Introduction to the Green River Formation

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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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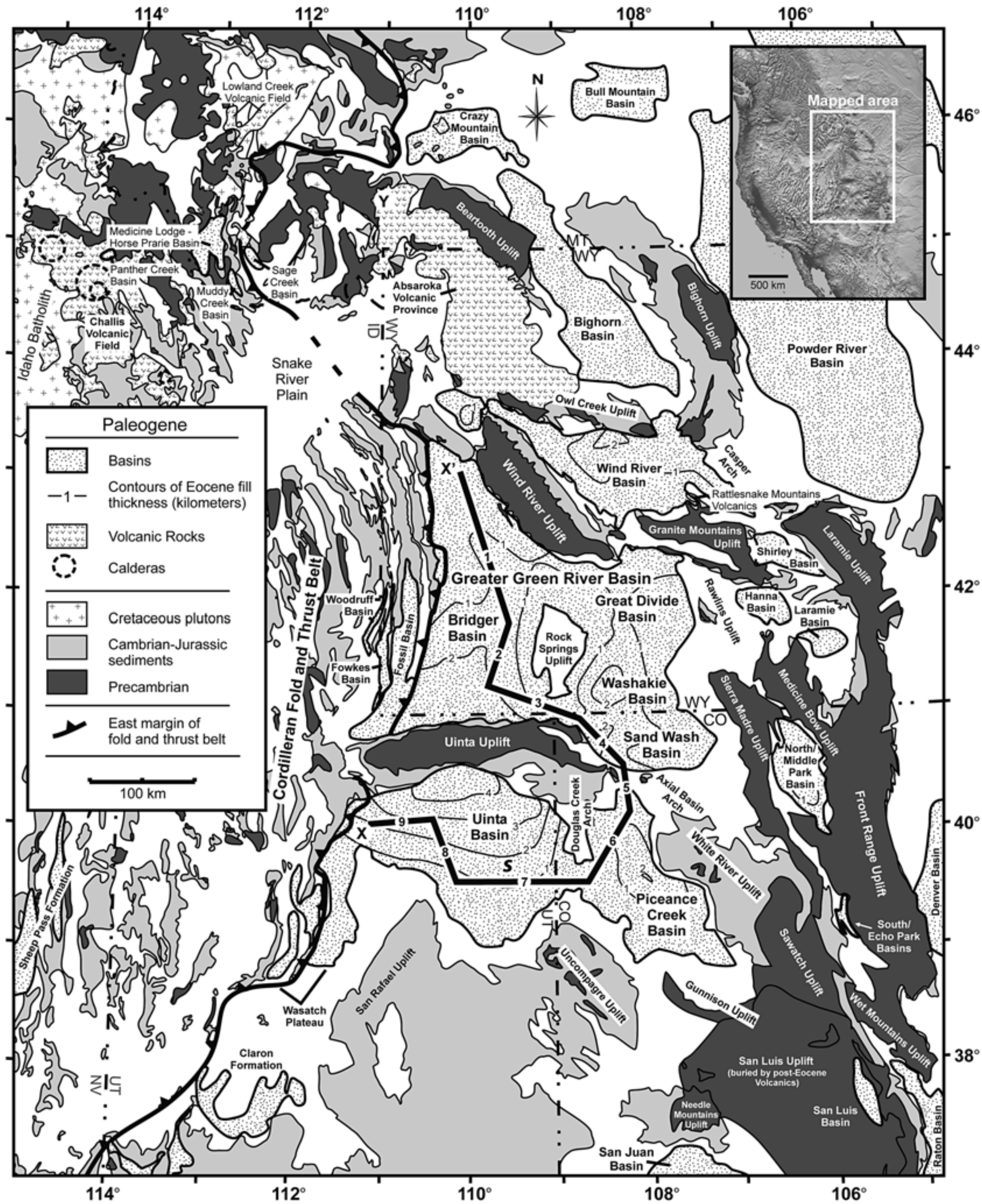

Fig. 1.1 Map showing the location of Eocene basins and basin-bounding uplifts (Adapted from Smith et al. 2008). The location of the Skyline 16 core from which the Skyline tuff was sampled from is indicated by an ***S*** (cf. Fig. 1.4)

