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The effect of drainage reorganization on paleoaltimetry studies: An example from the Paleogene Laramide foreland

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ABSTRACT

Using multiple isotope systems, we examine the complex effects of drainage reorganization in the Laramide Foreland in the context of stable isotope paleoaltimetry. Strontium, oxygen and carbon isotopic data from lacustrine carbonates formed in the southwestern Uinta Basin, Utah between the Late Cretaceous and late Middle Eocene reveal a two stage expansion in the drainage basin of Lake Uinta beginning at ~53 Ma culminating in the Mahogany highstand at 48.6 Ma. A marked increase in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of samples from the Main Body of the Green River Formation is interpreted as the result of water overflowing the Greater Green River Basin in Wyoming and entering Lake Uinta from the east via the Piceance Creek Basin of northwestern Colorado. This large new source of water caused a rapid expansion of Lake Uinta and was accompanied by a significant and rapid increase in the O isotope record of carbonate samples by ~6‰. The periodic overspilling of Lake Gosiute probably became continuous at ~49 Ma, when the lake captured low- $\delta^{18}\text{O}$ water from the Challis and Absaroka Volcanic Fields to the north. However, evaporation in the Greater Green River and Piceance Creek Basins meant that the waters entering Lake Uinta were still enriched in ^{18}O . By ~46 Ma, inflows from the Greater Green River Basin ceased, resulting in a lowstand of Lake Uinta and the deposition of bedded evaporites in the Saline Facies of the Green River Formation.

We thus show that basin development and lake hydrology in the Laramide foreland were characterized by large-scale changes in Cordilleran drainage patterns, capable of confounding paleoaltimetry studies premised on too few isotopic systems, samples or localities. In the case of the North American Cordillera of the Paleogene, we further demonstrate the likelihood that (1) topographic evolution of distal source areas strongly influenced the isotopic records of intraforeland basins and (2) a pattern of drainage integration between the hinterland and foreland may correlate in space and time with the southward sweep of hinterland magmatism.

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1. Introduction

During the past decade, numerous stable isotopic studies have reconstructed the paleoaltimetry of mountain belts worldwide (Chamberlain and Poage, 2000; Garzzone et al., 2000; Rowley et al., 2001; Poage and Chamberlain, 2001; Kohn et al., 2002; Takeuchi and Larson, 2005; Graham et al., 2005; Kent-Corson et al., 2006). These studies use the O isotope composition of authigenic minerals as a proxy for past altitudes, and often assign isotopic shifts of these minerals over time to the growth of local topography. There are, however, other factors such as evaporation, temperature, and diagenesis that can influence the O isotope composition of authigenic minerals. These are generally taken into account in paleoaltimetry

studies. Not often considered in these studies is the regional drainage reorganization that occurs during mountain building events. Large-scale drainage reorganization and stream piracy can strongly influence the O isotope composition of water in basins. Such changes may confound paleoaltimetry estimates because: 1) drainage reorganization can occur on time-scales of 10^5 yr (Hilley and Strecker, 2005), whereas tectonism generally occurs on time-scales of 10^6 yr (although removal of the lower lithosphere can be faster Garzzone et al., 2006); and 2) the expanded drainage basin can tap waters with different O isotope values either as a result of draining areas with different atmospheric source regions or waters that have undergone evaporation.

As a case study, we examine the O, C and Sr isotopic composition and Sr/Ca ratios of authigenic carbonates formed in Late Cretaceous to late Middle Eocene lakes in the Laramide foreland. Laramide segmentation of the foreland impounded large lakes (>20,000 km²) whose sedimentological history suggests that their hydrology coevolved with accommodation space over millions of years (Pietras et al., 2003; Surdam and Stanley, 1980; Carroll et al., 2006; Smith et al., 2008). Studies using O

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isotopes (Norris et al., 1996; Dettman and Lohmann, 2000; Davis et al., in press) and Sr isotopes (Rhodes et al., 2002; Gierlowski-Kordesch et al., 2008) suggest that these lakes preserve a record of reorganizing drainage patterns attendant with rise of mountains. However, whether such reorganization occurs locally (Norris et al., 1996; Dettman and Lohmann, 2000) or on a more regional scale (Davis et al., in press) is unknown.

Our combined isotopic study shows that drainage reorganization has occurred in response to developing topography, both locally and as much as 1000 km away. Specifically, we show that large O isotopic shifts (6–7‰) are primarily the result of changing hydrologic regime of Lake Uinta. By combining data from O and C isotopes and Sr/Ca ratios with Sr isotope ratios, we are able to evaluate the role of drainage reorganization and suggest that lake hydrology was responding to both local and distal tectonic forcing.

2. Geological setting

Rivers draining eastward from the Sevier hinterland across the central North American Cordillera in Cretaceous and Paleocene time were large, persistent and relatively insensitive to the evolving frontal morphology of the fold-thrust belt (DeCelles, 1994; Horton and DeCelles, 2001). However, beginning in Late Campanian and Maastrichtian time (~80 Ma), Laramide deformation progressively impeded this eastward drainage, and block uplifts partitioned intraforeland basins (Dickinson et al., 1988). By Eocene time, sedimentary provenance and paleoflow directions document the evolution of drainages that transported substantial water and sediment fill to Laramide basins from areas within the foreland, both north and south along the strike of the fold-thrust belt (e.g., Anderson and Picard, 1972; Stanley and Collinson, 1979; Dickinson et al., 1986). In time, Laramide tectonism waned, and the accommodation created by intraforeland basins was completely infilled between the late Middle Eocene and Early Oligocene. The sedimentary units sampled in this study record each phase in the development of drainages feeding the Uinta Basin of northeast Utah (Fig. 1). The sedimentology of units examined in this study shows the evolution of intraforeland basins from fluvial systems draining the superjacent fold-thrust belt during the Cretaceous and Late Paleocene into a long-lived lake system whose depocenters and hydrology shifted over time during the Eocene. The four formations that we studied using isotopic methods are discussed below.

