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Michael Elliot Smith
Alan R. Carroll *Editors*

Stratigraphy and Paleolimnology of the Green River Formation, Western USA

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Cover illustration: View north towards carbonate mounds at the contact between the Wilkins Peak Member and overlying Laney Member of the Green River Formation near the southern edge of the Greater Green River Basin in southwest Wyoming. Flaming Gorge Reservoir can be seen in the background to the left of gently dipping mudstone strata of the Laney Member (photograph taken by Michael Elliot Smith, 2004)

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Preface

This book was originally conceived at a dinner meeting with Beth Gierlowski-Kordesch, Kevin Bohacs and Mike Rosen in Portland, Oregon during the GSA annual meeting of 2009. Its purpose is two-fold: (1) to provide a logical starting point to its strata; and (2) to showcase the wealth of sedimentary geology currently being conducted on its strata. Our hope is that the reader can efficiently discover a wealth of accumulated knowledge and at the same get a snapshot of the current cutting edge of sedimentary research on lacustrine depositional systems.

Our gratitude goes out to all of the contributors and reviewers of this volume.

Flagstaff, AZ, USA — Michael Elliot Smith
Madison, WI, USA — Alan R. Carroll
February, 2015

Contents

Introduction to the Green River Formation

1

Michael Elliot Smith and Alan R. Carroll

Abstract

The Green River Formation of Wyoming, Colorado and Utah contains an important record of the paleogeography, climate and lakes in the Rocky Mountains region during the Early Eocene epoch. Its have been a source of inspiration for paleolimnologists since before the term paleolimnology came to exist. Its strata contain fossil faunas and flora, extensive resources of trona and kerogenous shale, and one of the most complete records of the Early Eocene Climatic Optimum. Emerging geochronology has permitted correlations of the Green River Formation between the structural basins that contain it, and is beginning to bring to tempo and origins of the pronounced cyclity exhibited by the Green River Formation into focus. Each of the 11 subsequent chapters of this book presents a suite of detailed stratigraphic and sedimentologic investigations of the Green River Formation within the Green River Formation basins.

1.1 A Rich Lacustrine Archive of the Early Eocene Earth

The Green River Formation is a complex amalgam of Eocene lacustrine strata that was deposited within a series of intermontane basins surrounding the Uinta Uplift during the end phases of Laramide basement deformation in the U.S. foreland (Fig. 1.1). Since it was first named by the Hayden survey in 1869, the Green River Formation has been the subject of over 2,500 publications. Its strata occupy four structural basins arrayed around the Uinta Uplift: the Greater

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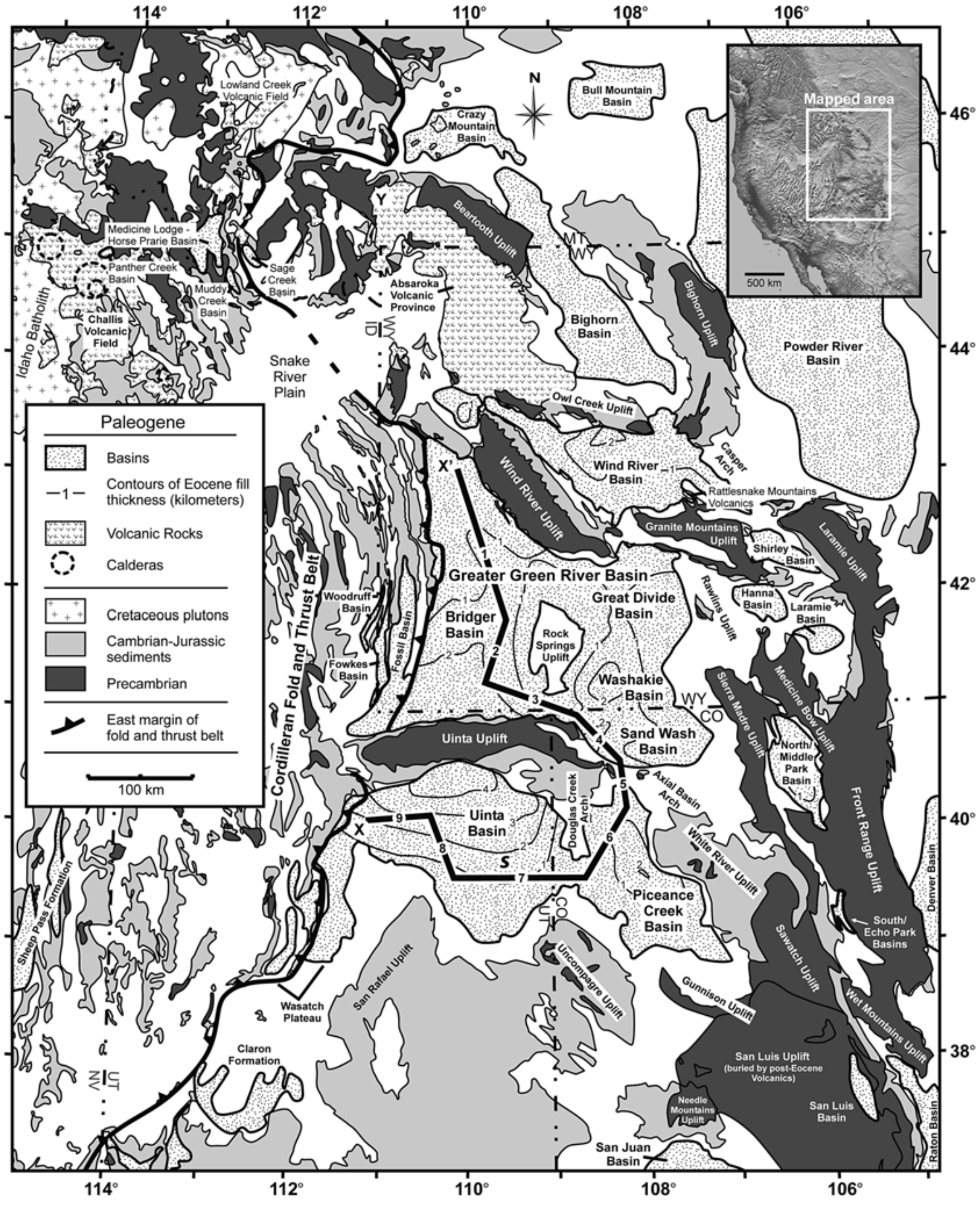

Fig. 1.1 Map showing the location of Eocene basins and basin-bounding uplifts (Adapted from Smith et al. 2008). The location of the Skyline 16 core from which the Skyline tuff was sampled from is indicated by an ***S*** (cf. Fig. 1.4)

Green River; Fossil; Piceance Creek; and Uinta basins (Fig 1.1), record a great variety of depositional environments (i.e., lake depth, lake water chemistry, and paleobiology), and interfinger extensively with predominantly alluvial facies of the Wasatch, DeBeque, Colton, Bridger and Uinta Formations (Fig. 1.2). In this volume alone, more than 100 distinct Green River Formation lithofacies are described and interpreted.

