mdst
Wkst
Pkst
Grst
Gyp
GR (cps)
Open marine
Shoal
Lagoon/restricted marine
Tidal flat/sabkha
Terrestiral
Relative Sea Level
rise / fall
T-R CYCLES
R
T
R
T
R
T

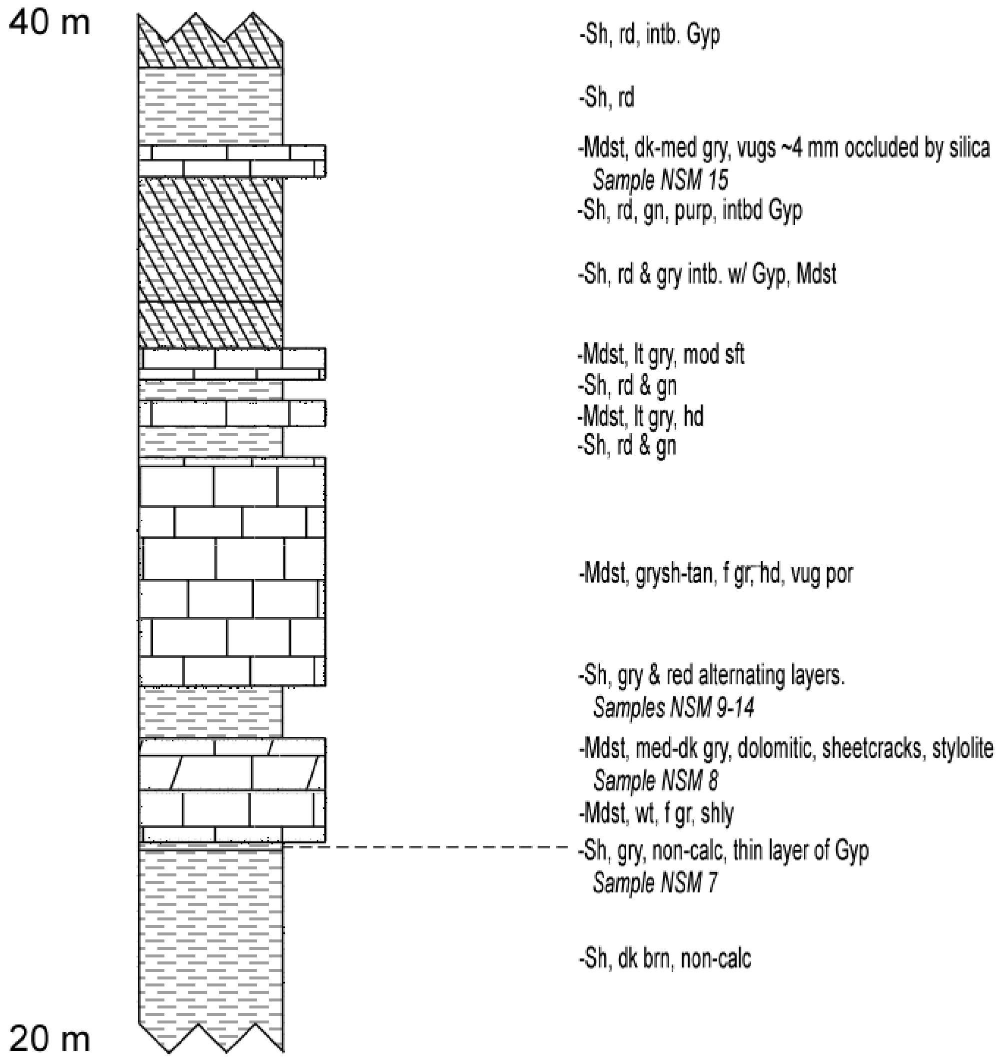
Appendix C-4 continued

NORTH SHEEP MOUNTAIN



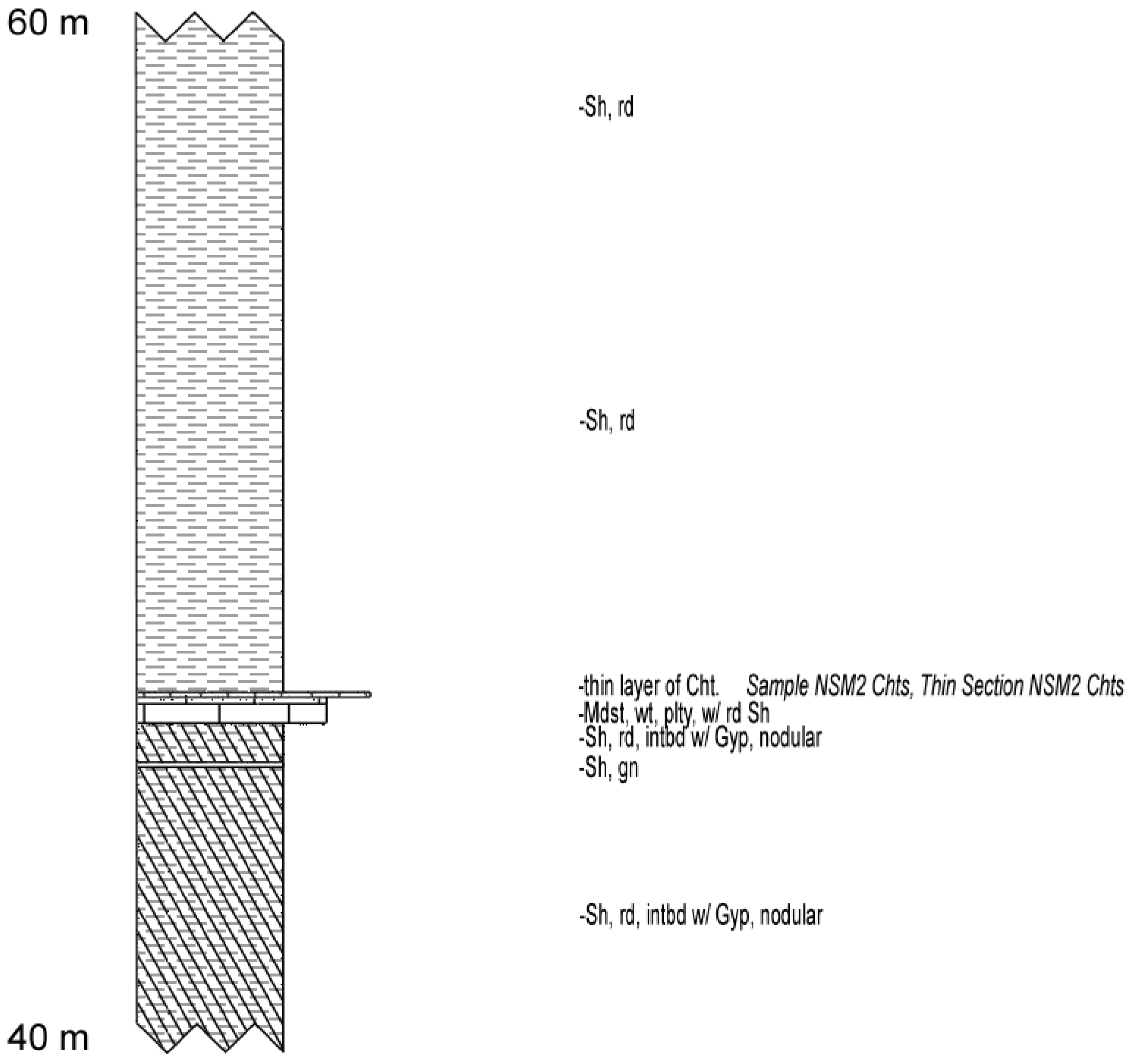
Appendix C-4 continued

NORTH SHEEP MOUNTAIN

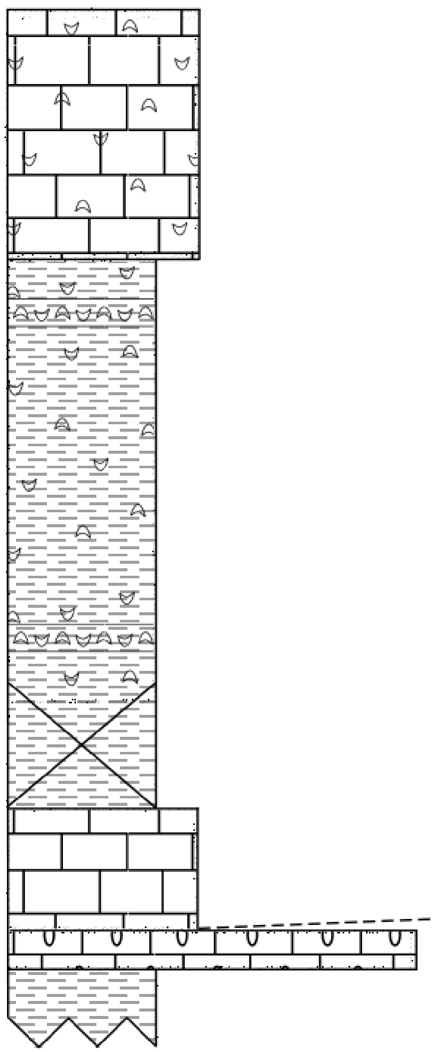


Appendix C-4 continued