2.1. North Horn Formation

From Maastrichtian to Late Paleocene time, a major deltaic complex deposited redbeds in the southwestern Uinta Basin (Ryder et al., 1976; Franczyk et al., 1991). Alluvial sand, silt and clay of this system, assigned to the North Horn Formation, were deposited at the margin of the nascent Lake Uinta by east-flowing rivers draining the fold-thrust belt, and smaller streams meandering north–northwest from the growing San Rafael Swell (Ryder et al., 1976; Fouch et al., 1983; Lawton, 1986; Franczyk et al., 1991).

2.2. Flagstaff and Colton Formations

Just south of the Uinta Basin, the topography of the San Rafael Swell began impounding eastward drainage of the Flagstaff Basin in the Late Paleocene (Fig. 1). Authigenic carbonates of the Flagstaff Formation mark the onset of widespread lacustrine deposition in the Flagstaff Basin between the fold-thrust belt and the San Rafael Swell (Stanley and Collinson, 1979). At the end of the Paleocene, this Lake Flagstaff had expanded into the central Uinta Basin and occupied ~150 km length of the foreland along the strike of the fold-thrust belt (See Fig. 1; Ryder et al., 1976; Stanley and Collinson, 1979).

Ongoing Laramide deformation eventually resulted in dissection of the deposits of Lake Flagstaff. During Early Eocene time, the lake transgressed west ahead of the northwest prograding fluvial mudstone and arkosic sandstone of the Colton Formation, interrupting lacustrine

deposition in most of the Flagstaff and southwestern Uinta Basins (Peterson, 1976; Stanley and Collinson, 1979; Morris et al., 1991). Where the lake persisted in the Uinta and westernmost Flagstaff Basins (the latter is sometimes referred to as the Axhandle Basin or Gunnison Plateau) (Stanley and Collinson, 1979; Volkert, 1980; Fouch et al., 1983; Talling et al., 1995), the freshwater limestone of the Flagstaff Formation grade upwards into carbonate of the Eocene Green River Formation (Fouch, 1976; Volkert, 1980). For this reason, the Flagstaff Formation in the southwest Uinta Basin (where we sampled it) is locally defined as the Flagstaff Member of the Green River Formation (See Fig. 1; Fouch, 1976).

2.3. Green River Formation

Though isolated from the Flagstaff depocenter to the south, open lacustrine deposition resumed in the Uinta Basin and continued throughout the Eocene (Bryant et al., 1989). In the Early Eocene, Lake Uinta was approximately hydrologically balanced; lake levels fluctuated so that the lake oscillated between periods of internal drainage and periods when the overfilled lake spilled south into the Flagstaff Basin (Davis et al., in press). During this period of fluctuating lake levels, cyclically interbedded limestone, marl, oil shale (kerogen-rich marl) and sandstone of the Main Body of the Green River Formation were deposited (Bradley, 1931; Picard and High, 1968). At 48.6 Ma, a pronounced lake highstand is delineated by oil shale and tuff of the Mahogany Zone (Smith et al., 2008). During the Mahogany highstand, Lake Uinta overtopped the Douglas Creek Arch (DCA) at its eastern end to merge with the lake in the Piceance Creek Basin, attaining an area in excess of 20,000 km² (Fig. 1; Picard and High, 1968).