The Green River Formation was deposited during the most geologically recent period of unusually warm climate (cf. Smith et al. 2014),

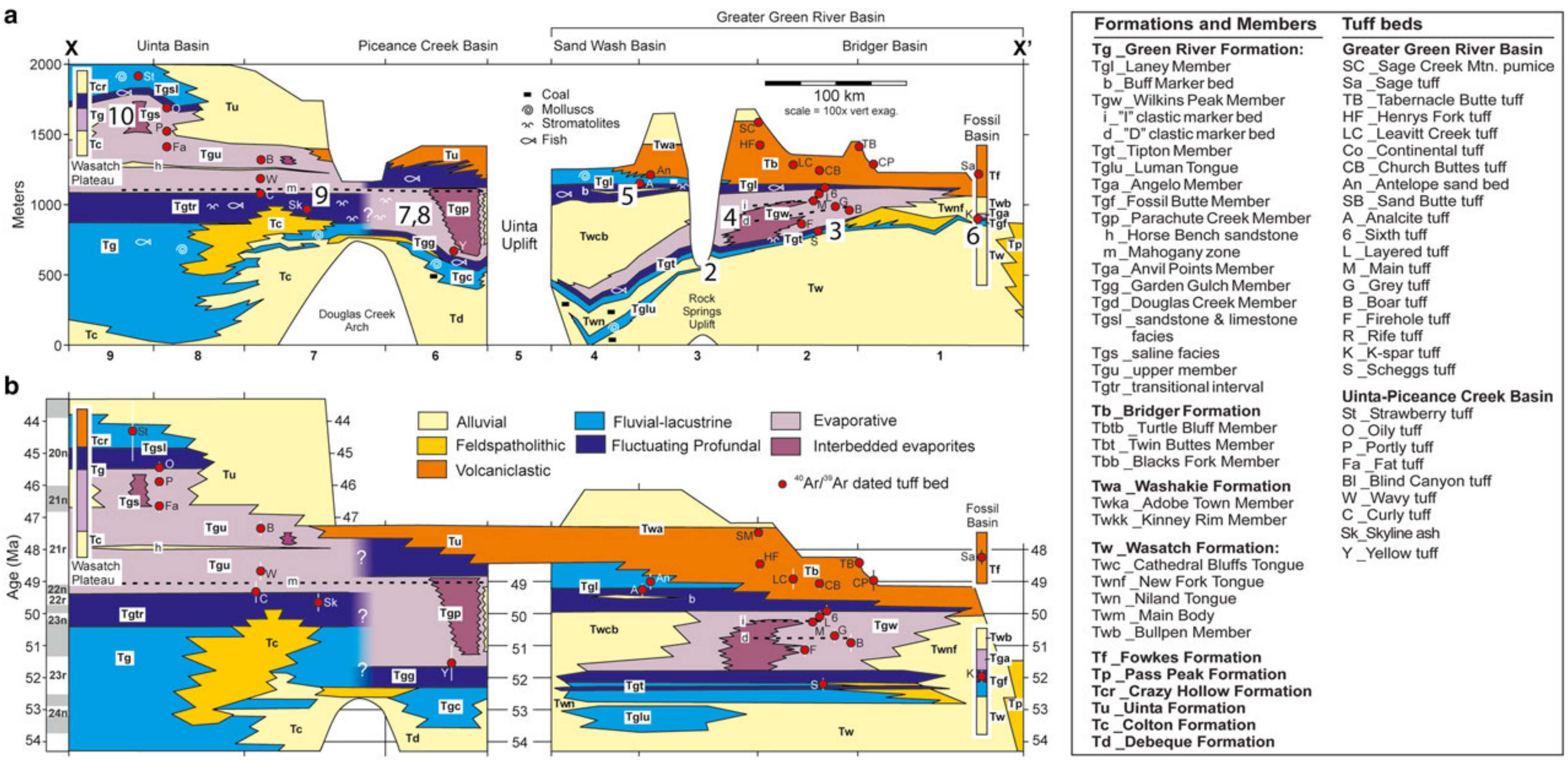

Fig. 1.2 Lithostratigraphic and time stratigraphic cross sections of Eocene strata in the Greater Green River, Piceance, and Uinta Basins along cross section X-X′ (see Fig. 1.1) showing the stratigraphic position of facies associations, structural features, and dated tuff beds. Cross section line was chosen in order to intersect area of thickest sediment accumulation, sites of bedded evaporites, and principle sills. Inset columns with white background depict stratigraphy and chronostratigraphy of the Green River Formation in the Fossil Basin and Wasatch Plateau regions (Modified from Smith et al. (2008) with the updated magnetostratigraphy and geochronology of Smith et al. (2014))

and as such it provides a valuable opportunity to examine the mode and tempo of past episodes of global warming. A number of studies have concluded that fluctuations in Eocene lake levels were caused by Milanovitch-scale orbital forcing of climate (Fischer and Roberts 1991; Roehler 1993; Machlus et al. 2008; Meyers 2008; Aswasereelert et al. 2013) or by shorter-period climatic oscillations related to ENSO or sunspots (Bradley 1929; Ripepe et al. 1991). The actual mechanisms by which any these putative forcing signals were transferred into Green River Formation strata remain enigmatic however.

Green River Formation strata and their alluvial equivalents also contain an unparalleled fossil treasure trove, famous for its well preserved vertebrate (both terrestrial and aquatic) and plant remains that have been preserved within its finely laminated strata (MacGinitie 1969; Grande 1984; Wilf 2000). It is also host to several rich and varied assemblages of trace fossils (see Chap. 12 of this volume). Vertebrate fossils collected from alluvial strata laterally equivalent to the Green River Formation throughout the Laramide broken foreland province have been utilized to define the North American land mammal "ages" (Wood et al. 1941), which have been refined and subdivided by subsequent paleontologic investigations (cf. Robinson et al. 2004). Though vertebrate fossils are rare to entirely absent in the Green River Formation itself, a great number of vertebrate faunas have been collected from Green River Formation-equivalent alluvial strata assigned to the Wasatch, DeBeque, Colton, Bridger and Uinta Formations (Osborn 1895; Morris 1954; McGrew and Roehler 1960; McGrew and Sullivan 1970; Gunnell and Bartels 1994, 1999; Gunnell 1998; Zonneveld et al. 2000) and indicate that the Green River Formation spans the Wasatchian, Bridgerian and Uinta land mammal ages (Fig. 1.2; cf. Smith et al. 2008).

The Green River Formation has also stimulated considerable interest due to its rich endowment of economic resources. Its potential to generate oil via retort of organic-rich mudstone has been recognized since at least 1916, when federal Naval Oil Shale Reserves were designated by Woodrow Wilson in Colorado and Utah. Recent U.S.G.S. estimates put the total in situ resource magnitude in Colorado, Utah, and Wyoming at approximately 4.3 trillion barrels of oil (Johnson et al. 2011), an amount 2.5 times greater than the currently proven oil reserves of the world. However, it remains unclear how much of this resource (if any) will be commercially exploited, or whether the environmental consequences of its use would outweigh the benefits. Although very rich, Green River Formation oil shale is generally too thermally immature to act as a conventional petroleum source rock across most of its area, except in the northern Uinta basin. There, oil generated from the lower Green River Formation accounted for approximately 30 million barrels of production in 2014 (Utah Division of Oil, Gas, and Mining).

The other main economic resource of the Green River Formation is soda ash, which is mined primarily in the form of trona (cf. Wiig et al. 1995). Trona deposits in the Bridger basin of Wyoming represent the single largest soda ash deposit in the world, and with more than 17 million metric tons of production in 2013 (U.S.G.S. 2013 Minerals Yearbook).

1.2 A Century and a Half of Geologic Inquiry

Wilmot H. Bradley's pioneering work on the Green River Formation during the 1920s through 1970s set a high bar for subsequent workers (Sears and Bradley 1924; Bradley 1926, 1928, 1929, 1931, 1964, 1974), and set the stage for the types of questions that are still being investigated nearly a century later (i.e., stratigraphic packaging, lacustrine sedimentology, and the identification of climate cycles from vertical facies stacking patterns).

During the 1950s through 1990s, and great number of scientists from the U.S. Geological Survey, industry and academia brought the Green River Formation into much greater focus by differentiating, mapping and correlating its member-scale units and lithofacies (Donovan 1950; Duncan and Belser 1950; Dane 1954; Picard 1955; Bradley 1959; Picard 1959; Culbertson 1961, 1965, 1966, 1971, 1998; Donnell 1961; Stuart 1963; Love 1964; Wiegman 1964; Hansen 1965; Sanborn and Goodwin 1965; Roehler 1968; Oriel and Tracey 1970; Trudell et al. 1970;

Wolfbauer 1971; Cashion and Donnell 1972, 1974; Roehler 1973; West 1973; Duncan et al. 1974; O'Sullivan 1974; Trudell et al. 1974; Fouch 1976; Burnside and Culbertson 1979; Surdam and Stanley 1979, 1980; Sullivan 1980; Dyni 1981, 1996; Johnson 1984, 1985; Dyni et al. 1985; Roehler 1985; Rowley et al. 1985; Hail 1987, 1990, 1992; Franczyk et al. 1989; Roehler 1991, 1992, 1993; Franczyk et al. 1992; Remy 1992; and works cited within; Buchheim 1994; Wiig et al. 1995; Buchheim and Eugster 1998). These efforts were aided by an extensive coring program funded by both industry and the U.S. Energy Research and Development Administration. Several of these cores are still available at the U.S.G.S. core repository in Denver, Colorado.