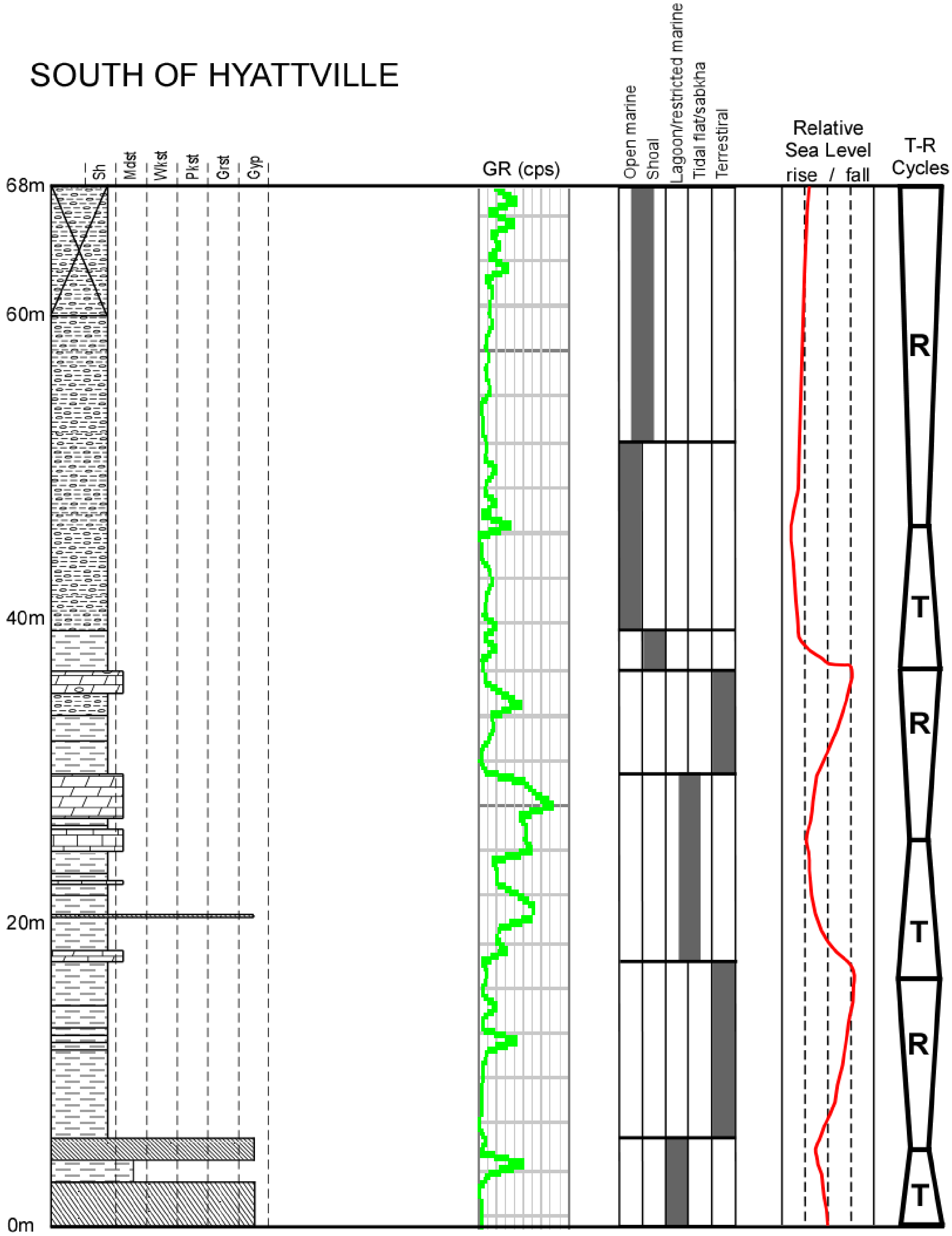
NORTH SHEEP MOUNTAIN



NORTH SHEEP MOUNTAIN

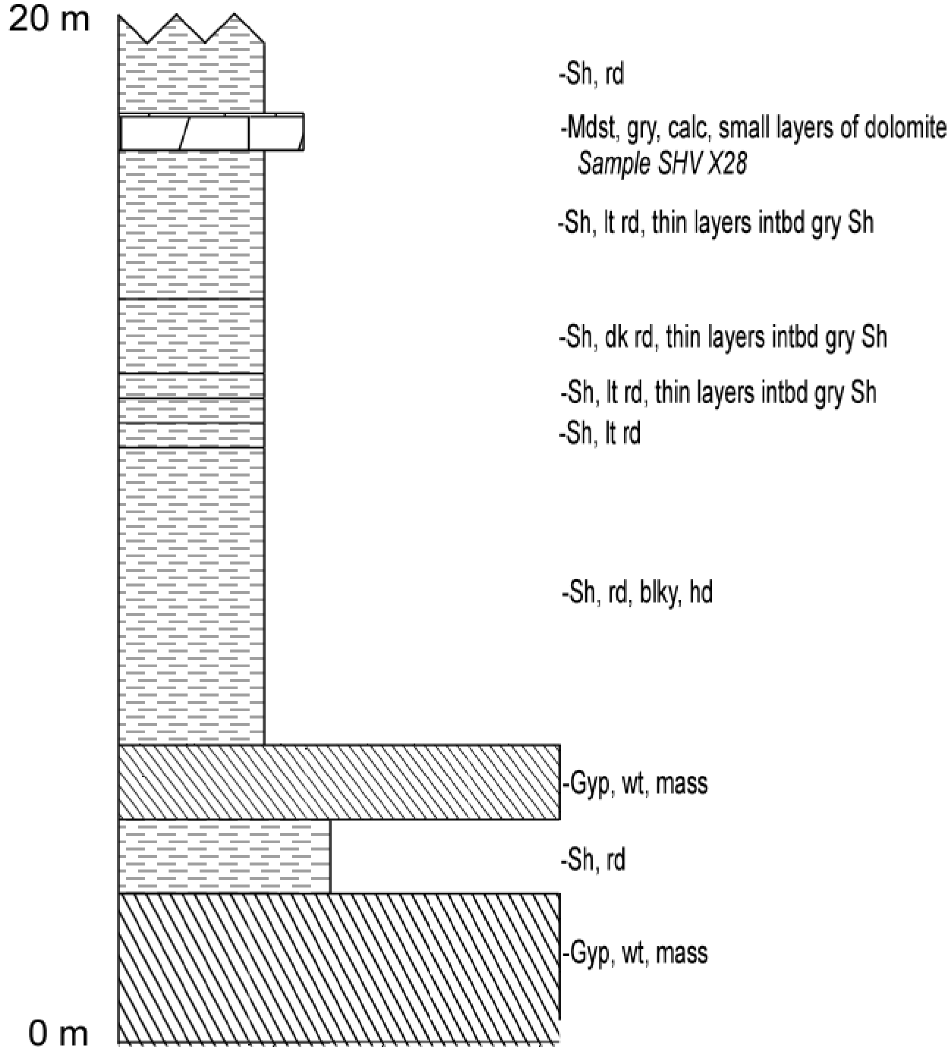


Appendix C-5



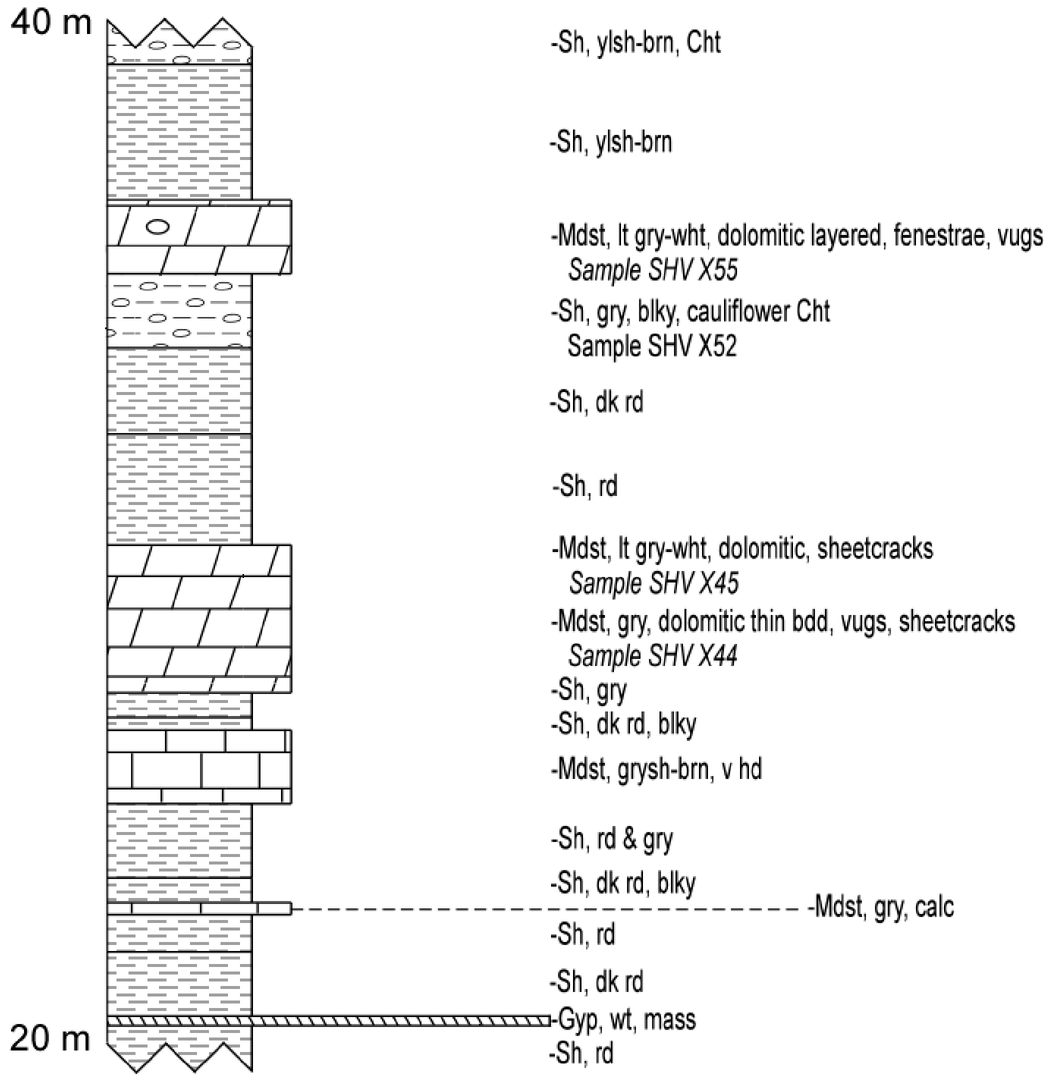
SOUTH OF HYATTVILLE
Sh
Mdst
Wkst
Pkst
Grst
Gyp
68m
60m
40m
20m
0m
GR (cps)
Open marine
Shoal
Lagoon/restricted marine
Tidal flat/sabkha
Terrestiral
Relative Sea Level
rise / fall
T-R Cycles
R
T
R
T
R
T