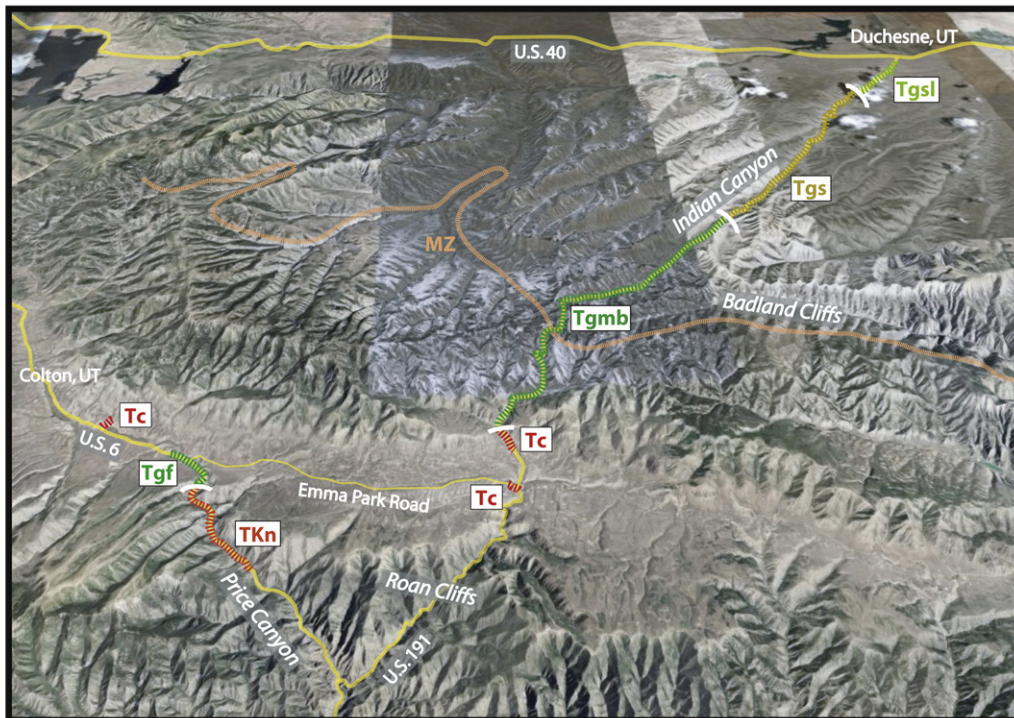
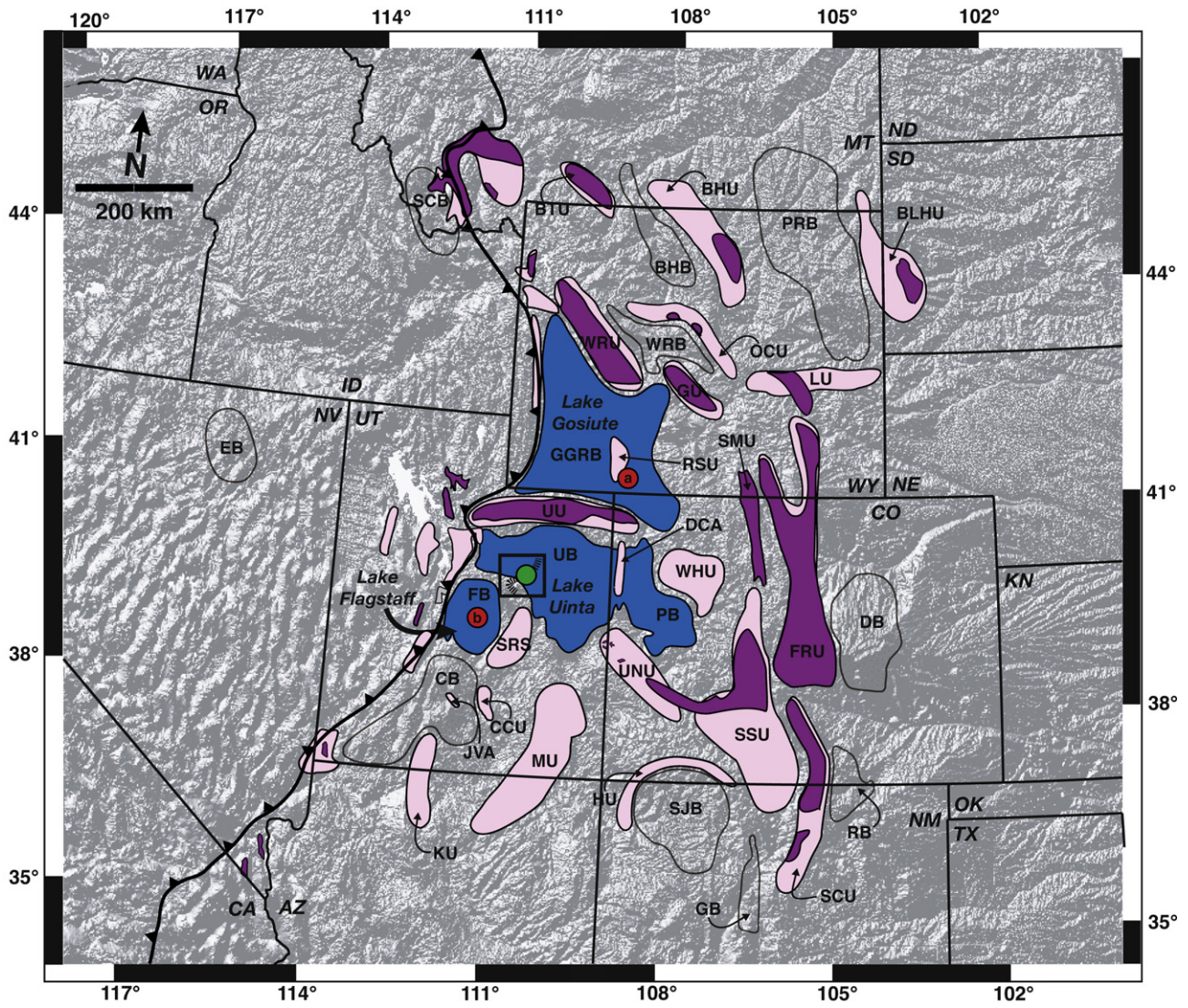
After the Mahogany highstand, Lake Uinta became internally drained for an extended period of time. Beginning ~46 Ma (Smith et al., 2008; Davis et al., in press) the evaporitic Saline Facies of the Green River Formation was deposited (Dyner et al., 1985) in the closed, hypersaline lake. At ~44 Ma, the lake gradually freshened, as recorded in sediments of the Sandstone and Limestone Facies of the Green River Formation, and lacustrine deposition ended at ~43 Ma (Bryant et al., 1989; Smith et al., 2008; Davis et al., in press).

3. Approach and methods

3.1. Isotopic and trace element studies

O, C and Sr isotopes of lacustrine carbonate are particularly useful for unraveling how climate and tectonics influence lake evolution because each system provides unique and complementary information on the paleohydrology of lakes. For example, O isotope composition of lake water ($\delta^{18}\text{O}_{\text{lw}}$) represents a weighted average of the freshwater input from extrabasinal drainages, intrabasinal precipitation, and groundwater seepage, stream and groundwater outflow from the basin, and evaporation from the lake (Criss, 1999; Winter, 2004). Whereas, C isotopes are useful in recognizing hydrologic closure of paleolakes and diagenetic alteration of carbonate samples. Strontium isotopes, in contrast, can be used to assess changes in the provenance of water flowing into the lake.

We used the following approach to determine the paleohydrology of the evolving Lake Uinta system. First, we constructed O isotopic profiles of the Cretaceous to Late Paleocene sediments exposed in the Uinta Basin. Second, we used C isotopes and Sr/Ca ratios of carbonate to evaluate the role of evaporation and diagenesis on the O isotope record. Evaporative effects can be assessed by the degree of covariance of $\delta^{13}\text{C}$ – $\delta^{18}\text{O}$ values and Sr/Ca ratios in carbonate samples. If evaporation is relatively high $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values will covary because hydrologically closed lakes have long residence times allowing preferential outgassing of ¹²C-rich CO₂ accompanied by evaporative enrichment of ¹⁸O (Talbot and Kelts, 1990). Sr/Ca ratios will also be high in evaporative lakes as the partitioning of Sr between host water