During the 1970s and early 1980s, detailed sedimentologic investigation of the Wilkins Peak Member of the Green River Formation in Wyoming revealed that a significant proportion of its lithofacies were accumulated on lake fringing playa rather than within a deep stratified lake (Eugster and Surdam 1973; Wolfbauer 1973; Wolfbauer and Surdam 1974; Eugster and Hardie 1975; Surdam and Wolfbauer 1975; Smoot 1978, 1983). The application of the playa-lake model to other members of the Green River Formation has proven less successful, however, because much of the Green River Formation, including portions of the Wilkins Peak Member, does in fact record deep lake conditions.

The Green River Formation was influential in the conception and development of the lake type concept (Carroll and Bohacs 1999; Bohacs et al. 2000), which relates lacustrine lithofacies and stacking patterns to the long term balance between precipitation, evaporation, and basinal accommodation. The criteria used for lake type subdivision of its strata are summarized in Table 1.1.

Since the advent of the new century, investigations of the Green River Formation have taken advantage of new radioisotopic dating methods (Smith et al. 2008, 2010, cf. Table 1.2), sedimentology and ichnology (cf. Chap. 12), stable and radiogenic isotopic proxies (Doebbert et al. 2010, 2014), and the application of sequence- and cyclo-stratigraphy to its strata (Bohacs et al. 2007; Machlus et al. 2008; Aswasereelert et al. 2013). Radioisotopic geochronology (^{40}Ar/^{39}Ar and U-Pb) in particular has facilitated viewing the Green River lake system as a whole in a paleogeographic context (Fig. 1.3). This volume contains nine chapters (Chaps. 2, 3, 4, 5, 6, 7, 8, 9, 10) that explore the member-scale stratigraphy and lithofacies of the Green River Formation within the individual basins it occupies (Fig. 1.2), and the two final Chaps. (11 and 12) which address the paleoenvironmental implications of evaporite deposits and ichnofossils from a regional perspective.

Acknowledgments We thank Michael Vanden Berg, Lauren P. Birgenheiler, and the Utah Geological Survey for kindly providing a core sample of the Skyline tuff. Laser fusion ^{40}Ar/^{39}Ar geochronology for the Skyline tuff was conducted by Brian Jicha and Brad S. Singer the University of Wisconsin-Madison. National Science Foundation grants EAR-0230123, EAR-0114055 and EAR-0516760, the Donors of the Petroleum Research Fund of the American Chemical Society, Chevron, and ConocoPhillips kindly provided funding for the geochronology and stratigraphy summarized in Figs. 1.1, 1.2, and 1.3.

Table 1.1 Criteria for classification of lake type in Green River Formation strata

Basin type	Facies Association	Typical facies	Stratigraphic stacking	Fauna	Hydrologic interpretation
Overfilled	Fluvial-lacustrine	Sandstone, coal, massive to laminated mudstone, coquina limestone	Dominantly progradational	Molluscs common, occasional fish	Freshwater "open" lake
Balanced Filled	Fluctuating profundal	Predominantly organic rich laminated mudstone, stromatolites, oolites	Mixed aggradational/ progradational	Fish, ostracodes	Fluctuating salinity, intermittently open/closed lake
Underfilled	Evaporative	Na-rich evaporites, may include basin interior alluvial units and palustrine mudstone	Aggradational	Fauna absent	Hypersaline "closed" lake

Table 1.2 ^{40}Ar/^{39}Ar ages for Eocene strata in the Laramide foreland province

Location Sample	Stratigraphy	Dated Material	Method	flux monitor	Age (Ma)	±2σ^{a}	±2σ^{b}	References
Greater Green River Basin								
Scheggs tuff	Tipton Member	san	fus	TCs	52.22	±0.09	±0.35	Smith et al. (2008, 2010)
Rife tuff	”	san	fus	”	51.62	±0.30	±0.45	”
Firehole tuff	Wilkins Peak Member	san	fus	”	51.41	±0.21	±0.39	”
Boar tuff	”	san	fus	”	51.14	±0.24	±0.41	”
Grey tuff	”	san	fus	”	50.86	±0.21	±0.39	”
Main tuff	”	san	fus	”	50.28	±0.09	±0.34	”
Layered tuff	”	san	fus	”	50.12	±0.09	±0.34	”
6th tuff	”	bio	ih	”	49.93	±0.10	±0.34	”
Analcite tuff	Laney Member	san	fus	”	49.25	±0.12	±0.34	”
Antelope sandstone	”	san	fus	”	49.00	±0.19	±0.37	”
Church Butte tuff	Bridger Formation	san	fus	”	49.06	±0.09	±0.33	”
Leavitt Creek tuff	”	san	fus	”	48.93	±0.28	±0.42	”
Henrys Fork tuff	”	san	fus	”	48.45	±0.08	±0.32	”
Tabernacle Butte tuff	”	san	fus	”	48.41	±0.08	±0.32	”
Sage Creek tuff	”	san	fus	”	47.46	±0.08	±0.32	”
Continental tuff	”	san	fus	”	48.97	±0.28	±0.42	”
Fossil Basin								
K-spar tuff	Fossil Butte Member	san	fus	”	51.98	±0.09	±0.35	”
Sage tuff	Fowkes Formation	san	fus	”	48.23	±0.17	±0.36	”
Piceance Creek Basin								
Yellow tuff	Parachute Creek Mb.	san	fus	”	51.56	±0.52	±0.62	”
Uinta Basin								
Skyline ash	Parachute Creek Mb.	san	fus	FCs	49.58	±0.28	±0.32	***This study*** (cf. Fig. 1.4 and Table 1.3)
Curly tuff	”	bio	ih	TCs	49.32	±0.30	±0.44	Smith et al. (2008, 2010)
Wavy tuff	”	bio	ih	”	48.67	±0.23	±0.39	”
Blind Canyon tuff	”	bio	ih	”	47.33	±0.18	±0.36	”
Fat tuff	Saline member	bio	ih	”	46.63	±0.13	±0.33	”
Portly tuff	”	bio	ih	”	45.86	±0.14	±0.33	”
Oily tuff	”	bio	ih	”	45.42	±0.10	±0.31	”
Strawberry tuff	sandstone and limestone member	san	fus	”	44.27	±0.93	±0.97	”

(continued)

Table 1.2 (continued)

Location Sample	Stratigraphy	Dated Material	Method	flux monitor	Age (Ma)	±2σ[a]	±2σ[b]	References
Wind River Basin								
Halfway Draw tuff	Wind River Formation	san	fus	”	52.07	±0.10	±0.35	”
Wagon Bed tuff	Wagon Bed Formation	san	fus	”	47.99	±0.12	±0.33	”
Bighorn Basin								
Willwood ash	Willwood Formation	san	fus	”	52.91	±0.12	±0.36	Smith et al. (2004)

Notes: All ages calculated relative to the 28.201 Ma age for FCs using the equations of Kuiper et al. (2008) and Renne et al. (1998), and are shown with 2σ analytical and fully propagated uncertainties. Mineral dated: san – sanidine, bio – biotite. Analysis type: ih – weighted mean of concordant plateau ages from incremental heating experiments, fus – weighted mean of multiple laser fusions. Neutron flux monitors: *TCs* Taylor Creek Rhyolite sanidine, *FCs* Fish Canyon Tuff sanidine, Cf. Smith et al. (2008) for analytical details

[a] Analytical uncertainty

[b] Fully propagated uncertainty for preferred age

Table 1.3 ^{40}Ar/^{39}Ar results for Skyline tuff single crystal laser fusion experiments