SOUTH OF HYATTVILLE



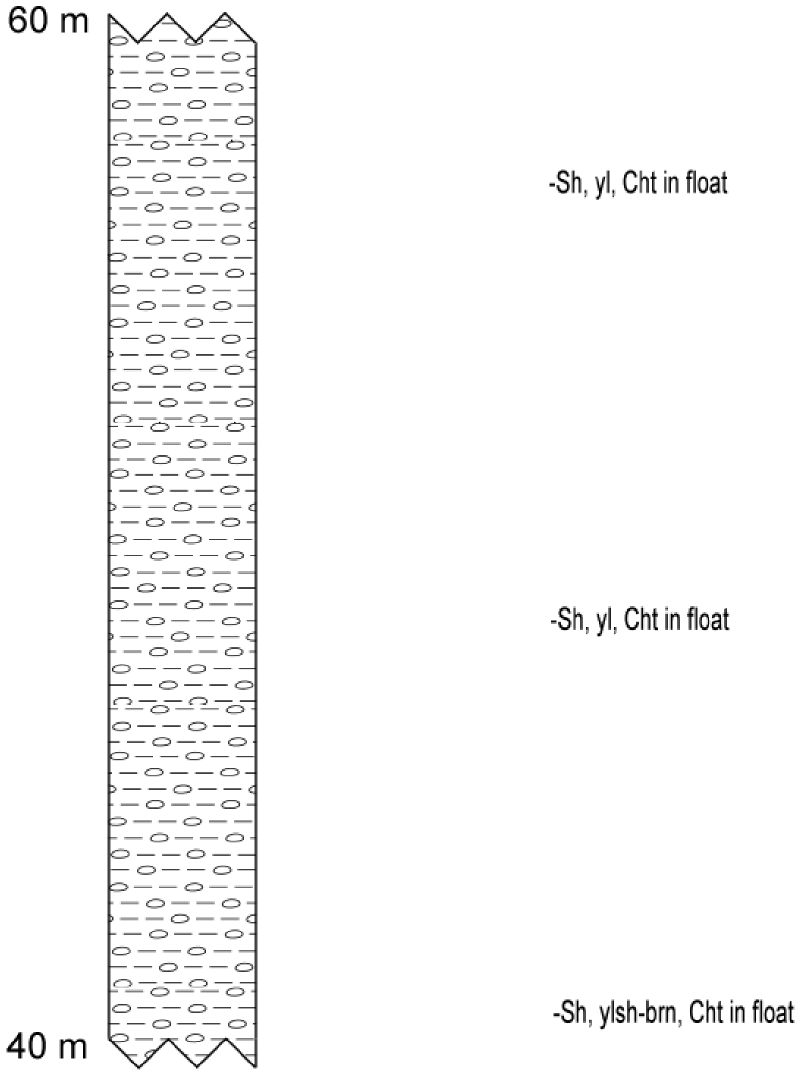
Appendix C-5 continued

SOUTH OF HYATTVILLE



Appendix C-5 continued

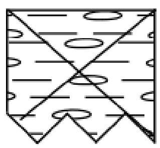
SOUTH OF HYATTVILLE



Appendix C-5 continued

SOUTH OF HYATTVILLE

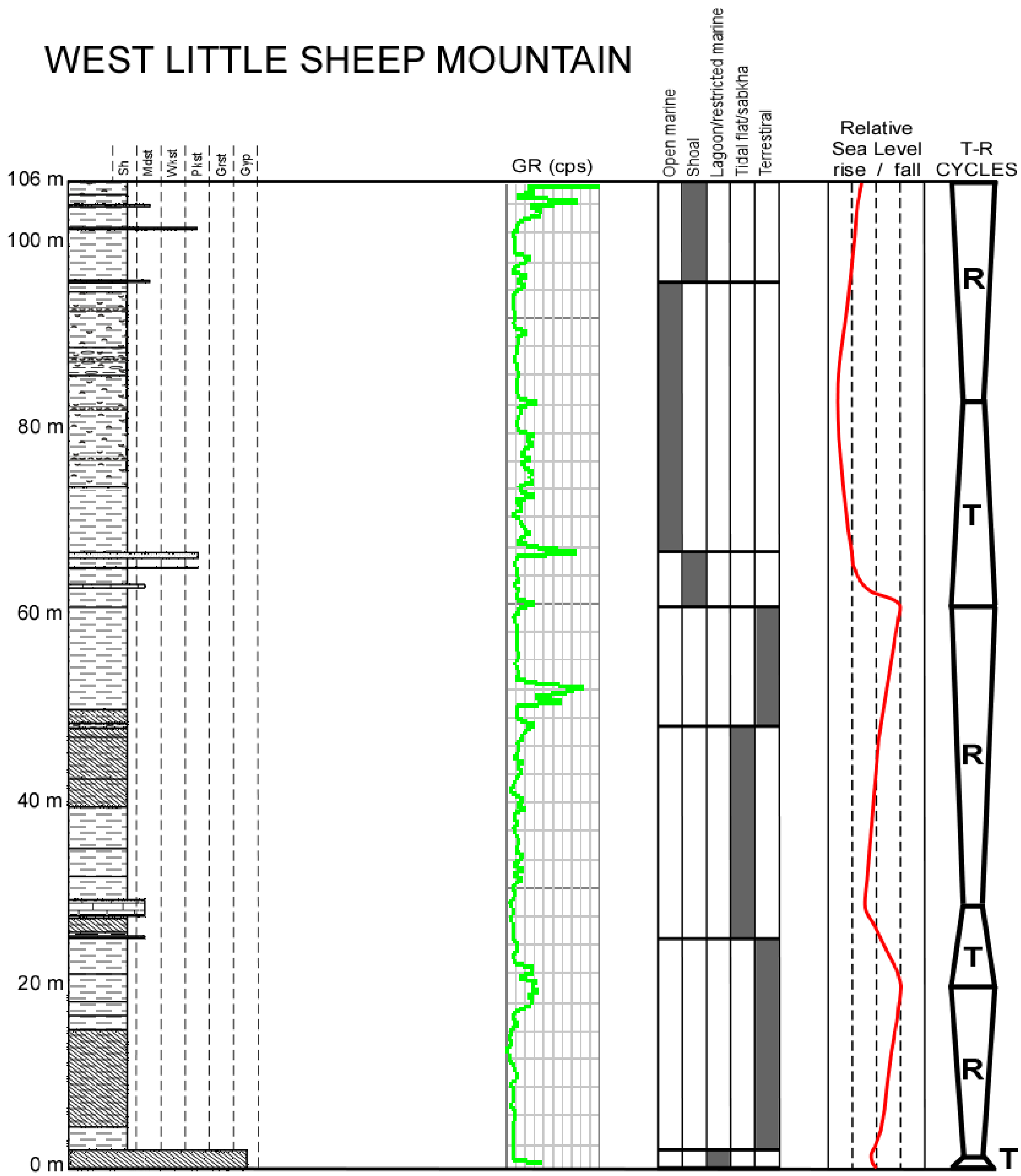
68 m



60 m

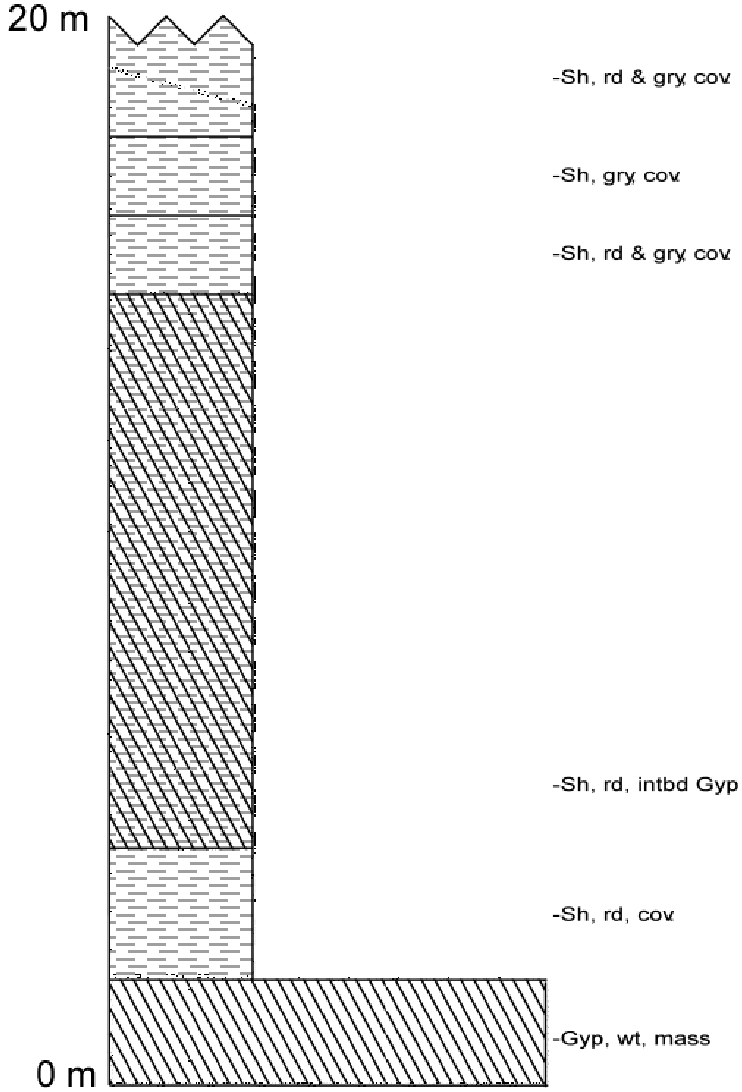
-Sh, yl, covered, Cht in float

Appendix C-6

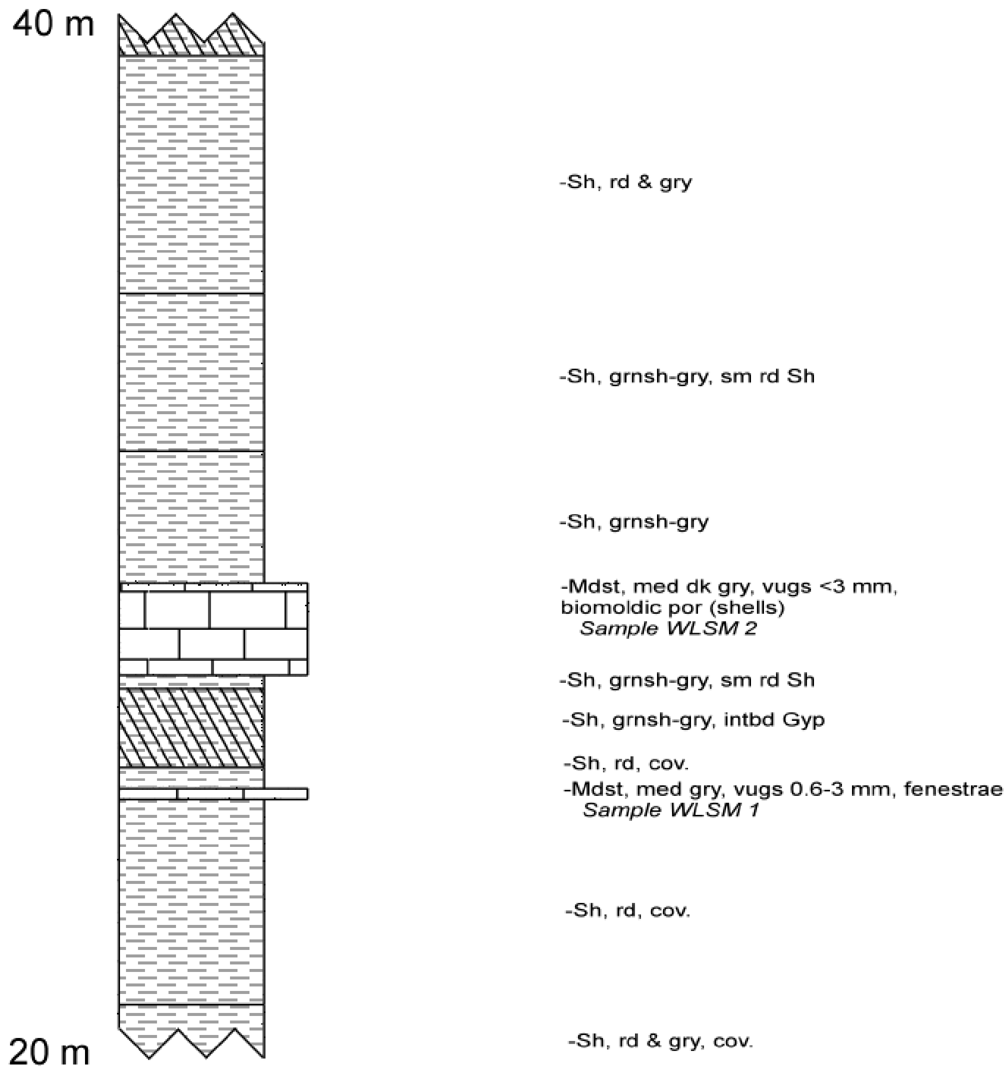

WEST LITTLE SHEEP MOUNTAIN
Sh
Mdst
Wkst
Pkst
Grst
Gyp
GR (cps)
Open marine
Shoal
Lagoon/restricted marine
Tidal flat/sabkha
Terrestiral
Relative Sea Level
rise / fall
T-R CYCLES
106 m
100 m
80 m
60 m
40 m
20 m
0 m
R
T
R
T
R
T