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),

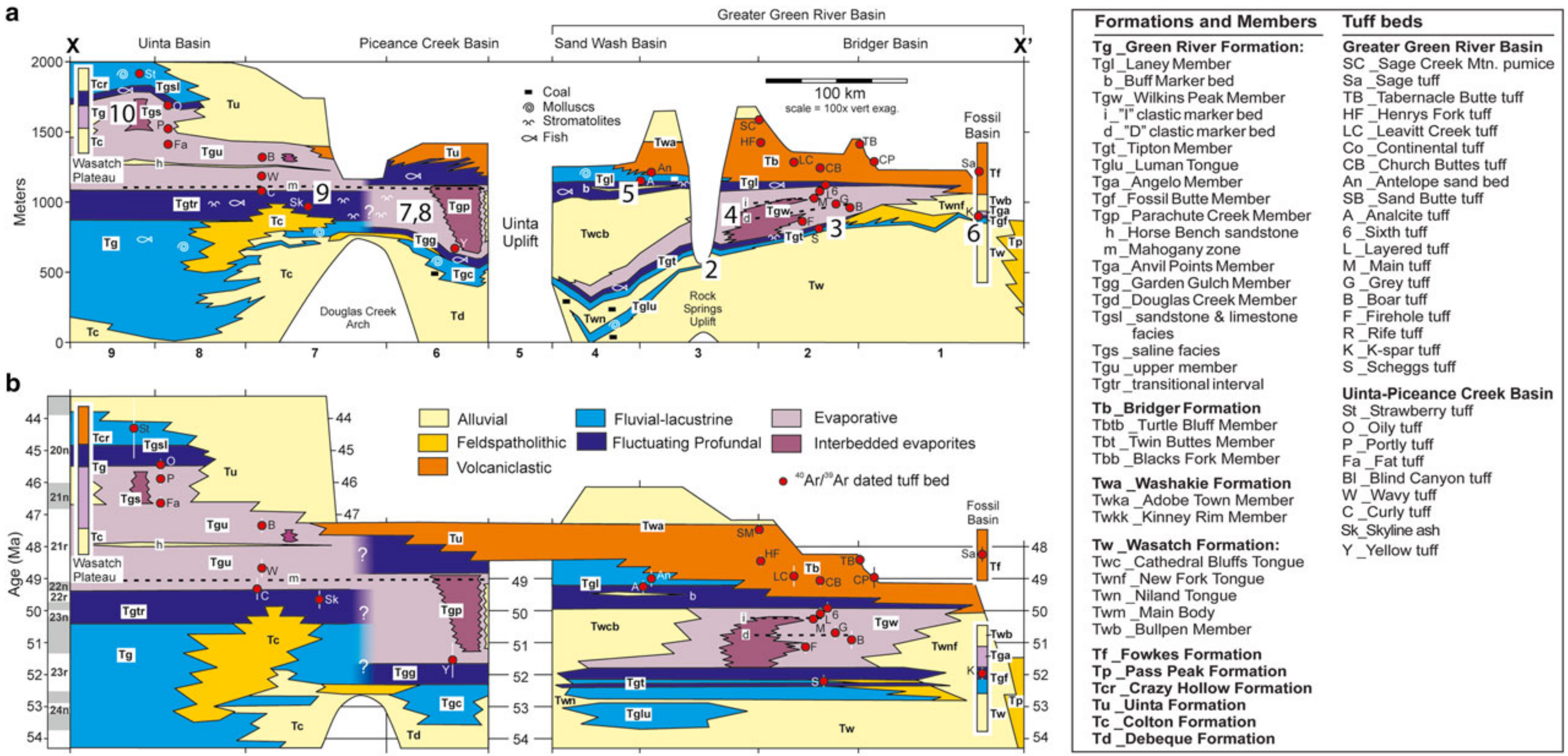

Fig. 1.2 Lithostratigraphic and time stratigraphic cross sections of Eocene strata in the Greater Green River, Piceance, and Uinta Basins along cross section X-X′ (see Fig. 1.1) showing the stratigraphic position of facies associations, structural features, and dated tuff beds. Cross section line was 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.

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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

$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	$^{40}Ar^*$ $\times10^{-14}$ 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