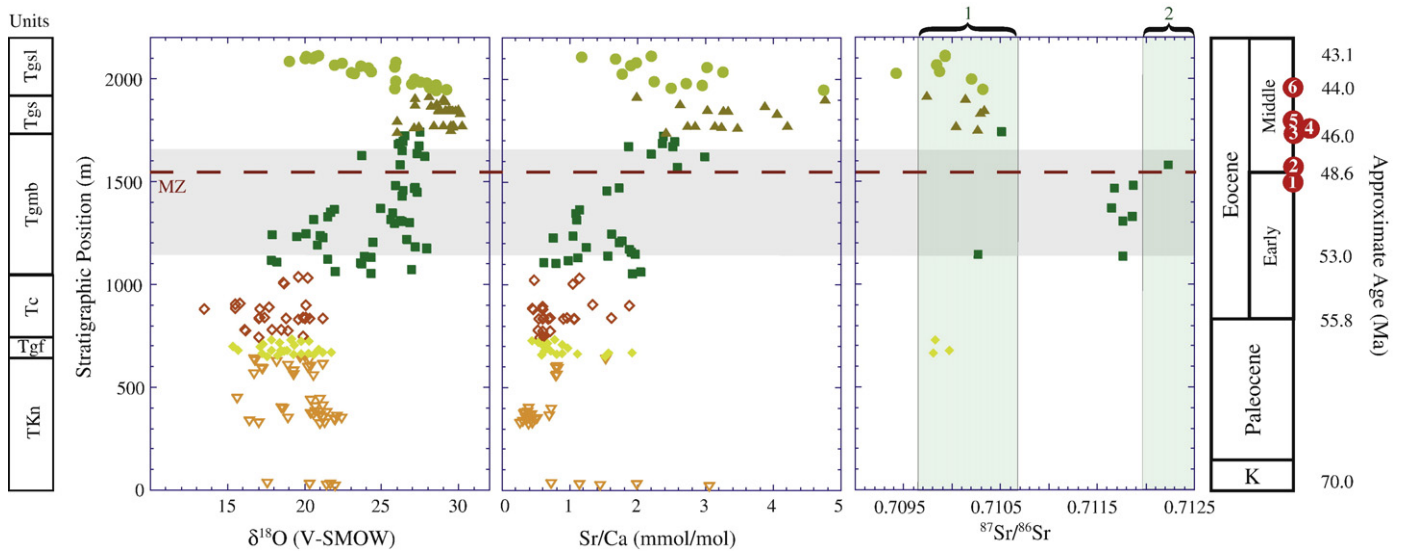


Fig. 2. O and Sr isotope and Sr/Ca ratios from the Uinta Basin plotted by stratigraphic position. Approximate age of samples is shown at right, along with radiometric age constraints numbered according to Table SM2. The dashed line MZ indicates the highstand of the Mahogany Zone at 48.6 Ma. Closed symbols represent lacustrine units of the Green River Formation: Tgf, Flagstaff Member; Tgmb, Main Body; Tgs, Saline Facies; Tgsl, Sandstone and Limestone Facies. Open symbols represent fluvial units: KTn, North Horn Formation; Tc, Colton Formation. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are elevated in the stratigraphic interval highlighted by horizontal shading. Vertical shading in the Sr isotope panel indicates the range of values observed in previous studies: (1) Flagstaff Formation in central Utah measured by Gierlowski-Kordesch et al. (2008) and (2) Laney Member of Green River Formation in Greater Green River Basin, Wyoming measured by Rhodes et al. (2002).

and authigenic carbonate is proportional to the ratio of Sr^{2+} to Ca^{2+} in the water (Müller et al., 1972). In hydrologically closed lakes, Sr^{2+} is not flushed from the system, and as CaCO_3 precipitates, Sr^{2+} is progressively concentrated and incorporated into authigenic carbonates (Eugster and Kelts, 1983). Carbon isotopes can also be used to assess the role of diagenesis on the O isotope composition of carbonates. Diagenesis often results in relatively low O isotope values (Morrill and Koch, 2002) as a result of equilibration of carbonate with meteoric waters at high temperatures. Since the $\delta^{13}\text{C}$ values of early diagenetic carbonates are determined by bacterially mediated redox reactions, while $\delta^{18}\text{O}$ values of such diagenetic phases continue to record the isotopic composition of sediment pore waters (Talbot and Kelts, 1990), diagenesis often results in non-covariance of C and O isotopes in lacustrine sediments (Talbot and Kelts, 1990; Talbot, 1990); although others (Garzione et al., 2004) have suggested this might not be the case.

Third, we used Sr isotopes of authigenic carbonate to determine whether the source of the water supplied to these lakes has changed with time. The isotopic signature of Sr in lacustrine carbonates has recently been recognized as a valuable method for reconstructing lake paleohydrology (Pietras et al., 2003; Gierlowski-Kordesch et al., 2008). Because mass-dependent fractionation of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios is insignificant and corrected for during analysis, authigenic minerals record the Sr isotope composition of lake water at the time of their precipitation. In turn, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of waters is dictated by contact with rocks in the drainage area, and especially carbonate rocks (Palmer and Edmond, 1992; Jacobsen and Blum, 2000). Heterogeneities in the Sr isotope ratios of lithologies present in the drainage basin are homogenized in lake water such that when carbonate precipitates, its Sr isotope

composition reflects the weighted average of isotopically distinct inflows to the lake. Although groundwater seepage into foreland lake basins can be significant (Winter, 2004), subsurface rocks contacted by groundwater in foreland basin systems are generally the same as those exposed in surficial watersheds.

3.2. Methods

We collected authigenic samples of micritic carbonate along a stratigraphic section of Paleogene fluvial-lacustrine facies spanning ~68 km within the southwest Uinta Basin (Fig. 1). Our samples include an existing dataset of 103 samples from the Uinta Basin (Davis et al., in press). We extended this existing collection with 101 new samples of limestone, marl, and calcite-cemented sandstone that are stratigraphically below our earlier collected samples. The details of the sampled section and key references are included in the Supplementary Materials (Table SM1).