Appendix C-6 continued

WEST LITTLE SHEEP MOUNTAIN

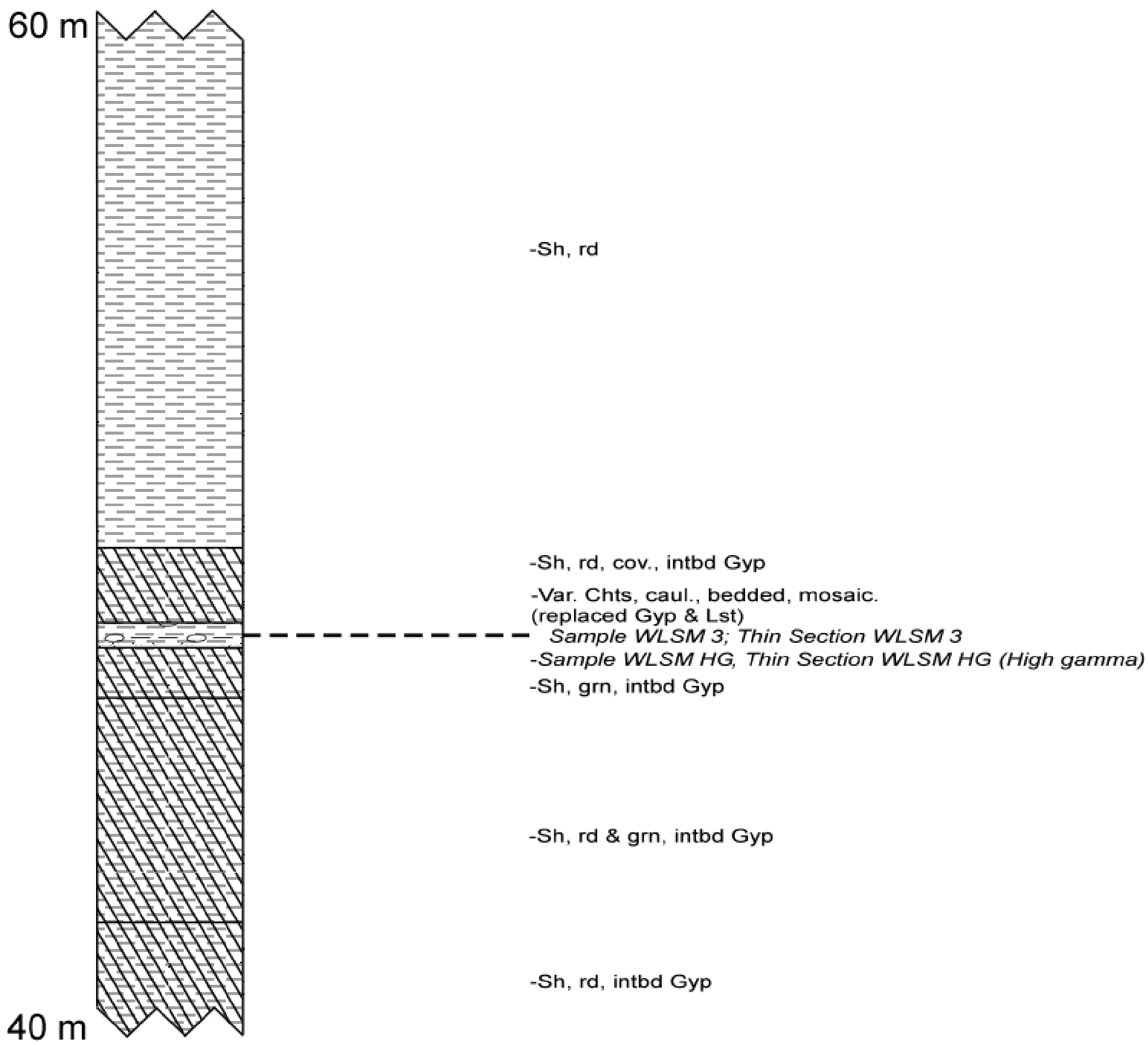


WEST LITTLE SHEEP MOUNTAIN



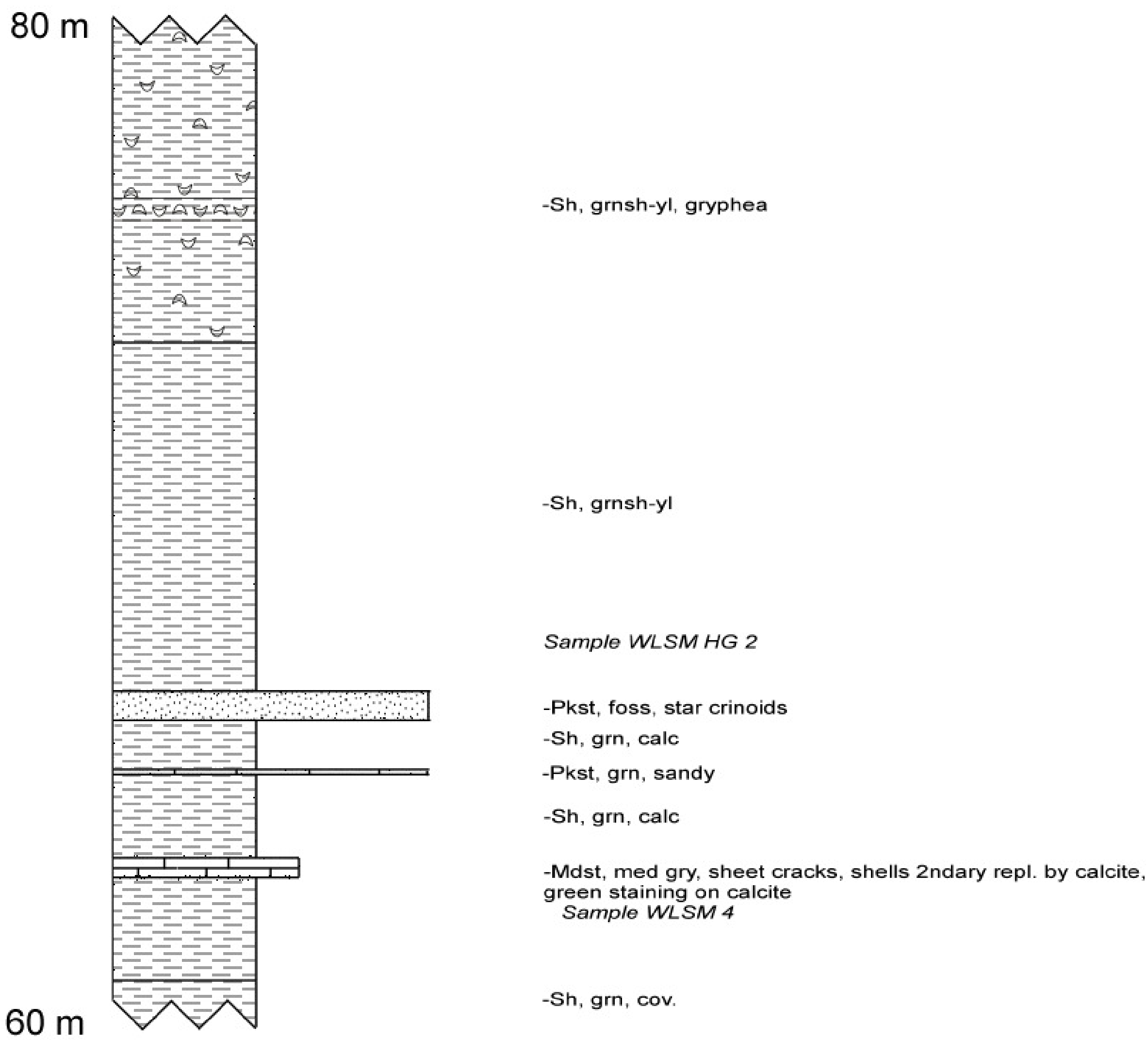
Appendix C-6 continued

WEST LITTLE SHEEP MOUNTAIN



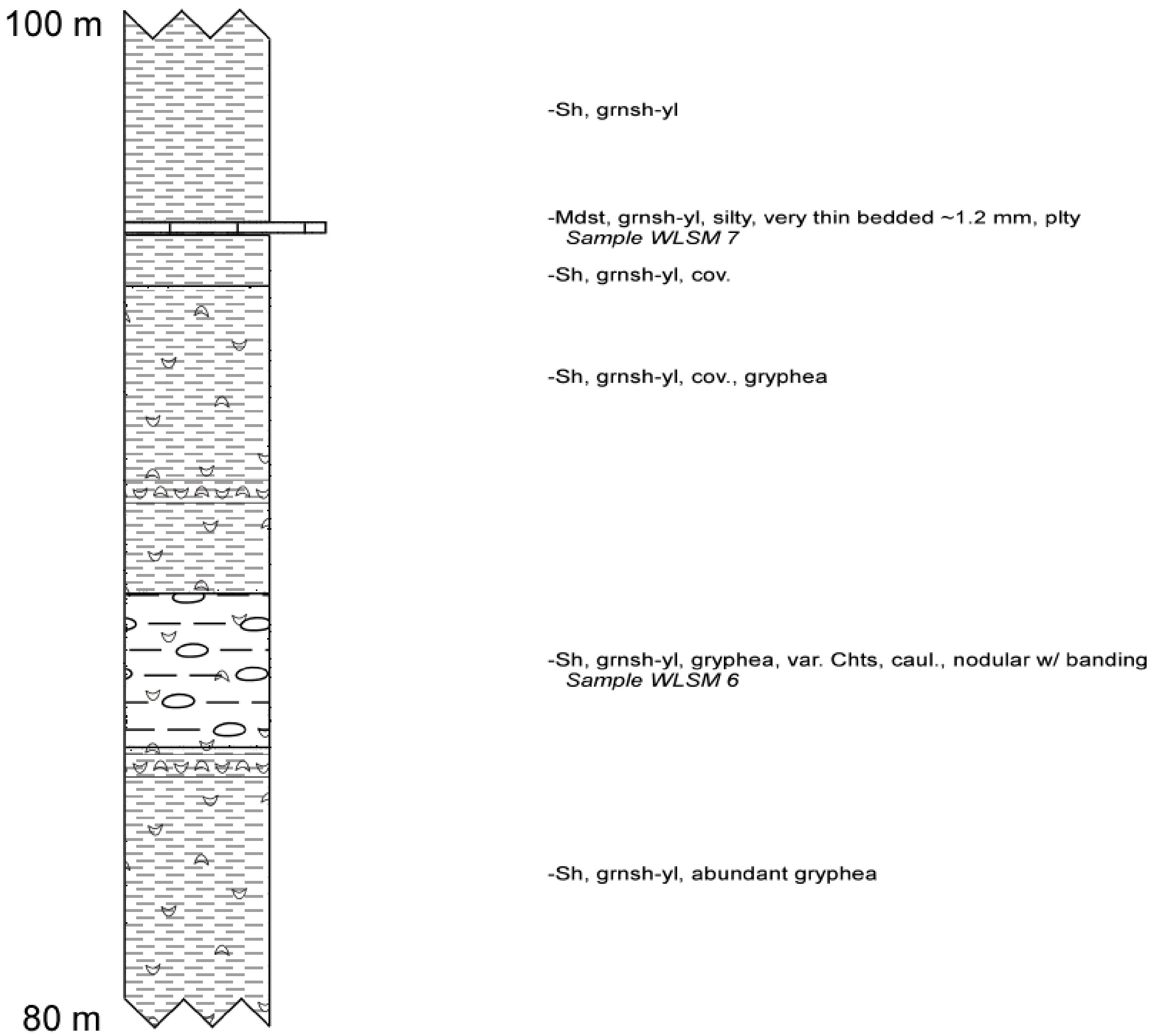
Appendix C-6 continued

WEST LITTLE SHEEP MOUNTAIN

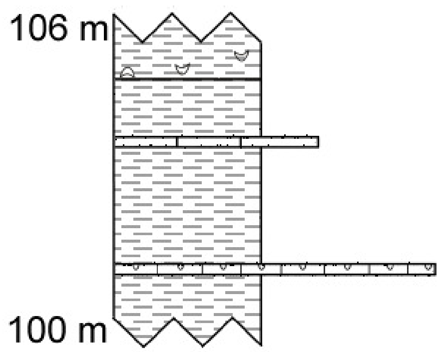


Appendix C-6 continued

WEST LITTLE SHEEP MOUNTAIN



WEST LITTLE SHEEP MOUNTAIN



-Sh, grnsh-yl, cov., gryphea

-Sh, grnsh-yl, cov.
Sample WLSM HG 2

-Mdst, yl, hor fracs, gastro shell, bivalves
Sample WLSM 9

-Sh, grnsh-yl, cov.

-Pkst-Grst, grnsh-yl, ooids 0.2-0.5 mm, skel. frags, qtz gr, prly srtd
Sample WLSM 8

-Sh, grnsh-yl, slightly orange

Appendix D: Well List										
Well Name	**No.**	**UWI**	**Latitude**	**Longitude**	**Operator Name**	**Status**	**Total Depth (ft)**	**GR**	**LLD**	**Rt**
ALTUS-KENAI STATE	36-1	49003205690000	84.4883	-98.8407	ALTUS EXPLORATION	Dry Hole	10020	X		
ALTUS-TEXAS AMER	41030	49043204010000	84.2915	-98.8638	ALTUS EXPLORATION	Oil Well	10795	X	X	
BLACK MOUNTAIN	68	49017210020000	43.6558	-107.7382	TEXACO	Oil Well	3560	X	X	
BOYLAN WEST	6	49003215780000	44.4859	-108.0656	ROCK WELL PETROLEUM US INC	Dry Hole	3448	X		X
CHRISTMANN TROJAN	40922	49003207410000	85.0237	-100.8048	CHRISTMANN ENERGY	Dry Hole	3312	X	X	
DOBIE CREEK UNIT	13-2	49003205270000	84.5788	-100.6057	AMERCN QUASAR PETROIEUM	Gas Well	12780	X		
EMMETT-FEDERAL	1	49003056360000	84.8245	-100.0614	GULF OIL CORP	Dry Hole	11968	X		
FEDERAL	40918	49003207810000	84.7248	-98.6122	SONAT EXPL INC	Dry Hole	4471	X	X	
FEDERAL	40923	49043205120000	84.1565	-98.0705	PIKE RESOURCES LTD	Dry Hole	9231	X	X	
FEDERAL	34-22	49003206910000	84.4804	-97.3225	DATA BIG HORN BASIN	Dry Hole	3265	X		
FEDERAL 6-57-96	1	49003202100000	85.3459	-101.9471	MIDWEST OIL	Dry Hole	2873	X		
FLYING M RANCH	1	49003200710000	84.7992	-99.7198	ROSEBUD ROYALTY	Dry Hole	3465	X	X	
FRISON-FEDERAL	15-1	49043205700000	84.4398	-98.1961	FAGIN EXPL. INC	Dry Hole	5520	X	X	
FUSSELMAN-EDWARDS	1	49043203000000	84.0832	-99.9981	GALLAGHER VICTOR R	Oil Well	5375	X	X	
GOVT	1	49043054710000	84.4147	-97.4302	COOK R A	Oil Well	2257	X		
GOVT	1	49043056010000	84.0066	-98.0966	CONSOLIDATED OIL & GAS	Dry Hole	5060	X		