^{40}Ar/^{39}Ar	^{37}Ar/^{39}Ar	^{36}Ar/^{39}Ar	^{40}Ar* ×10^{-14} mol	^{40}Ar* %	K/Ca	Apparent age ± 2σ Ma
3.669 ± 0.009	0.00305 ± 0.00185	0.000317 ± 0.000074	0.19	97.4	141	50.25 ± 0.65
4.763 ± 0.011	0.04946 ± 0.00312	0.004088 ± 0.000109	0.17	74.7	9	50.01 ± 0.93
4.012 ± 0.010	0.03922 ± 0.00198	0.001600 ± 0.000088	0.20	88.3	11	49.79 ± 0.76
4.079 ± 0.008	0.02443 ± 0.00139	0.002002 ± 0.000059	0.30	85.5	18	49.05 ± 0.52
3.657 ± 0.010	0.06422 ± 0.00397	0.000256 ± 0.000121	0.11	98.1	7	50.40 ± 1.02
3.937 ± 0.008	0.01221 ± 0.00210	0.001347 ± 0.000071	0.23	89.9	35	49.75 ± 0.62
3.867 ± 0.008	0.00993 ± 0.00218	0.001191 ± 0.000096	0.17	90.9	43	49.42 ± 0.82
4.419 ± 0.011	0.01673 ± 0.00287	0.002851 ± 0.000117	0.16	81.0	26	50.28 ± 0.99
4.435 ± 0.010	0.02423 ± 0.00290	0.003170 ± 0.000123	0.15	78.9	18	49.21 ± 1.04
4.006 ± 0.009	0.08356 ± 0.00343	0.001772 ± 0.000095	0.19	87.1	5	49.04 ± 0.81
4.496 ± 0.010	0.09342 ± 0.00393	0.003342 ± 0.000110	0.18	78.2	5	49.42 ± 0.93
4.644 ± 0.010	0.02280 ± 0.00227	0.003790 ± 0.000100	0.21	75.9	19	49.55 ± 0.85
4.269 ± 0.008	0.01886 ± 0.00214	0.002632 ± 0.000099	0.19	81.8	23	49.10 ± 0.84
4.697 ± 0.009	0.07262 ± 0.00376	0.004373 ± 0.000112	0.21	72.6	6	47.96 ± 0.94
Inverse isochron age	49.78 ± 0.55					
^{40}Ar/^{39}Ar intercept	288.2 ± 17.3	MSWD	1.52	**Weighted mean age**		**49.58 ± 0.28**

Notes: All ages calculated relative to 28.201 Ma for the Fish Canyon tuff sanidine (Kuiper et al. 2008); using the decay constants of Min et al. (2000); uncertainties in Ar isotope ratios are reported at 1σ analytical precision, uncertainties in ages are reported at 2σ analytical precision. Corrected for ^{37}Ar and ^{39}Ar decay, half lives of 35.2 days and 269 years, respectively. $J = 0.0078430 \pm 0.00000701$; $\mu = 1.0060$. Italics indicate analysis that were excluded from weighted mean age calculations

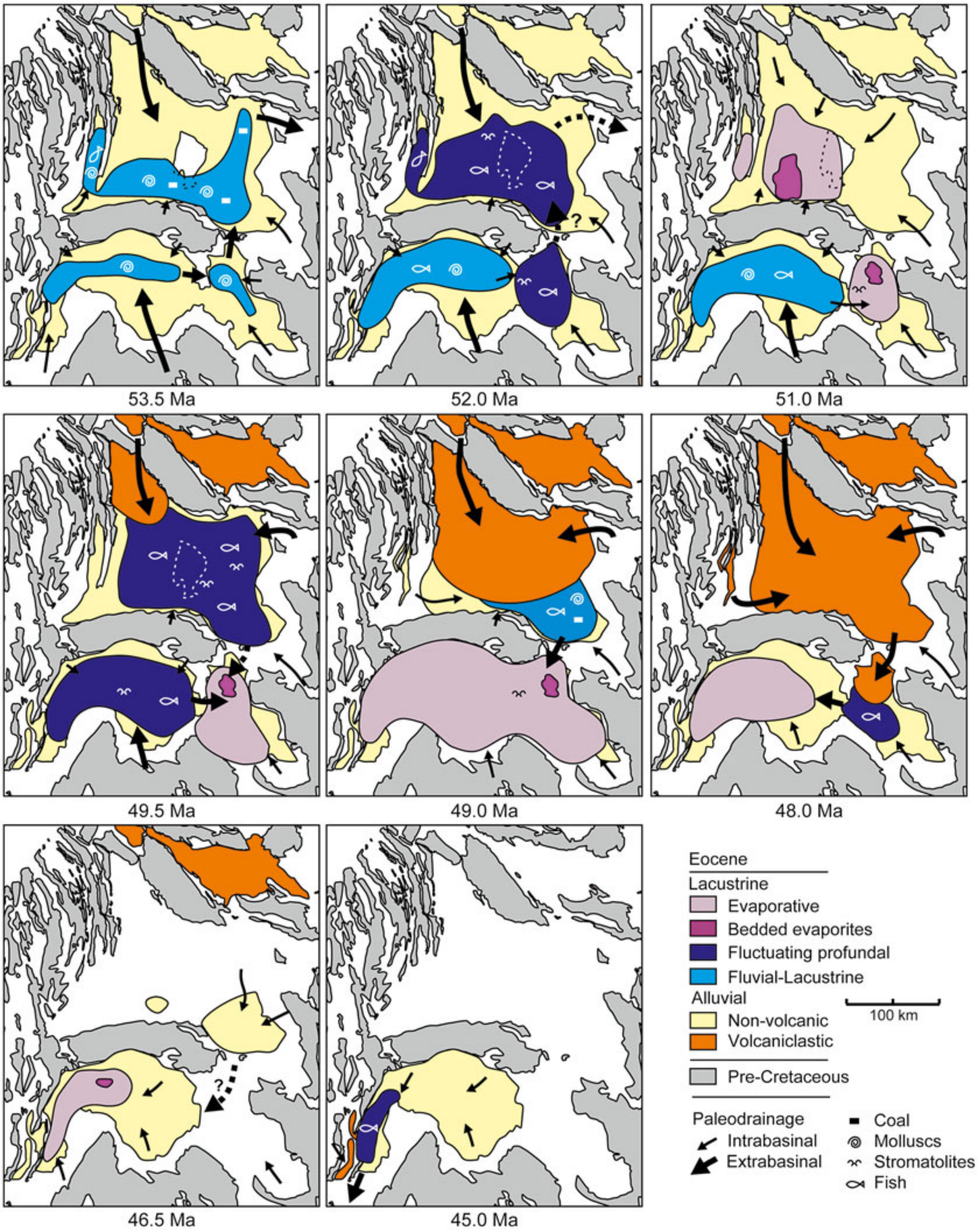

Fig. 1.3 Annotated synoptic maps showing paleohydrologic configuration of the Green River Formation lakes at 8 discrete times between 53.5 and 45 Ma (updated from Smith et al. 2008). Time slices were selected to highlight major hydrologic configurations of Green River Formation lake system (cf. Smith et al. 2008). Note that knowledge of the continuity of lacustrine deposition in the central Greater Green River Basin is limited by the absence of Eocene strata atop the Rock Springs uplift (*dashed outline*).

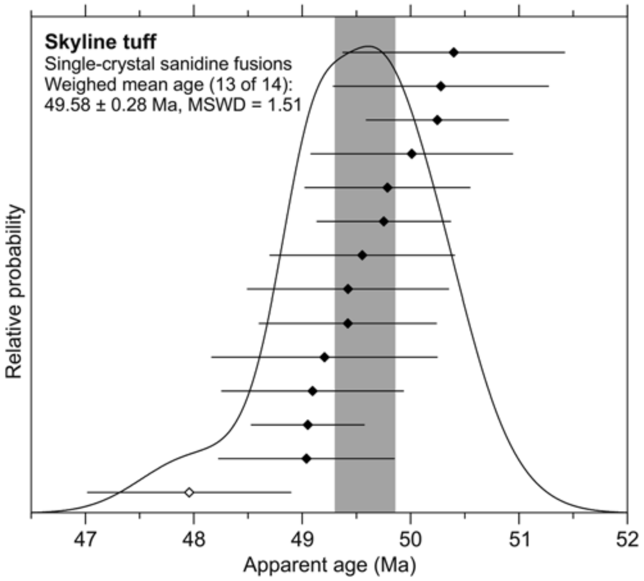

Fig. 1.4 Cumulative probability plot of $^{40}Ar/^{39}Ar$ laser fusion analyses of single sanidine from the Skyline tuff. The airfall ash was sampled from profundal facies of the R-4 oil shale zone in the Skyline 16 core in the R-4 oil shale zone (depth: 890.67–890.93 ft) in the Eastern Uinta Basin: (11S 25E sec. 10) 661506E, 4414904 N (UTM zone 12)