We measured Sr, C and O isotope values in the mass spectrometry laboratories at Stanford University. For Sr isotope analysis, Sr was extracted from bulk carbonate samples using 1 M acetic acid (CH_3COOH) to ensure that potentially existing silicate minerals were not dissolved. The clear solution was centrifuged, transferred into clean Teflon vials, and evaporated. The remaining sample residue was treated with concentrated HNO_3 prior to re-dissolution with 2.5 N HCl. Aliquots of each sample were loaded onto cation exchange columns using Biorad AG50x8 (200–400 mesh) resin, and eluted with 2.5 N HCl. All reagents were distilled. Purified Sr fractions were measured on a Finnigan MAT262 Thermal Ionization Mass Spectrometer using Ta single filaments and 0.25 N H_3PO_4 . Ratios of ^{88}Sr , ^{87}Sr , ^{86}Sr , and ^{84}Sr were scanned at least 80

Fig. 1. Digital elevation map of modern topography of the central North American Cordillera (UTM Zone 13 N) with Paleogene structures superimposed (location and extent of structures after Dickinson et al., 1986, 1988). Basins are lightly stippled and uplifts are shaded gray. Darker shading indicates exposed Precambrian rock where $^{87}\text{Sr}/^{86}\text{Sr}$ ratios can be in excess of 1.0, while lighter shading indicates exposures of Paleozoic and Mesozoic rocks with $^{87}\text{Sr}/^{86}\text{Sr}$ ratios <0.710 (isotopic composition from sources cited in text). Bold line shows the Sevier fold-and-thrust belt, teeth on the upper plate. Major structures are labeled as follows: BHB, Bighorn Basin; BHU, Bighorn Uplift; BLHU, Black Hills Uplift; BTU, Beartooth Uplift; CB, Claron Basin; CCU, Circle Cliffs Uplift; DB, Denver Basin; DCA, Douglas Creek Arch; EB, Elko Basin; FB, Flagstaff Basin; FRU, Front Range Uplift; GB, Galisteo Basin; GGRB, Greater Green River Basin; GU, Granite Mountain Uplift; HM, Hogback Monocline; JVA, Johns Valley and Upper Valley Anticlines; KU, Kaibab Uplift; LU, Laramie Uplift; MU, Monument Uplift; OCU, Owl Creek Uplift; PB, Piceance Creek Basin; PRB, Powder River Basin; RB, Raton Basin; RSU, Rock Springs Uplift; SCB, Sage Creek Basin; SCU, Sangre de Cristo Uplift; SJB, San Juan Basin; SMU, Sierra Madre Uplift; SSU, Sawatch-San Luis Uplift; SRS, San Rafael Swell; UB, Uinta Basin; UNU, Uncompahgre Uplift; UU, Uinta Uplift; WHU, White River Uplift; WRB, Wind River Basin; WRU, Wind River Uplift. Lettered circles indicate sampled sections within (a) the Washakie sub-basin of the Greater Green River Basin (Carroll et al., 2008) and (b) the Flagstaff Basin (Gierlowski-Kordesch et al., 2008). Sampled section indicated by a circle and dashed line; the inset shows detailed location of sampled units [Google Earth projection, unit abbreviations listed in Fig. 2].

times per sample. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were corrected for instrumental fractionation using the natural $^{88}\text{Sr}/^{86}\text{Sr}$ ratio of 8.375209. Routine standard measurements yield a $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.71033 ± 0.00001 (2σ ; $n=64$) for the NBS-987 Sr standard. The analytical precision is 0.003% or less. Blanks were less than 0.5 ng Sr. Samples from similar stratigraphic intervals yielded similar Sr isotope ratios irrespective of mineralogy, texture, O isotope composition and Sr/Ca ratio.

We determined the O and C isotope analyses of carbonate using the phosphoric acid digestion method of McCrea (1950) coupled on-line with a gas ratio mass spectrometer. Using this method, between 300 and 500 μg of sample material was drilled from each sample, sealed in reaction vials, flushed with helium and reacted with pure H_3PO_4 at 72 °C. Evolved CO_2 in the vial headspace was then sampled using a Finnigan GasBench II, connected to a Finnigan MAT Delta^{plus} XL mass spectrometer. Replicate analyses of NBS-19 (limestone) and laboratory standards yielded a precision $\pm 0.2\%$ or better for both $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$.

For Sr/Ca ratios of carbonate we used an inductively coupled plasma-atomic emission spectroscopy (ICP-AES) at Stanford University. Samples were first digested in 67% HNO_3 , diluted with Mega-Pure water and filtered. Total dissolved Ca^{2+} and Sr^{2+} were measured at wavelengths 317.9 and 407 nm, respectively (cf. de Villiers et al., 2002). Replicate analyses of prepared blanks and standard solutions of varying known concentrations indicated detection limits for Ca^{2+} and Sr^{2+} of 6 and 0.1 $\mu\text{g L}^{-1}$, respectively, and precision better than 15 $\mu\text{g L}^{-1}$ for Ca^{2+} and 1 $\mu\text{g L}^{-1}$ for Sr^{2+} (i.e. better than 0.1 mmol/mol for Sr/Ca ratios).