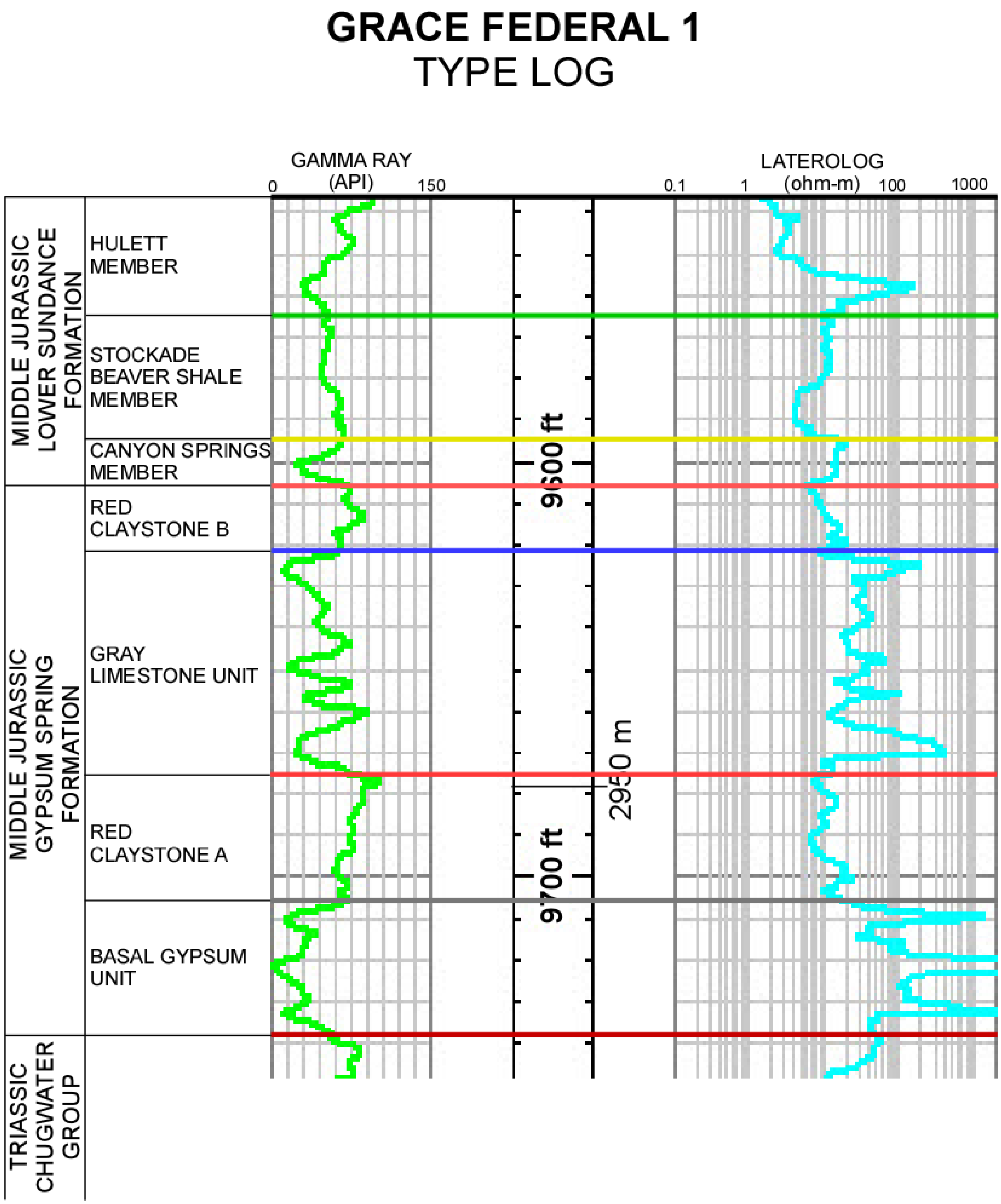
Appendix D continued										
Well Name	**No.**	**UWI**	**Latitude**	**Longitude**	**Operator Name**	**Status**	**Total Depth (ft)**	**GR**	**LLD**	**Rt**
GOVT	40916	49043051150000	43.8847	-107.5458	ASHLAND EXPL INC	Oil Well	7850	X	X	
GOVT-DUFF	41239	49003058990000	85.0302	-97.7947	MOBIL OIL CORP	Dry Hole	2045	X	X	
GRACE-FEDERAL	1	49043204190000	84.2854	-99.4075	CORONADO OIL CO	Oil Well	10920	X	X	
HAGER-GOVT	1	49017200250000	84.1934	-102.7754	CORONADO OIL CO	Dry Hole	6812	X	X	
HERRON GULCH	2	49003203110000	84.8617	-98.4174	CONSOLIDATED OIL & GAS	Dry Hole	2922	X		
HILAND ALTUS	23-4	49043204540000	84.3573	-99.2685	ALTUS EXPLORATION	Oil Well	10904	X		
HUCKABAY LTD	14-20	49003207600000	44.7359	-108.3112	FARLEIGH BILL D	Dry Hole	5209	X	X	
KENTTA-GOVT	1	49003202320000	84.7133	-99.4856	CORONADO OIL CO	Dry Hole	3691	X	X	
KINNEY COASTAL	71	49029206970000	44.8120	-108.5934	MARATHON OIL COMPANY	Oil Well	4534	X	X	
KIRBY CREEK	12	49017206890000	84.0429	-100.3535	GETTY OIL COMPANY	Oil Well	4099	X	X	
KLAENHAMMER-FEDERAL	1-B	49003204500000	84.8155	-100.0142	OIL DEV CO OF TEXAS	Gas Well	11410	X	X	
KYNE	4	49017209460000	43.6808	-107.8893	THOROFARE RES	Oil Well	3537	X		
LAMB-FEDERAL	40920	49003206080000	84.7353	-99.2044	FLORIDA EXPL CO	Oil Well	4890	X	X	
LEE A K	2A	49017206900000	84.0207	-100.2028	GETTY OIL COMPANY	Oil Well	3650	X	X	
MANDERSON UNIT	34-2P	49003209750000	84.6669	-99.5674	KCS MOUNTAIN RES	Oil Well	8095	X		
MASSEY DRAW	1-26-49-90	49003207130000	84.4673	-97.2385	COASTAL O&G CORP	Dry Hole	2480	X	X	

Appendix D continued										
Well Name	No.	UWI	Latitude	Longitude	Operator Name	Status	Total Depth (ft)	GR	LLD	Rt
MASSEY DRAW	2-13-49-90	49003207230000	84.4921	-97.0228	COASTAL O&G CORP	Dry Hole	2276	X	X	
MC DERMOTT GULCH	1-19-50-90	49003207140000	84.5746	-97.4943	COASTAL O&G CORP	Dry Hole	3315	X	X	
MCDERMOTT`S GULCH	2-13-50-91	49003207250000	84.5993	-97.7524	COASTAL O&G CORP	Dry Hole	3488	X	X	
MEYERS GULCH WEST	41209	49043206180000	84.3001	-97.6822	ENERGY RESV GRP INC	Dry Hole	7707	X	X	
MILDRED SNYDER	2	49003200230000	85.1509	-102.0566	TENNECO OIL CO	Dry Hole	6493	X		
NELSON-GOVT	1	49017202430000	84.0736	-100.9248	CORONADO OIL CO	Dry Hole	4524	X	X	
NORTHEAST OTTO-FED	1	49003203160000	84.8149	-101.0987	GULF OIL CORP	Dry Hole	14650	X	X	
NUPEC LAMB FEDERAL	40910	49003206240000	84.7523	-99.4259	FLORIDA EXPL CO	Oil Well	4146	X	X	
ORCHARD RANCH	1	49043206970000	83.9761	-97.6693	PETROLEUM INC	Dry Hole	3595	X	X	
PAUMER-PAINTROCK	1	49003207530000	84.4965	-97.8211	AMOCO PROD CO	Dry Hole	2360	X	X	
PRIMA-APC	21-1	49003208160000	84.8106	-99.5983	PRIMA OIL & GAS CO	Dry Hole	3262	X		X
RAGS-FEDERAL	1	49003207710000	44.2062	-107.6738	BEARD OIL CO INC	Dry Hole	3102	X	X	
REEVES-FEDERAL	1	49043204020000	84.0179	-98.5379	BREHM C E	Dry Hole	5576	X	X	
REPUBLIC-A	1	49043055900000	84.0918	-99.4460	ANADARKO PROD CO	Dry Hole	7472	X	X	
SPEAR-FEDERAL	33-31	49003203640000	84.9928	-101.5505	TRUE OIL LLC	Gas Well	13380	X	X	

Appendix D continued

Well Name	No.	UWI	Latitude	Longitude	Operator Name	Status	Total Depth (ft)	GR	LLD	Rt
THOR STATE	13516	49003207850000	85.0947	-102.6426	CHEVRON USA INC	Dry Hole	9850	X	X	
UNIT	1	49043050840000	84.1979	-101.0029	SINCLAIR OIL & GAS CO	Dry Hole	11972	X		
UNIT	1	49043051720000	84.3902	-102.2144	ANDERSON-PRCHRD OIL	Dry Hole	14780	X		
UNIT	11	49043050890000	84.1785	-99.6670	CALIFORNIA OIL CO	Oil Well	10440	X		X
UNIT-FEDERAL	40915	49003208790000	84.5259	-97.7122	MCKENZIE PETROLEUM COMPANY	Dry Hole	3100	X	X	
USA-DAVID	1	49003203670000	84.5662	-97.9773	ENERGY RESV GROUP INC	Dry Hole	2745	X		X
WOUNDED KNEE UNIT	1	49003206480000	84.7652	-99.9405	DAVIS OIL CO	Dry Hole	11985	X		
WYOMING-STATE	B-1	49017053350000	84.0712	-101.8823	MCALESTER FUEL CO	Dry Hole	2435	X		