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Initiation of Eocene Lacustrine Sedimentation in the Greater Green River Basin: Luman Member of the Green River Formation

2

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Abstract

The Luman Member is the lowermost unit of the lacustrine Green River Formation, and provides an opportunity to examine in detail the initiation of lacustrine deposition within the Greater Green River Basin during the Early Eocene. Well-drained alluvial and fluvial strata of the Wasatch Formation are overlain by carbonaceous mudstone, channelized sandstone and isolated interbedded pond deposits of the lower Luman Member, which are in turn overlain by laterally extensive calcareous mudstone of the upper Luman Member, and together record a conformable progression alluvial to paludal to lacustrine environments. Here we describe alluvial, paludal and lacustrine lithofacies along a basin-scale transect through the Luman Member depocenter. Based on detailed correlation of Luman Member strata, freshwater lakes formed first in isolated regions of high subsidence to the east and west of the Rock Springs Uplift, then expanded and became more prone to carbonate deposition.

2.1 Introduction

Lacustrine systems commonly occur within and adjacent to active orogens. Uplifts are known to influence not only the distribution of lakes but also the character and architecture of lacustrine sedimentation patterns (e.g., Anadón et al. 1989; Sáez and Cabrera 2002). However, the interaction of large scale tectonic and climatic forcing on lacustrine depositional systems is poorly understood. Field exposures of the lacustrine Luman Member of the Green River Formation

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along the southern margin of the Greater Green River Basin permit detailed observation of initiation and sedimentation in the context of growth of the Uinta and Rock Springs Uplifts.

This study examines sedimentology and stratigraphy of the Luman Member along an east-west cross-section that exposes the transgression of lacustrine facies over alluvial facies with the aim of constructing a genetic model for the embryonic stages of Lake Gosiute. Though ancient palustrine depositional environments are well described (cf. Sagri et al. 1989; Alonso-Zarza and Calvo 2000; Alonso-Zarza et al. 1992; Armenteros et al. 1997), less is known about the dynamics and stratal geometries associated with the transition from paludal to lacustrine environments.

2.2 Geologic Setting

2.2.1 Stratigraphic Framework

Terrestrial lithofacies within late Paleocene through the early Eocene strata in the southern part of the Greater Green River Basin record large-scale changes in accommodation and alluvial and lacustrine deposition that occurred in response to basin-bounding basement uplifts. The earliest Cenozoic deposits in the region consist of the Late Paleocene Fort Union Formation strata, which is comprised of sandstone and mudstone and sporadic coal beds that were deposited in fluvial, alluvial and limited paludal environments, respectively (McDonald 1972). The Fort Union Formation thickens to the north and east in the Greater Green River Basin, which likely records fluxurally-driven subsidence in response to growth of the Sierra Madre, Rawlins, and Wind River Uplifts (Beck et al. 1988). Overlying the Fort Union Formation are gray, green and red mudstones and light-gray to red sandstones were deposited in fluviatile and floodplain environments and constitute the Main Body of the Wasatch Formation (Roehler 1993). The Wasatch Formation is thickest in the south of the Greater Green River Basin, and thins to the north, indicating increased accommodation resulting from flexural loading by the Uinta Uplift coupled with high sediment supply rates in the southern part of the basin triggered by denudation of the Uinta Uplift (Roehler 1969). Overlying the Wasatch Formation (Fig. 2.1), the Green River Formation constitutes the deposits of Lake Gosiute, which occupied the 48,500 mi^2 of southwestern Wyoming in the early Eocene from 53 to 48 million years ago (Smith et al. 2008).

The term "Luman Tongue of the Green River Formation" was first applied by Pipiringos (1955) to a package of lacustrine strata within the upper part of the Wasatch Formation in the Great Divide sub-basin of the Greater Green River Basin. In its naming and in much of the subsequent literature, Luman strata have been considered a tongue. According to the North American Stratigraphic Code (1983), a tongue is "a wedging member that extends outward beyond a formation or wedges out within another formation." This definition implies lithological continuity between the tongue and the main body from which it is extending. Like all other members of the Green River Formation, on its margins, Luman strata exhibit intertonguing geometries with the adjacent Wasatch Formation. As a whole, however, the Luman is a lithologically distinct unit within the Green River Formation that is not laterally equivalent to any other parts of the GRF. We therefore adopt the term Luman Member for these deposits.

The Luman Member ranges in thickness from 10 to 125 m, however it is thickest in the southern part of the Greater Green River Basin in a trough that runs east-west, roughly parallel to the Uinta Mountains until bending to the northeast in the Washakie sub-basin (Roehler 1973). Complex intertonguing relationships and gradational transitions with both the overlying and underlying units contribute to significant lateral thickness gradients in the Luman Member thickness (Roehler 1987, this study; Culbertson 1965; Pipiringos 1955). The Luman Member is separated in many places from the Tipton Member and the rest of the Green River Formation proper by the Niland Tongue of the Wasatch Formation (Fig. 2.1). The Niland Tongue represents a return to widespread fluvial conditions before the

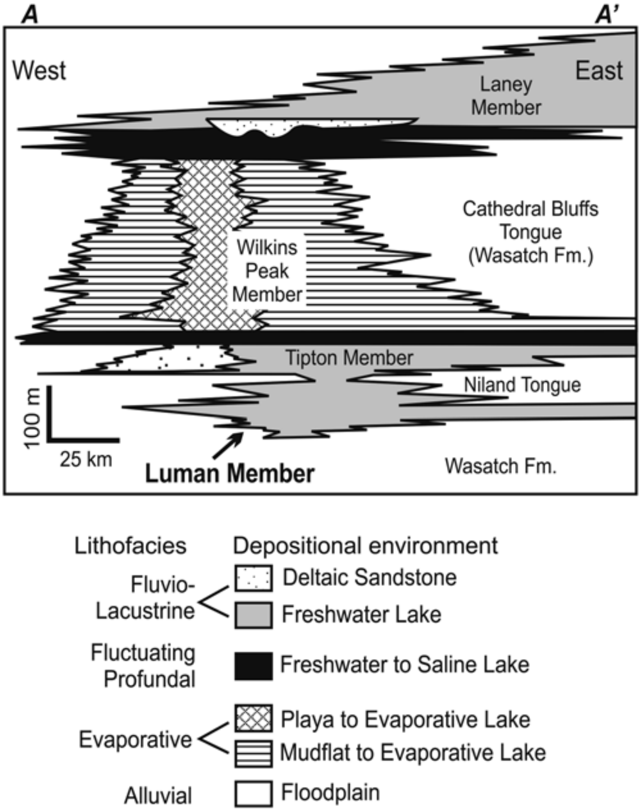


Fig. 2.1 Generalized cross-section illustrating the general stratigraphy of the Greater Green River Basin. The Luman Member is laterally equivalent to floodplain and fluvial deposits of the Wasatch Formation. Luman Member-equivalent strata contain mammals associated with the Lysitean subage of the Wasatchian North American land mammal age (Holroyd and Smith 2000) (Modified from Roehler 1991)

deposition of the Tipton Member of the Green River Formation.