4. Results

Four results come out of our analyses of O, C and Sr isotopes and Sr/Ca ratios of authigenic carbonate from Lake Uinta. First, between Late

Cretaceous and Early Eocene time (~ 70 – 53 Ma), $\delta^{18}\text{O}_{\text{calcite}}$ values of fluvial and lacustrine samples vary from 15‰ to 21‰, displaying no clear trend (Fig. 2). However, near the boundary between the fluvial deposits of the Colton Formation and the lacustrine Green River Formation (Main Body, at ~ 53 Ma), mean $\delta^{18}\text{O}_{\text{calcite}}$ values increase by $\sim 6\%$ (Fig. 2). Second, roughly coeval with the increase in $\delta^{18}\text{O}_{\text{calcite}}$ values, $^{87}\text{Sr}/^{86}\text{Sr}$ ratios also increase from a mean of 0.70986 ± 0.00022 to a more radiogenic mean of 0.71183 ± 0.00018 (Fig. 2). Thirdly, the higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratios persist as $\delta^{18}\text{O}_{\text{calcite}}$ values and Sr/Ca ratios trend higher within the Main Body of the Green River Formation, until ~ 46 Ma, when $^{87}\text{Sr}/^{86}\text{Sr}$ ratios abruptly decrease and $\delta^{18}\text{O}_{\text{calcite}}$ values and Sr/Ca ratios continue to a maximum within the Saline Facies of the Green River Formation (Fig. 2). Four, $^{87}\text{Sr}/^{86}\text{Sr}$ ratios remain low (mean of 0.71002 ± 0.00016) as $\delta^{18}\text{O}_{\text{calcite}}$ values and Sr/Ca ratios gradually decline during deposition of the Sandstone and Limestone Facies of the Green River Formation. For clarity, we discuss these results in three intervals of time: Late Cretaceous through Early Eocene (~ 70 – 53 Ma), the Early Eocene and early Middle Eocene (~ 53 – 46 Ma), and the late Middle Eocene (~ 46 – 43 Ma). Because O and C isotope results and Sr/Ca ratios from the latter two intervals are presented in Davis et al. (in press), discussion of those results are only reviewed here.

4.1. Late Cretaceous–Early Eocene

Between the Late Cretaceous and Early Eocene (~ 70 – 53 Ma), $\delta^{18}\text{O}_{\text{calcite}}$ values of fluvial and lacustrine samples vary between 15‰ and 21‰ (Fig. 2) around a mean of 18.9‰ ($n=93$, $1\sigma=1.9$), with no obvious trend. $\delta^{13}\text{C}_{\text{calcite}}$ and $\delta^{18}\text{O}_{\text{calcite}}$ values in samples from the North Horn Formation do not covary (~ 70 to ~ 60 Ma, $r^2=0.07$, $n=40$; Fig. 3), nor do values from the Flagstaff Member of the Green River Formation (~ 60 to ~ 57 Ma, $r^2=0.11$, $n=25$; Fig. 3) or those from the

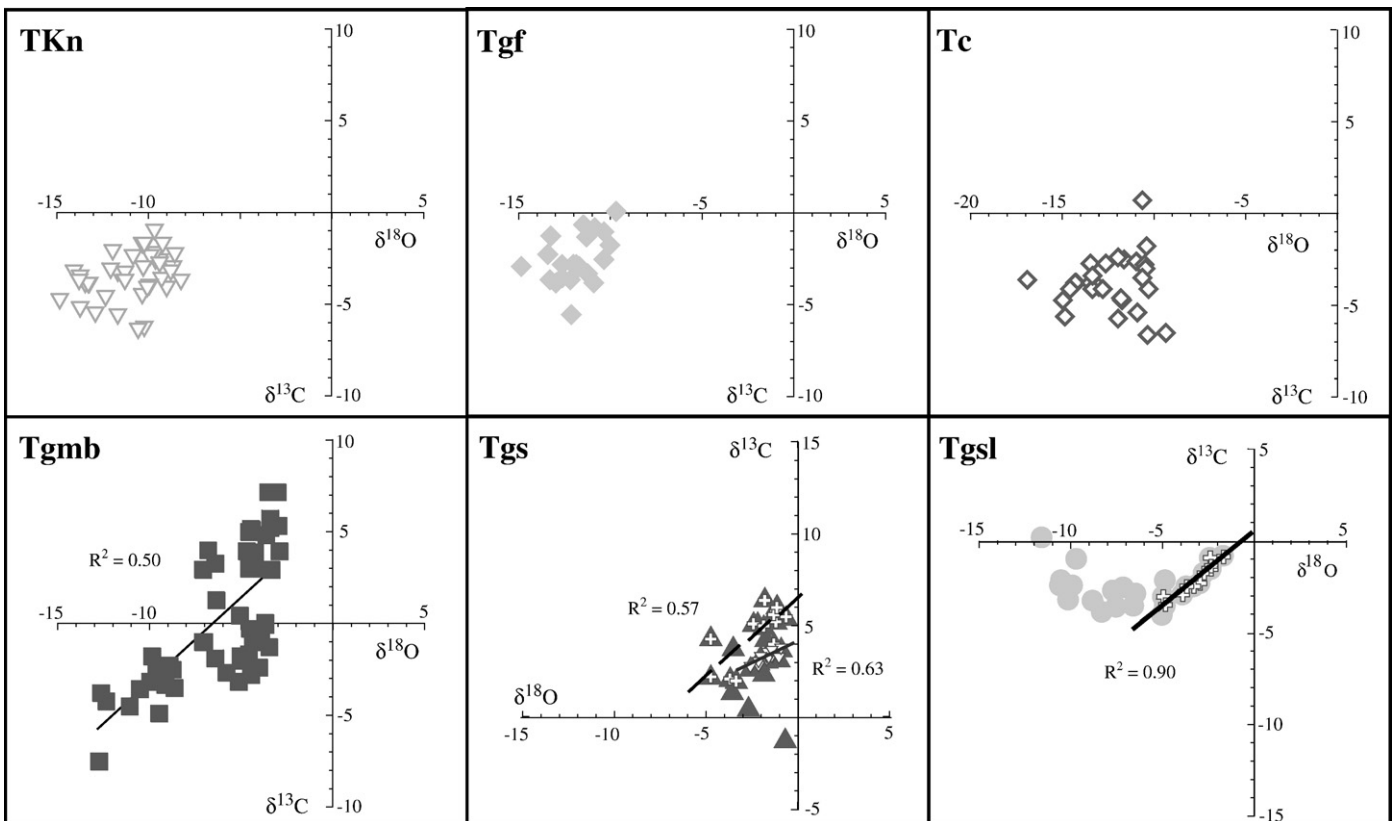


Fig. 3. Covariance of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ in fluvial and lacustrine carbonates (symbology identical to Fig. 2) of units sampled in the southwest Uinta Basin. Units are abbreviated as follows: TKn, North Horn Formation; Tgf, Flagstaff Member of the Green River Formation; Tc, Colton Formation; Tgmb, Main Body of the Green River Formation; Tgs, Saline Facies of the Green River Formation; Tgsl, Sandstone and Limestone Facies of the Green River Formation. Covariance in stratigraphically continuous subsets of Tgs and Tgsl units are described in the text. Both $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ are plotted relative to the PeeDee Belemnite (V-PDB) standard. $\delta^{18}\text{O}_{\text{calcite}}$ values discussed in the text are relative to Standard Mean Ocean Water (V-SMOW).