Appendix E: Type Log



PLATES

Plate 1

BASAL GYPSUM ISOPACHOUS MAP

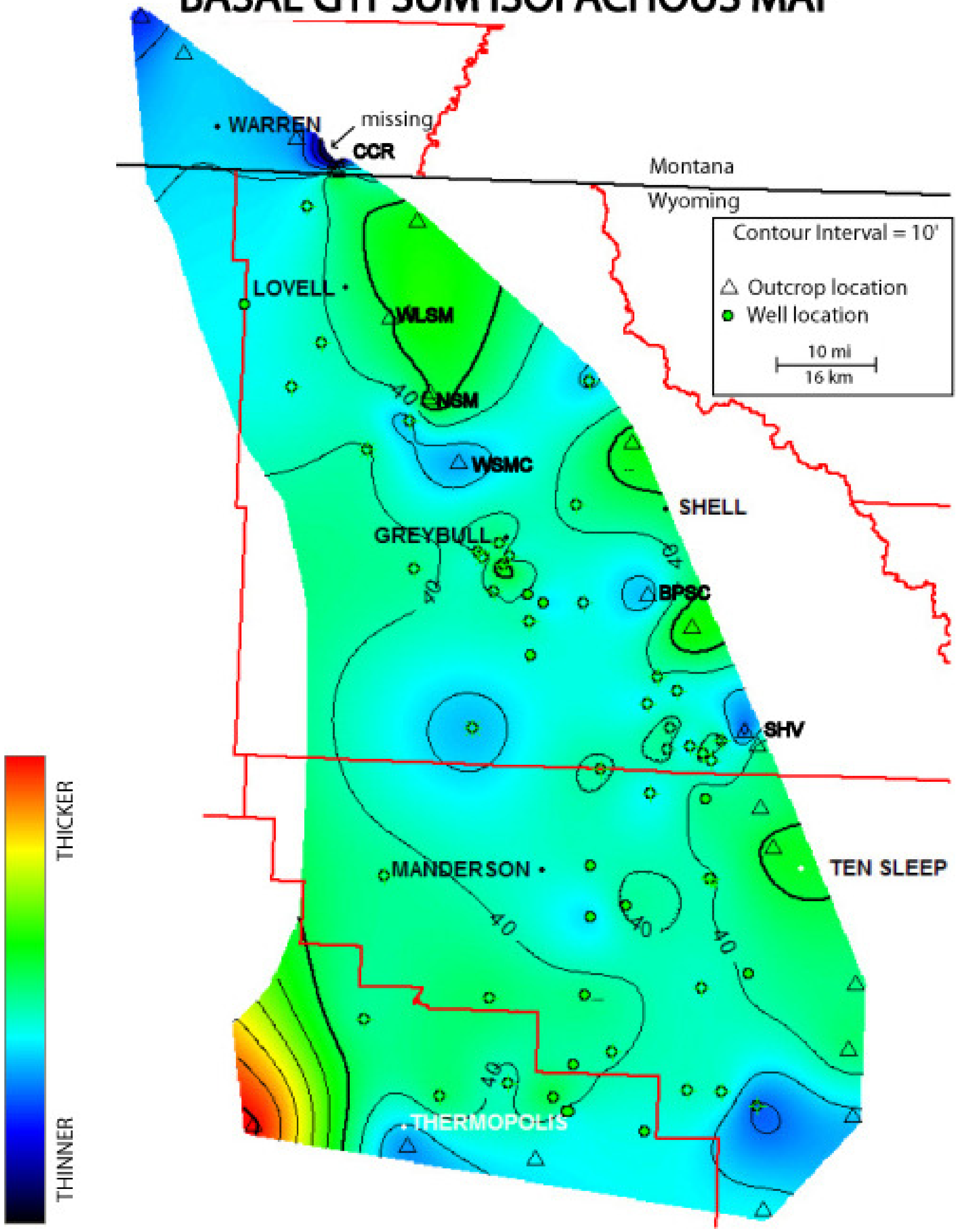


Plate 2

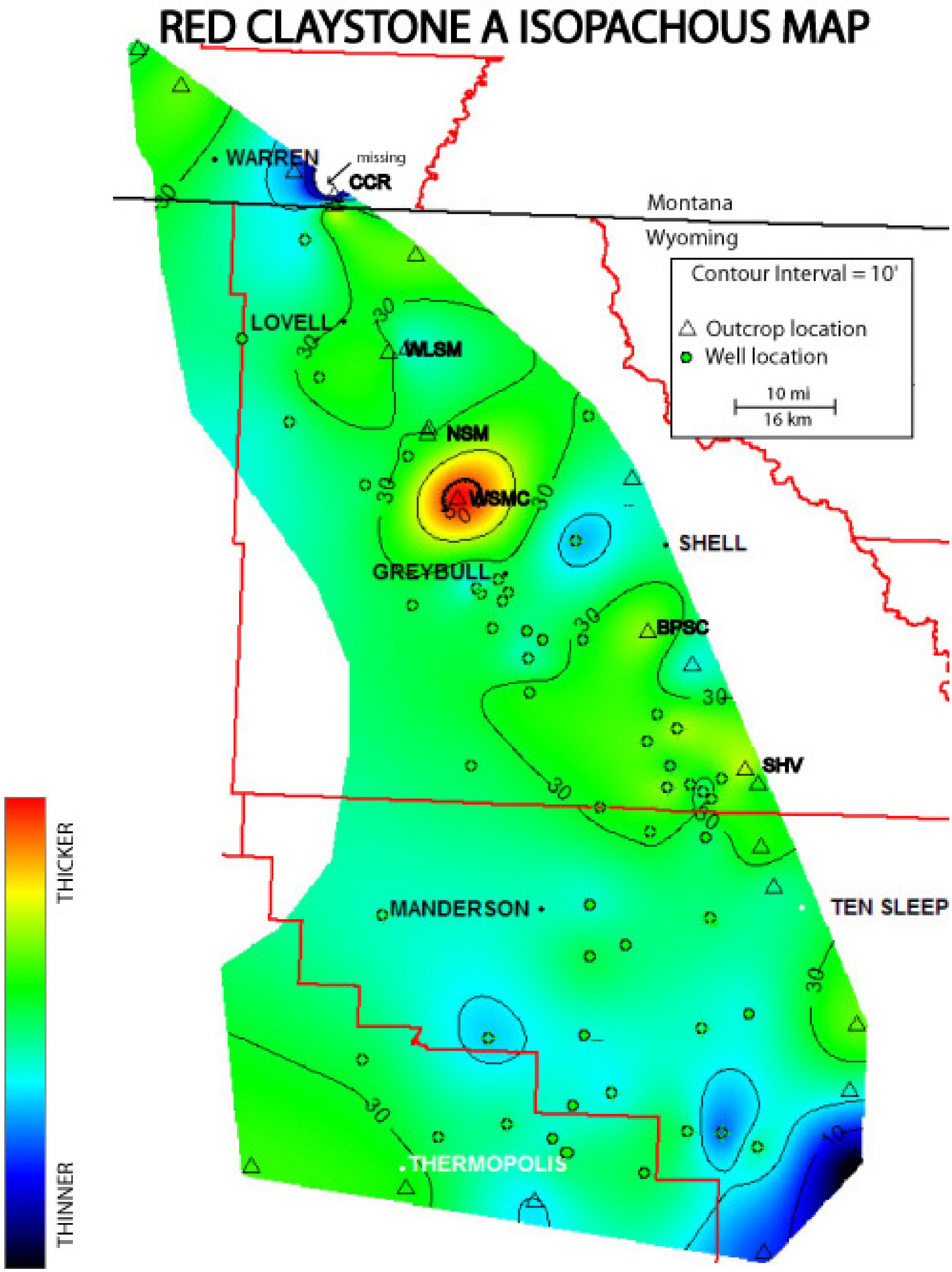

RED CLAYSTONE A ISOPACHOUS MAP
WARREN
missing
CCR
Montana
Wyoming
Contour Interval = 10'
Outcrop location
Well location
10 mi
16 km
LOVELL
WLSM
NSM
WSMC
SHELL
GREYBULL
BPSC
SHV
MANDERSON
TEN SLEEP
THERMOPOLIS
THICKER
THINNER

Plate 3

GRAY LIMESTONE UNIT ISOPACHOUS MAP

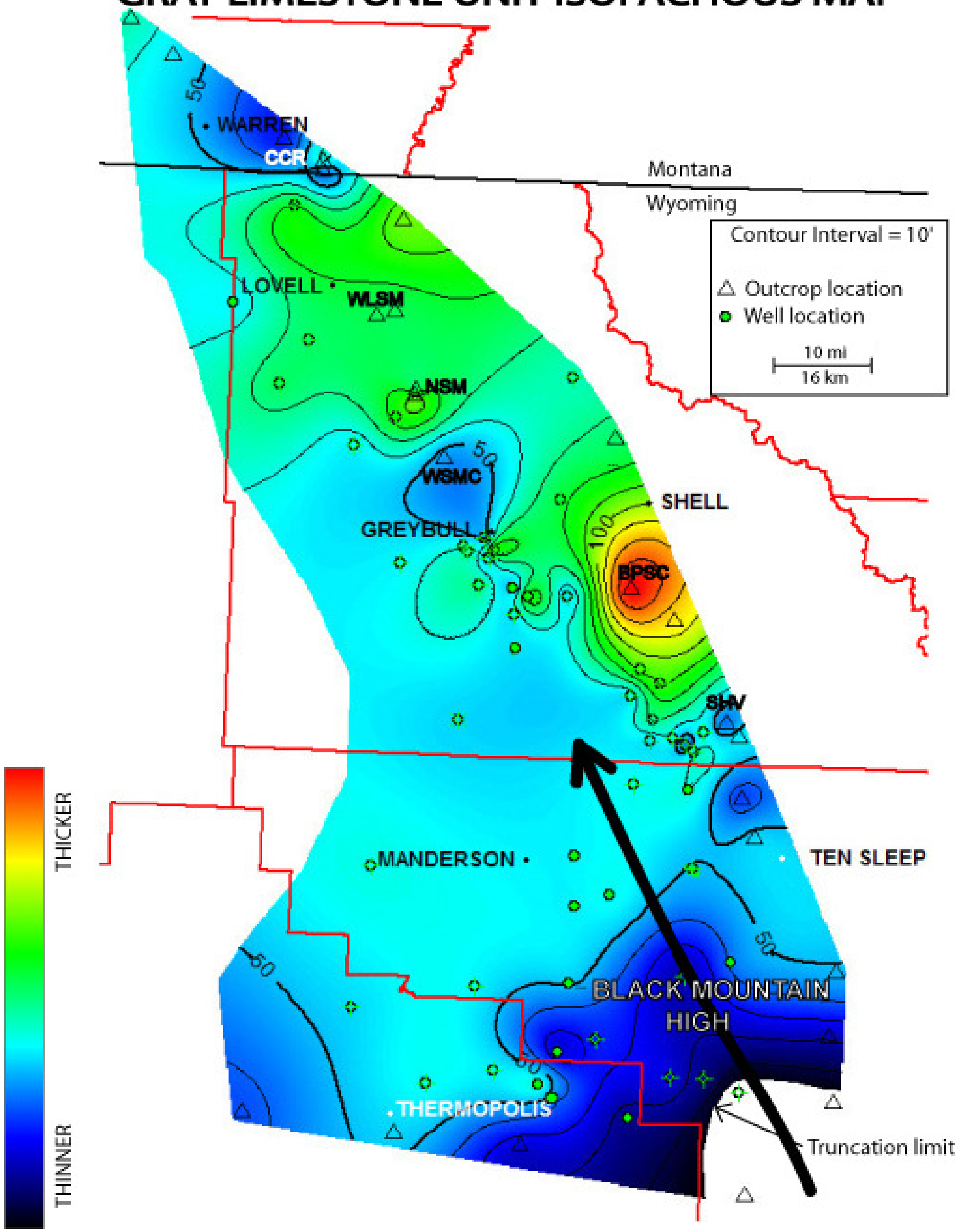


Plate 4

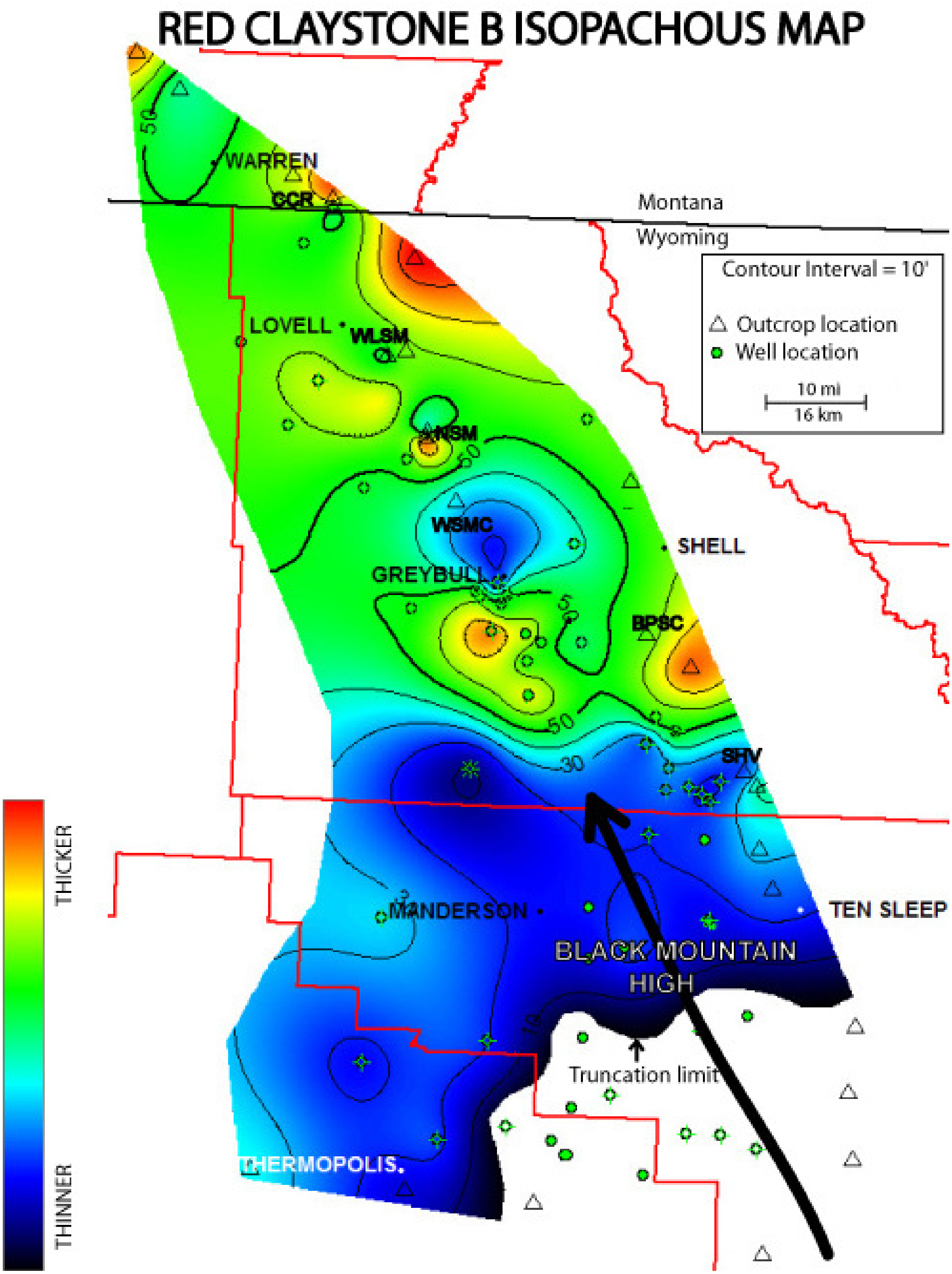

RED CLAYSTONE B ISOPACHOUS MAP
Montana
Wyoming
Contour Interval = 10'
Outcrop location
Well location
10 mi
16 km
WARREN
CCR
LOVELL
WLSM
NSM
WSMC
GREYBULL
SHELL
BPSC
SHV
MANDERSON
TEN SLEEP
BLACK MOUNTAIN HIGH
Truncation limit
THERMOPOLIS
THICKER
THINNER
50
30