2.2.2 Geochronology

Age determinations within the Greater Green River Basin are established through mammalian biostratigraphy and the ^{40}Ar/^{39}Ar dating of tuffs. At present, the Luman Member has not yielded any tuffs for dating, leaving biostratigraphy as the primary tool for age control in this unit. Within the early Eocene of southwestern Wyoming, Wasatchian and Bridgerian provincial Land Mammal ages (Wood et al. 1941) have been subdivided into several subzones based on mammalian and reptilian faunas (Gingerich and Clyde 2001; Gunnell and Bartels 1994; Robinson et al. 2004). Fossils found at Little Mountain, the Washakie sub-basin, and Tipton Buttes in laterally equivalent strata to the Luman Member correlate it to the Lysitean subage of the Wasatchian NALMA (McGrew and Roehler 1960; Holroyd and Smith 2000; Anemone 2001). A bentonite near the Lystitean – Lostcabinian boundary in the upper Willwood Formation in the Bighorn Basin yields a sanidine ^{40}Ar/^{39}Ar age of 52.91 ± 0.36 Ma (Wing et al. 1991; Smith et al. 2004, 2010), which provides a minimum age for Luman Member deposition (all ages shown with 2 s uncertainties relative to 28.201 Ma for FCs). Based on interpolation between the Lysitean-Lostcabinian age and the 52.22 ± 0.35 Ma sanidine ^{40}Ar/^{39}Ar age for the Scheggs tuff in the overlying Tipton Member

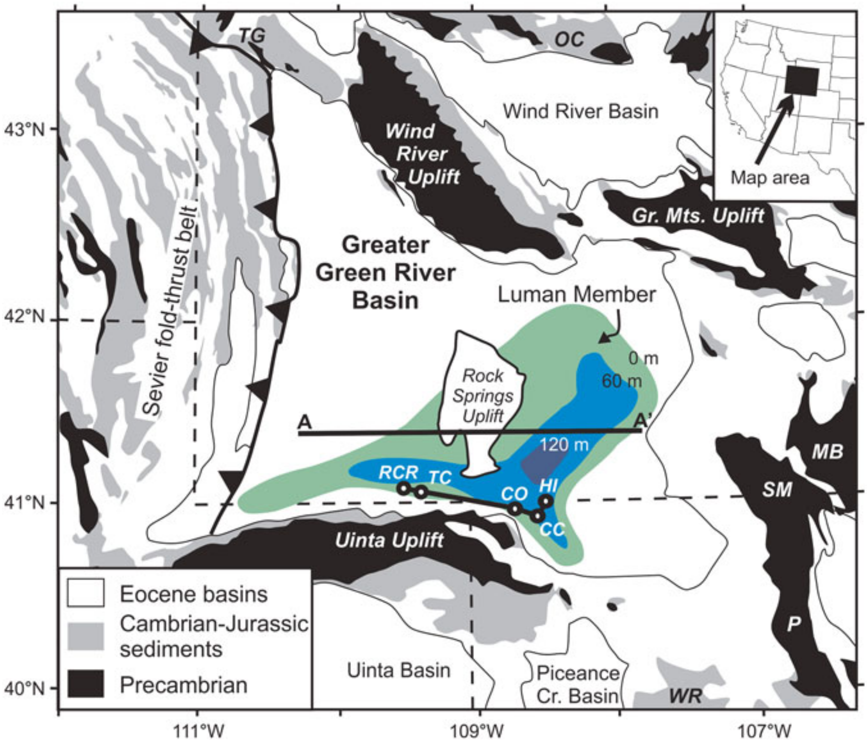


Fig. 2.2 Map showing the extent and tectonic context of the Luman Member of the Green River Formation in Wyoming and Colorado. Labels indicate the locations of measured sections and locales discussed in this report: Red Creek Rim (*RCR*); Telephone Canyon (*TC*); Colorado (*CO*); Canyon Creek (*CC*); and Hiawatha (*HI*). Luman Member maximum extent and thicknesses (in meters) are from Roehler (1993); base map modified from Witkind and Grose (1972). Abbreviations for Laramide uplifts: *TG* Teton-Gros Ventre; *OC* Owl Creek; *MB* Medicine Bow, *SM* Medicine Bow, *P* Park, *WR* White River. Cross section A is illustrated in Fig. 2.1. *Colors* correspond to thickness contours (see Carroll and Bohacs 2001)

(Smith et al. 2008, 2010), the duration of Luman Member deposition was ca. 400 ka, which translates to an average basin-center accumulation rate of ~150 µm/year.

2.2.3 Regional Tectonics

The Greater Green River Basin is bounded by the Sevier fold-thrust belt, and by Laramide-style basement uplifts (Fig. 2.2). These structures formed during the latest Cretaceous through early Cenozoic, with many experiencing late growth coeval with the deposition of the Green River Formation. Major movement along the Uinta-Sparks Fault, which bounds the north edge of the Uinta Uplift, occurred in the late Cretaceous to early Paleogene. Assuming that Phanerozoic strata were isopachous prior to uplift, angular unconformity and included fragments indicate that approximately 3 km of Cretaceous strata were eroded from parts of the Uinta Mountains prior to Paleocene deposition of the alluvial Fort Union Formation (Hansen 1965; Bradley 1995). Later early Eocene uplift is recorded by alluvial fan deposition (Crews and Ethridge 1993) and deformation and truncation of Wasatch and Green River Formation strata adjacent to the North Flank thrust, Sparks Ranch thrust and Uinta thrust (Roehler 1993; Hansen 1965, 1986; Bradley 1995). Coarse conglomerates north of the Uinta Uplift in Luman Member-equivalent deposits at Sugarloaf Butte and Richards Mountain imply steep gradients between the basin floor and the crest of the Uinta Mountains during Luman time (Crews and Ethridge 1993; Rowley et al. 1985).

The Rock Springs Uplift (RSU) intersects with the Uinta Uplift and likely experienced growth during Luman Member deposition. The RSU is a north-south oriented anticlinal structure that lies in the south-central portion of the Greater Green River Basin (Gosar and Hopkins 1969), separating it into distinct subbasins to the east and west of it. Isopach mapping of upper Cretaceous Blair and Rock Springs Formation strata show thickening off the flanks of the uplift (Beaubouef et al. 1995). Syn-depositional movement along north-south trending faults on the west side of the Rock Springs Uplift is evident in large-scale lithofacies and thickness distributions of the upper Cretaceous Almond Formation (Van Horn 1979; Martinsen et al. 1995; Mongomery 1996). Additionally, the Paleocene Fort Union and Wasatch Formations, both of which underlie the Green River Formation, are observed to onlap the flanks of the uplift (Roehler 1965) which has been speculated to have been a topographic high during Green River Formation deposition (Bradley 1964; Roehler 1993). Isopach maps and depocenter depictions of the Green River Formation along the north flank of the Uinta Mountains show beds thinning with proximity to the Uinta Uplift, with depocenters on either side of its intersection with the Rock Springs Uplift (Burchfiel et al. 1992; Roehler 1993; Johnson and Anderson 2009; Mederos et al. 2005), implying either its active uplift or to less-rapid subsidence of the structure relative to adjacent subbasins.

2.2.4 Eocene Climate

Luman Member deposition occurred during the early Eocene just subsequent to the Paleocene-Eocene thermal maximum and prior to the early Eocene climatic optimum. Beginning in the late Paleocene, a warming trend led to frost-free conditions and a humid, warm-temperate to subtropical climate prior to and during deposition of the Green River Formation (MacGinitie 1969; Wilf 2000). Paleontologic records of continental flora and faunas suggest warm climates during the Eocene (Wolfe 1978; Wolfe and Poore 1982). Leaf-margin analyses of plant assemblages from the late Paleocene through the Early Eocene in the Greater Green River Basin indicate maximum temperatures in the Cenozoic were reached in middle Early Eocene time (Wilf 2000). During deposition of the Luman Member, plant assemblages from the Bighorn and Greater Green River Basins include tree ferns, palms and cycads, all of which are unable to survive prolonged freezes (Wing et al. 1991; Wilf 2000). Based on taxonomic affinities with modern plants and leaf margin analysis, mean annual temperatures in the Greater Green River Basin during deposition of the Luman Member are estimated to have been between 16 and 21 ° C (Greenwood and Wing 1995). Coals and ferns found in the Luman Member-equivalent Latham assemblage imply wet conditions in southwestern Wyoming during the Lysitean (Masursky 1962). Based on leaf-area analysis on leaf assemblages found within the Green River Formation, regional Eocene mean annual rainfall is estimated between 113 and 140 cm (Wilf 2000). Crocodilians have been identified in the Green River and Bridger Formations in southwestern Wyoming and northeastern Utah (Grande 1984) indicating a MAT >16 ° C (Markwick 1994).