Colton Formation (~57 to ~52 Ma, $r^2=0.02$, $n=28$; Fig. 3). Examination of stratigraphically continuous subsets from these units do not significantly improve isotopic covariance.

During the same time interval, Sr/Ca ratios are consistently low (mean 0.75 mmol/mol, $n=79$, $1\sigma=0.47$), except for a few short-lived excursions in each unit that do not exceed 2 mmol/mol (except for a single anomalous but otherwise unremarkable sample from the Colton Formation with a measured composition of 3.76) (Fig. 2). No relationship between Sr/Ca ratios and $\delta^{18}\text{O}_{\text{calcite}}$ values is observed in samples from the North Horn or Colton Formations or the Flagstaff Member of the Green River Formation (r^2 values of 0.09, <0.01 and <0.01, respectively; Fig. 4).

The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of lacustrine carbonate from the Flagstaff Member of the Green River Formation have a mean of 0.70986 ± 0.00022 ($n=3$).

4.2. Early Eocene–early Middle Eocene

Samples from the interval of time between the Early Eocene and early Middle Eocene (~53–46 Ma) are characterized by elevated $^{87}\text{Sr}/^{86}\text{Sr}$ ratios relative to any of our samples deposited before or after (see shaded area, Fig. 2). The transition to higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratios occurs near the base of the Main Body of the Green River Formation, and samples from that unit comprise a statistically distinct population from samples deposited before and after (mean= 0.71183 ± 0.00018 ; ANOVA single factor and nonparametric Kruskal–Wallis tests conducted at 95% confidence show samples are not derived from the same population: $F=22.13$, $F_{\text{crit}}=3.07$, $H=16.595$ and $\chi^2_{\text{crit}}=7.81$).

Coeval with the increase in Sr isotope ratios, the range of $\delta^{18}\text{O}_{\text{calcite}}$ values increases by ~6‰ between the Colton Formation (mean = 18.1‰, $1\sigma=1.9$, $n=28$) and the lower Main Body of the Green River Formation (mean = 24.1‰, $1\sigma=3.5$, $n=16$). Upsection, while Sr isotope ratios remain high, $\delta^{18}\text{O}_{\text{calcite}}$ values of Main Body samples show reduced variability, with the lowest measured values gradually increasing by ~7‰ (Davis et al., in press). Also during this time, Sr/Ca ratios increase from ~1 mmol/mol to a maximum in excess of 2 mmol/mol (Davis et al., in press).

Between ~53 and 46 Ma, $\delta^{13}\text{C}_{\text{calcite}}$ values covary with $\delta^{18}\text{O}_{\text{calcite}}$ values in samples of the Main Body of the Green River Formation ($r^2=0.50$, $n=50$) (Fig. 3, DeCelles, 1994).

4.3. Late Middle Eocene

At ~46 Ma, roughly coeval with the onset of deposition of the Saline Facies of the Green River Formation, $^{87}\text{Sr}/^{86}\text{Sr}$ ratios decrease as suddenly as they increased, returning to values that are statistically indistinguishable from samples deposited prior to the Early Eocene (Fig. 2). The mean of ratios measured in samples of the Saline and Sandstone and Limestone Facies is 0.71002 ± 0.00016 ($n=13$). $^{87}\text{Sr}/^{86}\text{Sr}$ ratios remain low throughout the life of Lake Uinta.

The change in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios is not correlated with a sudden change in $\delta^{18}\text{O}_{\text{calcite}}$ values or Sr/Ca ratios, which instead continue to a maximum of ~30‰ and 5 mmol/mol, respectively, within the Saline Facies of the Green River Formation (Fig. 2; DeCelles, 1994). In the late Middle Eocene, $\delta^{18}\text{O}_{\text{calcite}}$ values and Sr/Ca ratios steadily decrease by 8‰ and ~3 mmol/mol, respectively (Fig. 2; DeCelles, 1994).