Plate 5

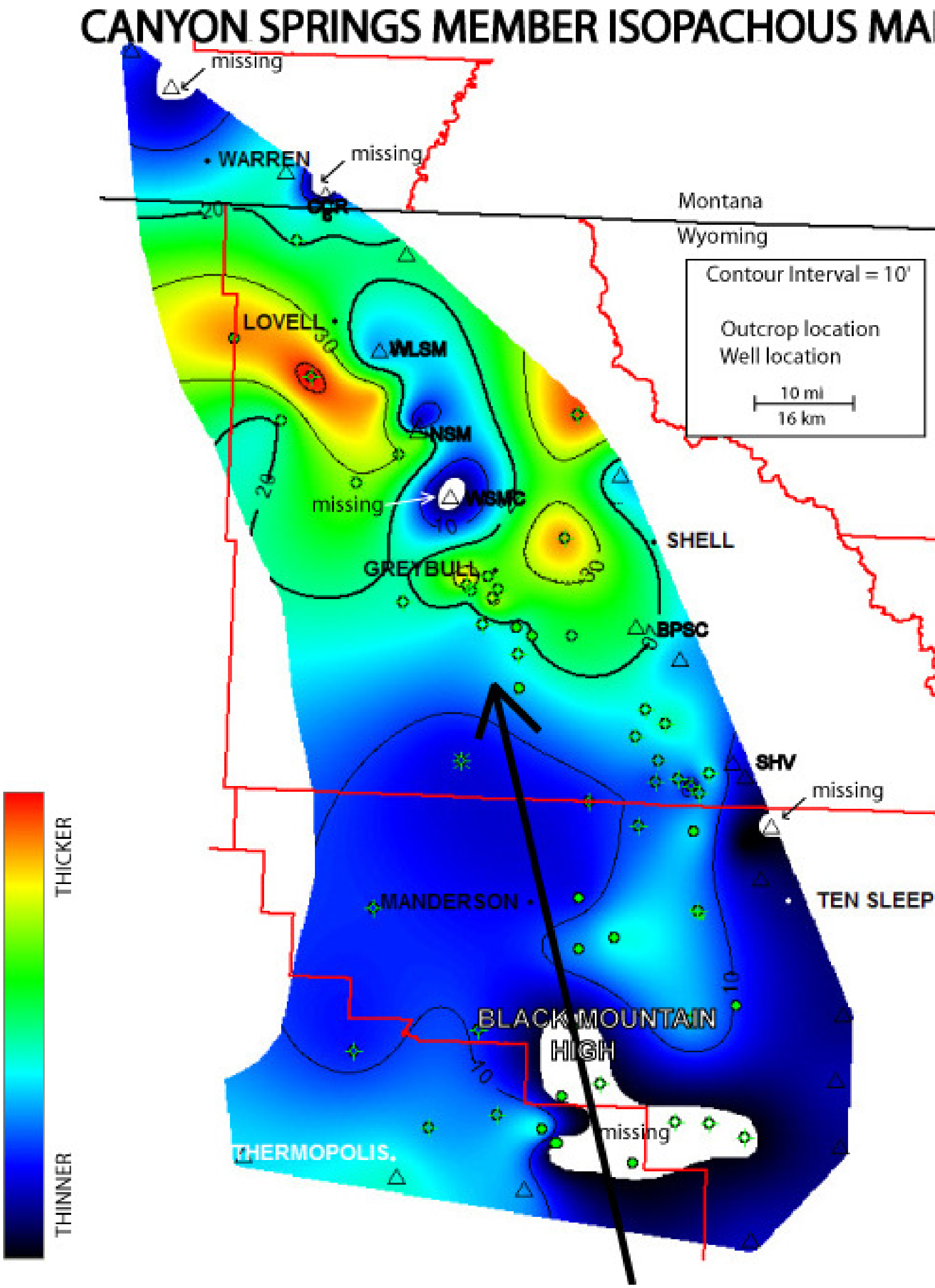

CANYON SPRINGS MEMBER ISOPACHOUS MAP
missing
WARREN
missing
Montana
Wyoming
Contour Interval = 10'
Outcrop location
Well location
10 mi
16 km
LOVELL
WLSM
NSM
missing
WSMC
SHELL
GREYBULL
BPSC
SHV
missing
TEN SLEEP
MANDERSON
BLACK MOUNTAIN HIGH
missing
THERMOPOLIS
THICKER
THINNER

Plate 6

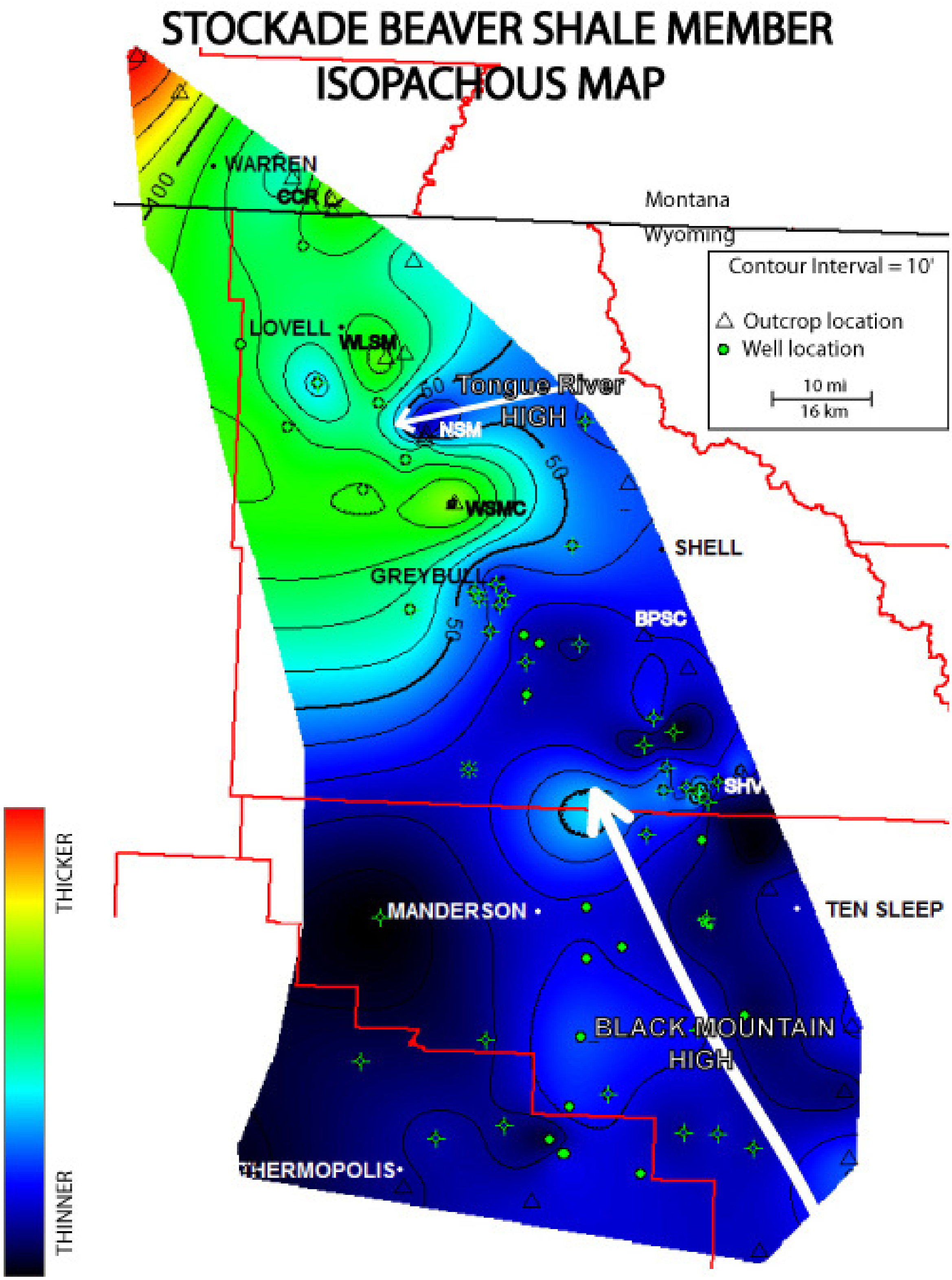

STOCKADE BEAVER SHALE MEMBER
ISOPACHOUS MAP
WARREN
CCR
Montana
Wyoming
Contour Interval = 10'
Outcrop location
Well location
10 mi
16 km
LOVELL
WLSM
Tongue River
HIGH
NSM
WSMC
SHELL
GREYBULL
BPSC
SHV
MANDERSON
TEN SLEEP
BLACK MOUNTAIN
HIGH
THERMOPOLIS
THICKER
THINNER

Plate 7

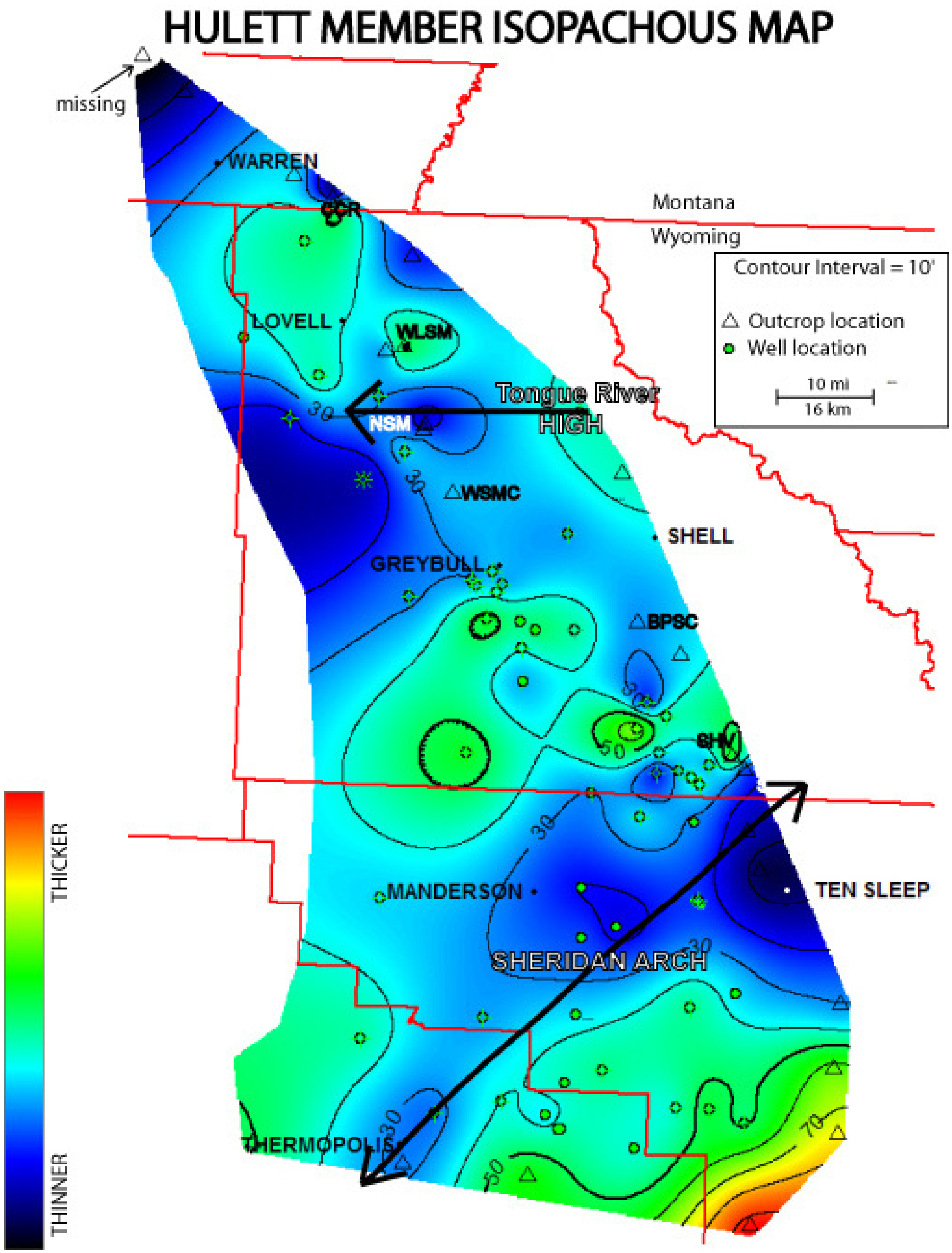

HULETT MEMBER ISOPACHOUS MAP
missing
WARREN
CCR
Montana
Wyoming
Contour Interval = 10'
Outcrop location
Well location
10 mi
16 km
LOVELL
WLSM
Tongue River
HIGH
NSM
30
WSMC
SHELL
GREYBULL
BPSC
50
SHV
30
MANDERSON
TEN SLEEP
SHERIDAN ARCH
30
70
30
50
THERMOPOLIS
THICKER
THINNER