2.3 Field Methodology and Results

To understand the sedimentology and stratigraphic relationships between the Luman Member and the Wasatch Formation, four vertical sections along a ~10 km transect were measured and described at 10 cm detail along an east-west transect in the southern part of the Greater Green River Basin (see section line in Fig. 2.2). Gamma ray scintillometry was conducted using a multi-channel spectrometer at the outcrop using an Exploranium GR-320 enviSpec hand-held spectrometer, with individual abundances of uranium, thorium, and potassium measured every 0.5 m. A detail photographic and lithofacies investigation of a large, particularly well-exposed exposure of intertonguing lacustrine, paludal and alluvial facies was performed at Telephone Canyon.

2.3.1 Sedimentary Lithofacies

Lacustrine lithofacies within the Luman Member consist of mudstone; fossiliferous calcareous sandstone, and coquina (Pipiringos 1955, this study; Roehler 1993; Sklenar and Anderson 1985). These deposits alternate with coal, carbonaceous mudstone, and trough cross-bedded sandstone of fluvial and paludal origin (Figs. 2.3 and 2.4). This study identifies three major lacustrine lithofacies within the Luman Member and two associated lithofacies of fluvial-paludal origin. Gastropods, pelycopods and ostracodes found throughout the Luman Member support the interpretation of a freshwater depositional environment (Taylor 1972; Kuchta 2000).

Calcareous mudstone This facies consists of homogeneous gray to cream or brown calcareous mudstone that is infrequently thinly-laminated (Fig. 2.3a). The mudstone often contains ostracodes as well as both broken and complete mollusc shells. Within the Luman Member, calcareous mudstone may form low grade oil shale (Horsfield et al. 1994; Carroll and Bohacs 2001) and forms thick (1–15 m), recessive units generally bounded above and below by sand facies (Fig. 2.3). Crude 10 cm scale bedding is most common, with intervals of fine laminations (Fig. 2.4b).

Interpretation: Thinly-laminated strata are interpreted to represent of deposition in relatively deep or sheltered aquatic environments where disruption by wave action of biogenic activity is restricted (e.g. Anadón et al. 1989). The lack of pervasive laminated strata in the calcareous mudstone facies supports an interpretation of deposition in a moderately deep, yet dominantly unrestricted lacustrine setting during Luman time. Laminated facies likely are the result of deposition in the deepest part of Lake Gosiute during periods of higher lake levels or in more restricted settings within the lake.

Coquina Luman Member coquina is composed of limestone-cemented shells generally 1 to 3 cm in size and contain mollusc assemblages of *Goniobasis tenera*, *Viviparus* sp., and various unidentified unionid bivalves (Figs. 2.3b and 2.4c, h, i, j) (Hanley 1976; Kuchta 2000). Various degrees of transport are evident between different coquina beds. In general, shells are disarticulated and show mild breakage and rounding implying minimal transport. Thick (1 m) coquina beds can be traced for up to 5 km; thinner (2–10 cm) coquina beds are traceable less than 500 m.

Interpretation: These deposits are interpreted as sediment-starved stages of Lake Gosiute during which littoral and sublittoral shells were exposed and concentrated due to the winnowing of finer sediment. A possible analogous setting may exist in Lake Tanganyika, where shell communities live in the littoral zone and lake level fluctuations (on the order of ~10 m) expose shells to increased wave and wind action, winnowing finer sediment away and leaving broad, tabular shell lag surfaces. Hanley (1976) considers accumulations of *Goniobasis* and *Viviparus* shells in the Green River Formation indicative of littoral-lacustrine habitats where accumulations of these communities in coquinas record shoreline fluctuations, concentrating shells in widespread, tabular benches similar to those seen in the modern at Lake Tanganyika (Cohen 1989). Some coquinas cap bioturbated shoreface sandstone intervals, suggesting that molluscs were likely the burrowers.

Laminated sandstone This facies consists of horizontal to wavy non-parallel laminated, well-sorted, well-rounded, calcareous very-fine to fine-grained sandstone containing interbeds of coal and carbonaceous mudstone (Figs. 2.3c and 2.4e). Low-angle cross-stratification, wavy parallel bedding and wave ripples are commonly found in this facies. Iron nodules are occasionally present and often define bedding planes. Sandstone beds vary in thickness from 10 cm to 5 m and can be traced laterally within outcrops.

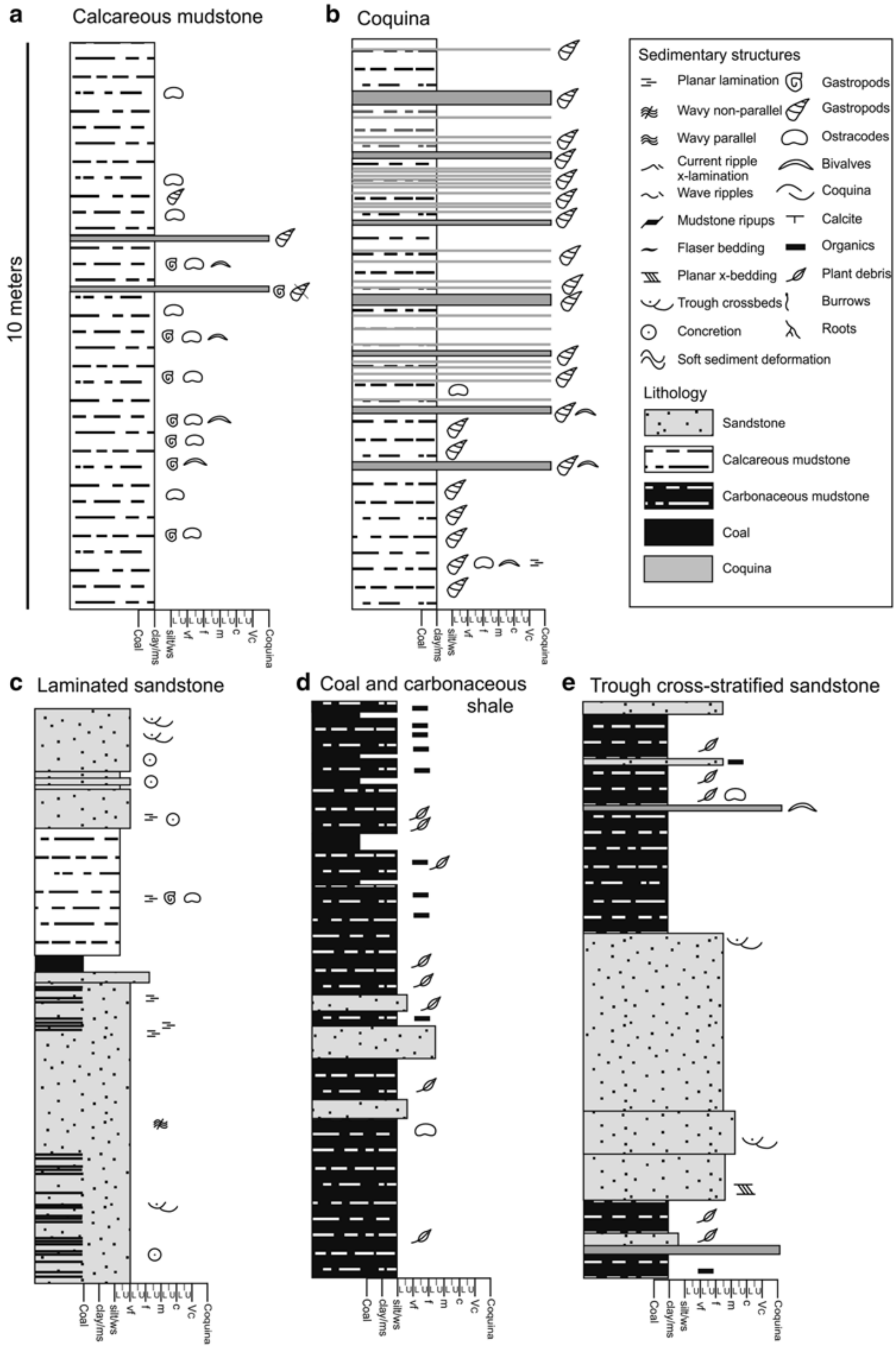
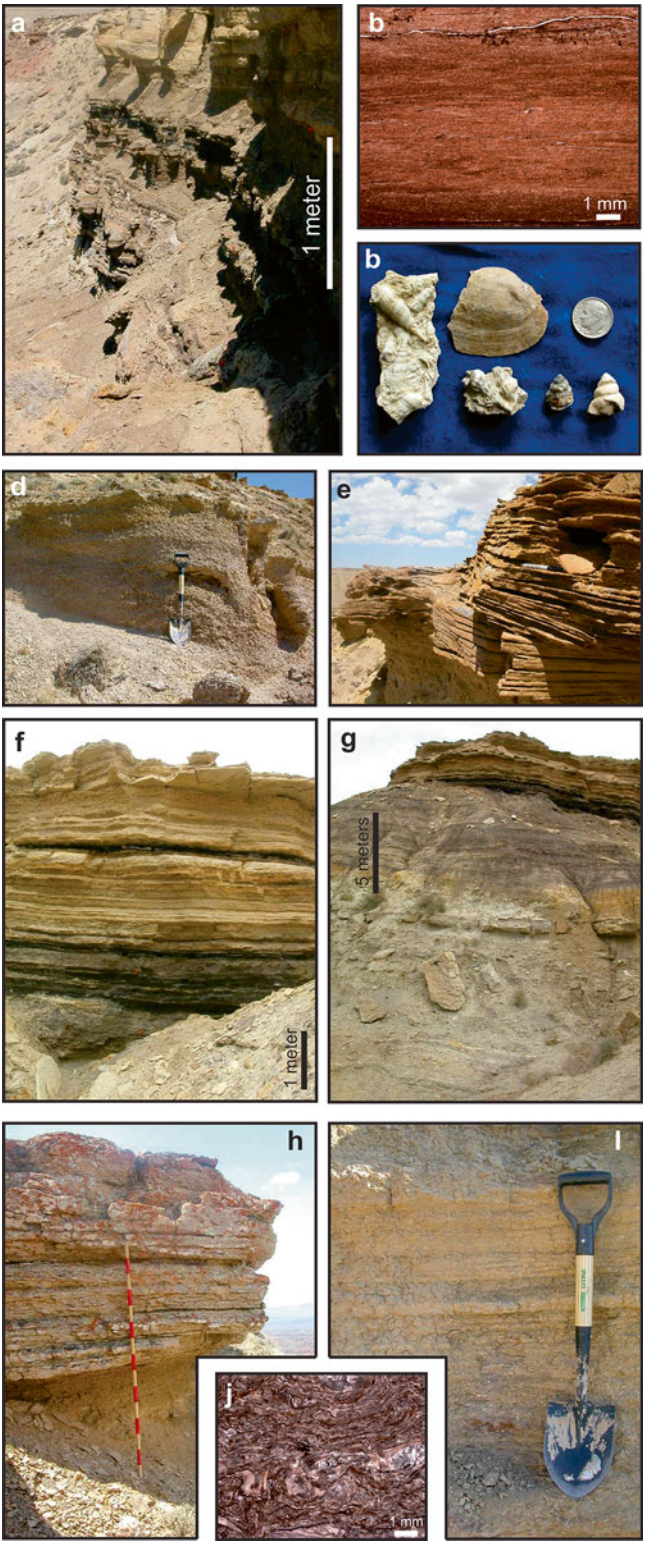