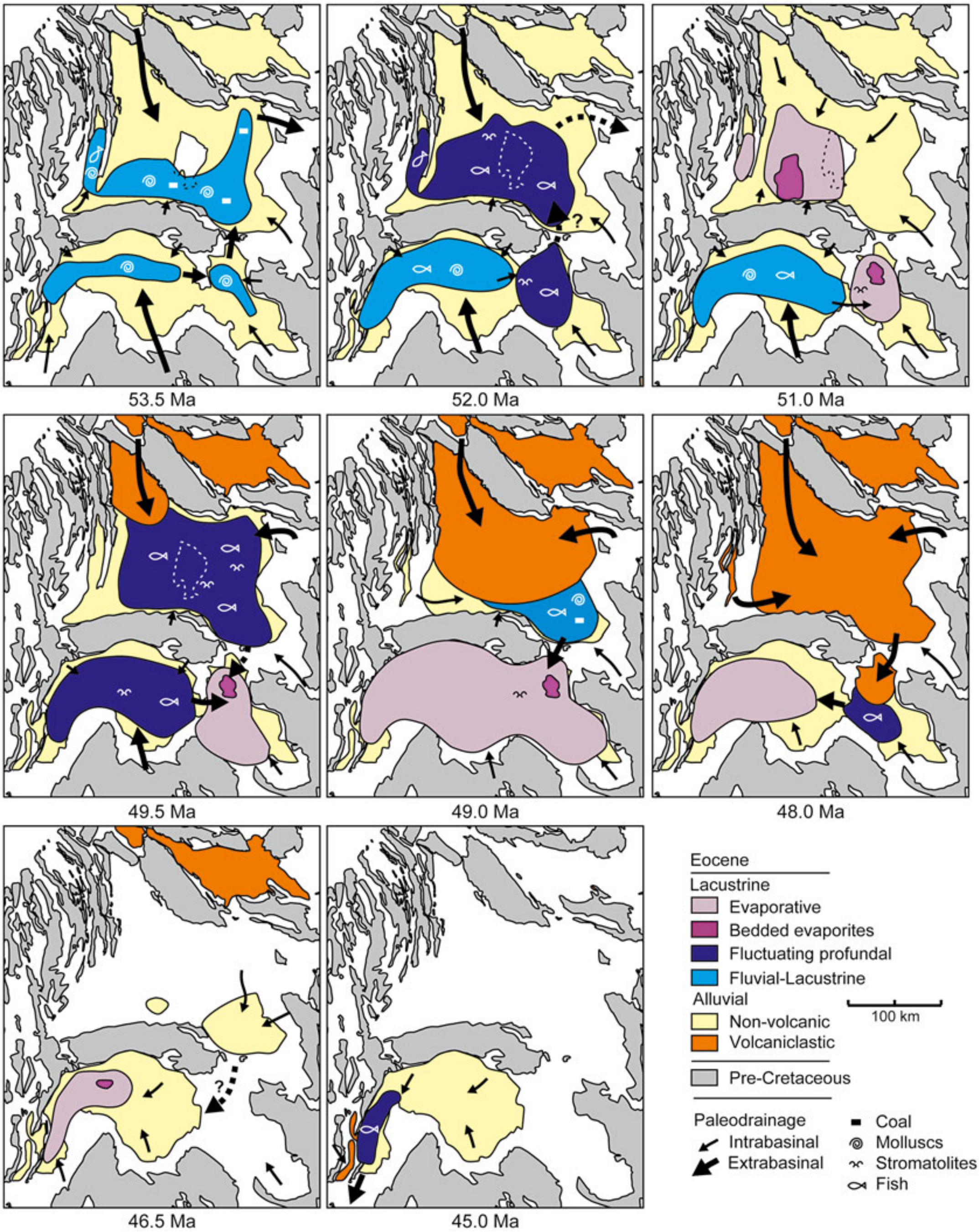

Fig. 1.3 Annotated synoptic maps showing paleohydrologic configuration of the Green River Formation lakes at 8 discrete times between 53.5 and 45 Ma (updated from Smith et al. 2008). Time slices were selected to highlight major hydrologic configurations of Green River Formation lake system (cf. Smith 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*).

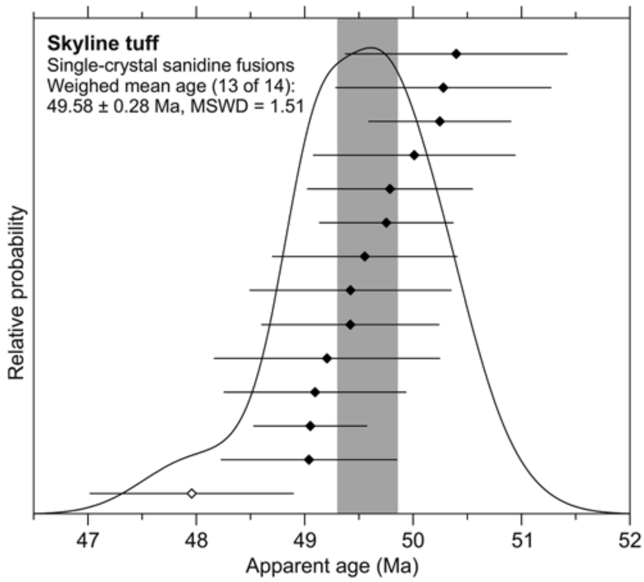

Fig. 1.4 Cumulative probability plot of $^{40}Ar/^{39}Ar$ laser fusion analyses of single sanidine from the Skyline tuff. The airfall ash was sampled from profundal facies of the R-4 oil shale zone in the Skyline 16 core in the R-4 oil shale zone (depth: 890.67–890.93 ft) in the Eastern Uinta Basin: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

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