Plate 8: Cross-Section Map

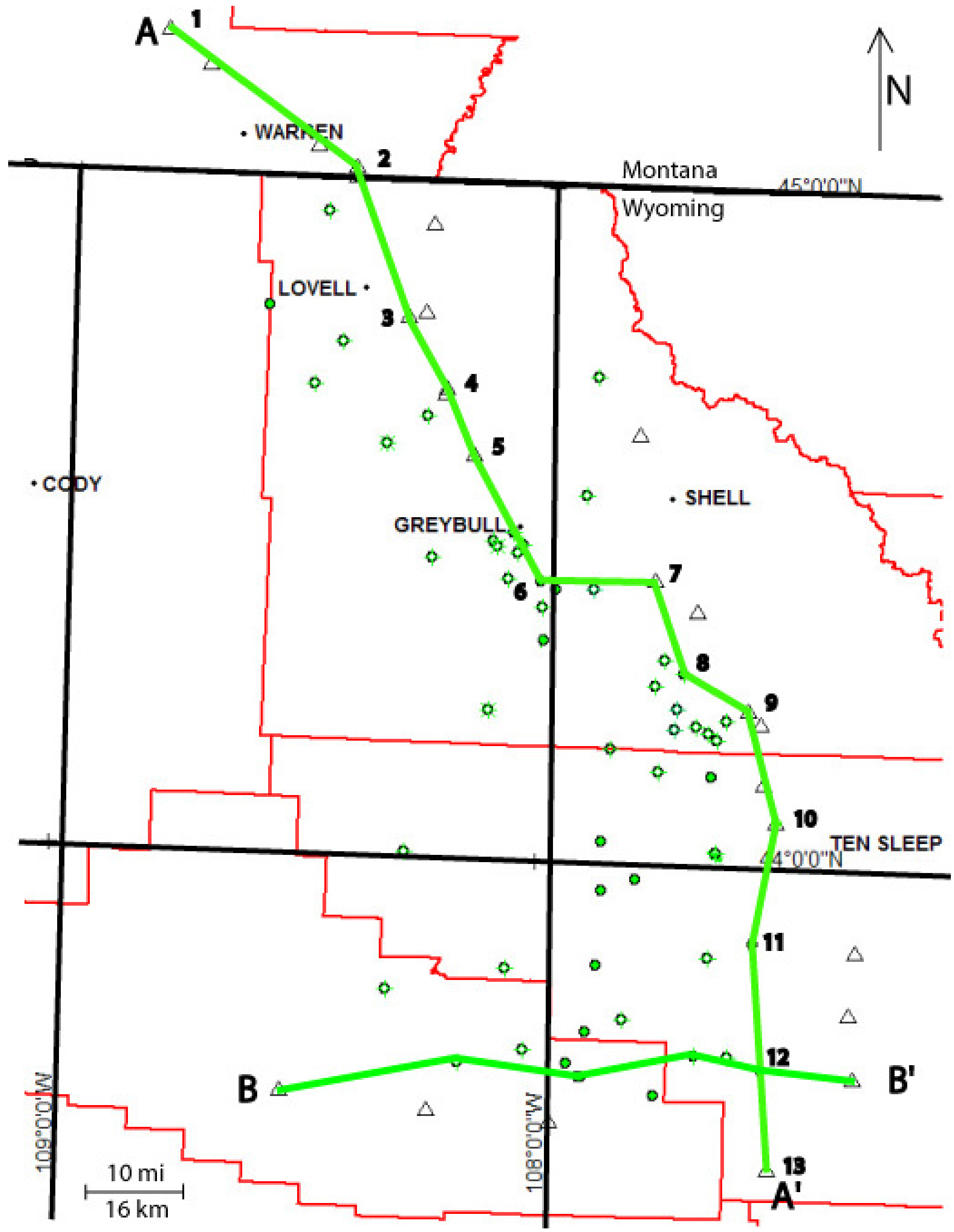


Plate 9: West-East cross-section over Black Mountain High

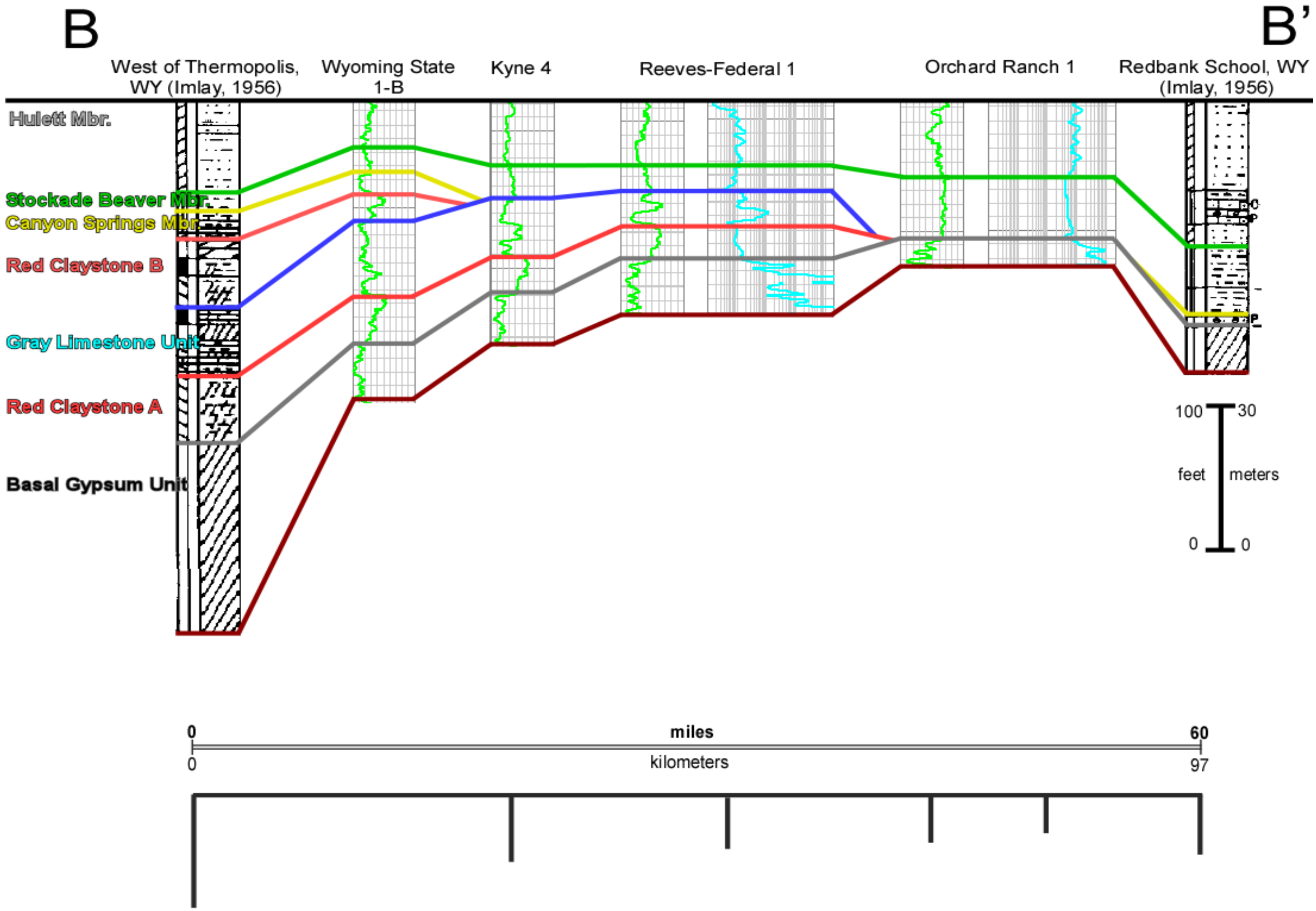


Plate 10: North-South cross-section

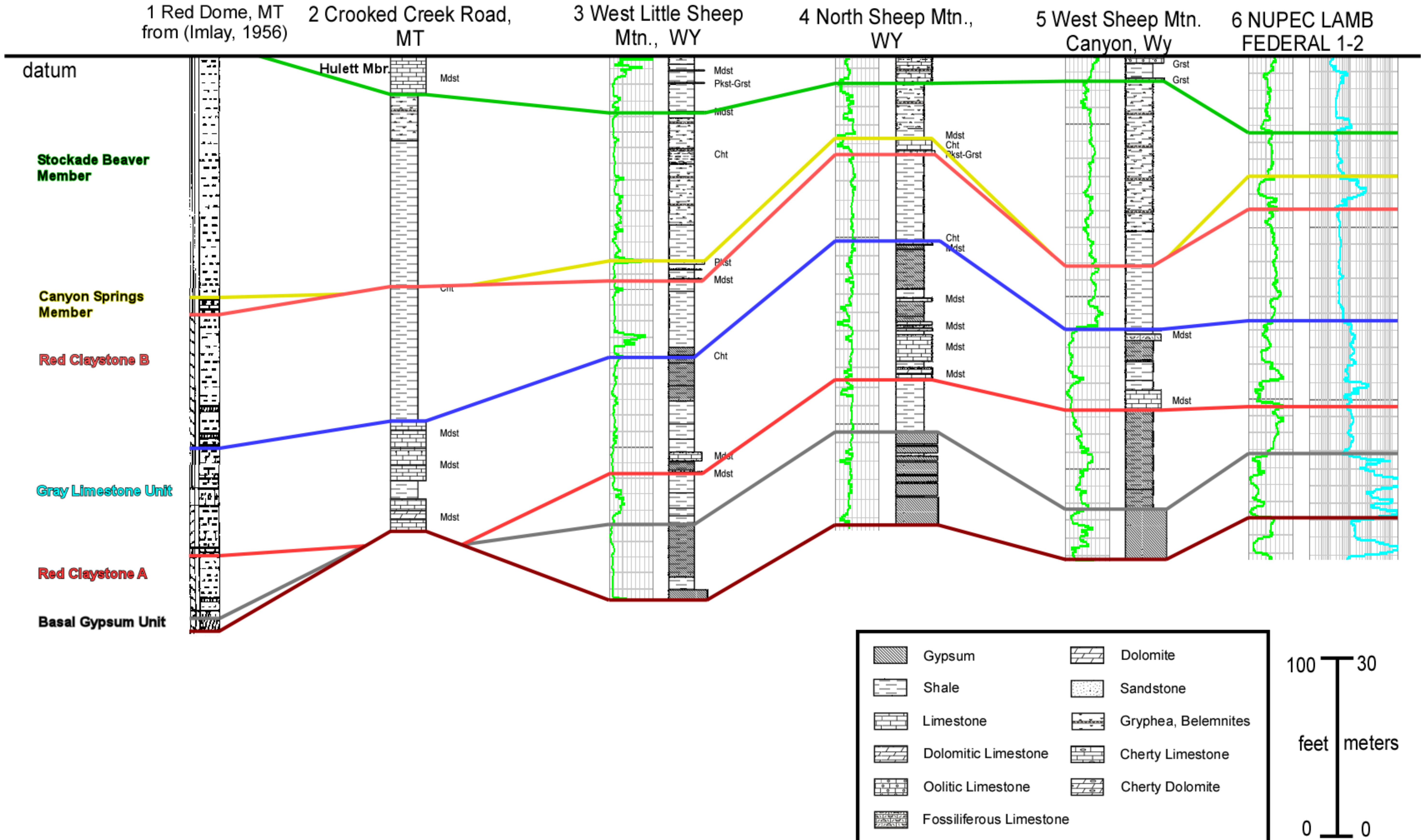


Plate 11: North-South cross-section