Fig. 2.3 Representative measured sections illustrating: (**a**) calcareous mudstone lithofacies from the Hiawatha section meters 108–118 (Chicken Creek SW 7.5′ quadrangle; NW1/4, NW1/4, NW1/4 Section 22, T12N, R100W); (**b**) interbedded coquina and calcareous mudstone lithofacies from the Hiawatha section meters 80–90 (Chicken Creek SW 7.5′ quadrangle; NW1/4, NW1/4, NW1/4 Section 22, T12N, R100W); (**c**) laminated sandstone from the Canyon Creek section meters 53–63 (Sugarloaf Butte 7.5′ quadrangle; NW1/4, NW1/4 Section 25, T12N, R101W); (**d**) coal and carbonaceous mudstone from the Colorado section meters 27–37 (Sparks 7.5′ quadrangle; SE1/4, NW1/4, SE1/4 Section 18, T12N, R101W); (**e**) trough cross-bedded sandstone from the Colorado section meters 27–37 (Sparks 7.5′ quadrangle; SE1/4, NW1/4, SE1/4 Section 18, T12N, R101W)


a
1 meter
b
1 mm
b
d
e
f
1 meter
g
5 meters
h
i
j
1 mm

Interpretation: We interpret these sandstone beds to be beach deposits. Sedimentary structures indicate wave action and well-sorted, well-rounded grains support a high energy environment. Repeated, sustained lake level rise and fall are represented by the alternation over the 1–8 m scale of these laminated sandstones with paludal coals and littoral shell-rich mudstones respectively (Figs. 2.4f and 2.5b).

Coal and carbonaceous mudstone This facies consists of vitrinitic to amorphous coals in beds that are often interbedded with carbonaceous mudstone and fine-grained sandstone (Figs. 2.3d and 2.4f). Generally 10–15 cm thick, these coal beds are laterally continuous for 100 m but are not useful as marker beds between stratigraphic sections. Millimeter-scale, planar-laminated mudstone contains carbonaceous matter of varying preservational quality. Unidentifiable plant material comprises the majority of the carbon content found in this facies. Root traces, woody debris, and invertebrate traces are also present.

Interpretation: Coal and carbonaceous mudstone are interpreted to represent overbank deposits and paludal, marginal lacustrine environments characterized by still water, abundant organic debris and reducing conditions. This type of environment is likely a complex of poorly-drained backswamps with networks of effective drainage systems where high sediment supply supports carbonaceous mudstone accumulation instead of thick coal bed formation (Flores 1981). Additionally, the deposition of non-laterally extensive or patchy coal deposits such as those seen in the Luman Member is generally restricted to nearshore and paludal environments and may be indicative of instable lake levels due to tectonic activity (Sáez and Cabrera 2002) and/or shoreline progradation (Bohacs et al. 2000).

Trough cross-bedded sandstone This fine to medium grained sandstone is often micaceous, hosting trough crossbeds and planar cross-lamination (Fig. 2.3e). This facies is often channelized at the meter scale, with cut-and-fill relationships and lateral accretion surfaces visible. Trough cross-bedded sandstone bodies typically cannot be traced more than approximately 5 m in outcrop and are replaced laterally by carbonaceous mudstone and coal. Individual channel bodies are commonly observable in outcrop, and are typically no more than 1 m thick. Amalgamated channel horizons are less common but can reach up to 5 m in thickness.

Interpretation: Trough cross-bedded sandstone is interpreted to represent fluvial sand deposited in alluvial systems adjacent to Lake Gosiute. Such fluvial-alluvial systems have been well-characterized (e.g., Miall 1988; Platt and Keller 1992) and contain lateral and vertical alternation between channel sand and overbank mud that record the lateral migration of fluvial channels across floodplains.

2.3.2 Stratigraphy

In many locations, an abrupt color change from red to drab gray-green occurs at the contact of the Main Body of the Wasatch Formation and the Luman Member (Fig. 2.5a). This color change is interpreted to represent a shift from oxidizing to reducing conditions of interstitial waters (cf. Walker 1967; Berner 1971), and corresponds to an increase in organic matter preservation and

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Fig. 2.4 Photographs and photomicrographs of lithofacies described in this report: (**a**) Alternating calcareous mudstone and laminated sandstone on the meter scale; (**b**) photomicrograph of siliciclastic mudstone (UW1954/18); (**c**) representative fossils found within calcareous mudstone from Hiawatha section (*HI*); (**d**) shell-rich calcareous mudstone; (**e**) laminated sandstone at Canyon Creek section (*CC*) Sharpie for scale; (**f**) alternating coal (black) and carbonaceous mudstone (cream); (**g**) outcrop character of coal and carbonaceous mudstone at Colorado section (*CO*); (**h**) 2.5 m thick coquina bed capping Telephone Canyon (*TC*) and Red Creek Rim (*RCR*) sections. (**i**) Thinly-bedded coquina at Hiawatha section (*HI*); (**j**) Photomicrograph of coquina (UW1954/11)