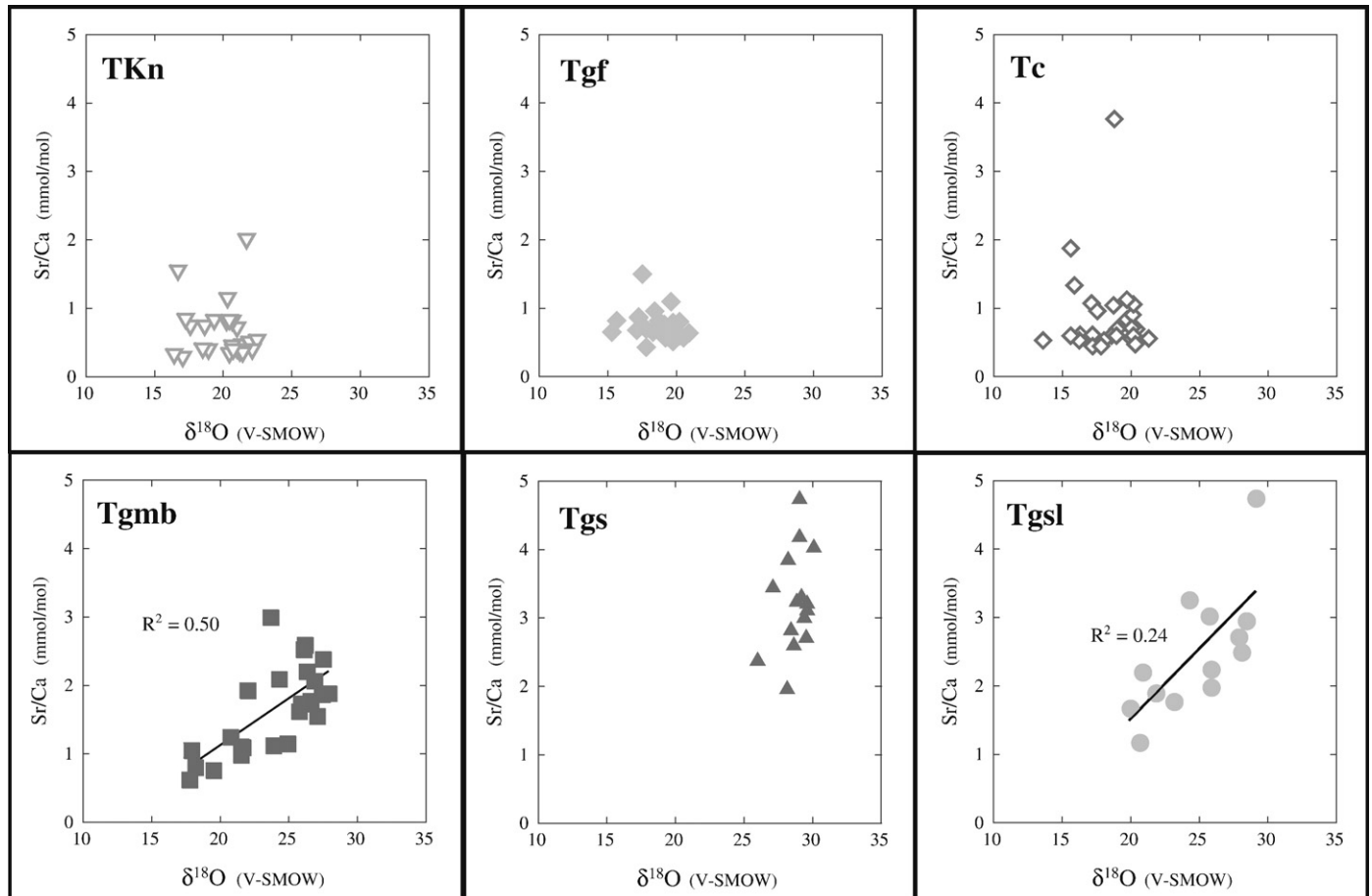


Fig. 4. Correlation of Sr/Ca ratios and $\delta^{18}\text{O}$ in fluvial and lacustrine carbonates (symbology identical to Fig. 2) of units sampled in the southwest Uinta Basin. Units are abbreviated as follows: TKn, North Horn Formation; Tgf, Flagstaff Member of the Green River Formation; Tc, Colton Formation; Tgmb, Main Body of the Green River Formation; Tgs, Saline Facies of the Green River Formation; Tgsl, Sandstone and Limestone Facies of the Green River Formation. Note that r^2 value shown for Tgsl excludes the outlying point.

Between ~46 and 44 Ma, $\delta^{13}\text{C}_{\text{calcite}}$ and $\delta^{18}\text{O}_{\text{calcite}}$ values in the Saline Facies, when examined as a single population, do not exhibit isotopic covariance ($r^2=0.08$, $n=35$), perhaps owing to small variation in either isotope systems. However, subsets of stratigraphically continuous Saline Facies samples do reveal a positive correlation of $\delta^{13}\text{C}_{\text{calcite}}$ and $\delta^{18}\text{O}_{\text{calcite}}$ over spans of ~600 kyr ($r^2=0.57$, $n=14$, 46.0 to 45.4 Ma) and ~200 kyr ($r^2=0.63$, $n=14$, 44.9 to 44.7 Ma) (Fig. 3). Similarly, isotopic covariance exists in only a subset of the oldest rocks from the Sandstone and Limestone Facies, representing approximately 400 kyr ($r^2=0.90$, $n=11$, 44.2 to 43.8 Ma) (Fig. 3, DeCelles, 1994).

5. Interpretation

5.1. Overview

We interpret the increase of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios as recording a period of large-scale drainage integration in the Cordillera between ~53 and 46 Ma, when substantial inflows to Lake Uinta were derived from Lake Gosiute to the north (Fig. 5, 48.6 Ma Panel). Our data coupled with those from other studies (Kent-Corson et al., 2006; Carroll et al., 2008) suggest that by ~49 Ma the drainage basin of Lake Uinta incorporated rivers draining the Challis Volcanic Field nearly 1000 km away in Idaho, with water flowing through Lake Gosiute into Lake Uinta. Lower $^{87}\text{Sr}/^{86}\text{Sr}$ ratios observed prior to 53 Ma and after 46 Ma represent times when little or none of the water entering Lake Uinta was sourced from the foreland north of the Uinta Uplift. Instead, catchments feeding Lake Uinta during these times drained areas in the hinterland to the west, as well as distal regions in the foreland to the

southeast, as well as adjacent Laramide block uplifts. Evidence for this interpretation is given below.

5.2. Evidence for drainage reorganization

Prior to ~53 Ma, the Uinta Basin was host to fluvial systems and a freshwater lake with major inflows entering from the southwest and the southeast (e.g., Dickinson et al., 1986; Lawton, 1986; Dickinson et al., 1988; Franczyk et al., 1991; Morris et al., 1991; Remy, 1992). This interpretation is further supported by the O, C, and Sr isotope data presented here (Fig. 2). Lack of covariance of C and O isotopes (Fig. 3), relatively low $\delta^{18}\text{O}_{\text{calcite}}$ values, and low Sr/Ca ratios prior to ~53 Ma all evidence a hydrologically open basin. Moreover, a recent study of coeval lacustrine carbonates in the Flagstaff Basin (~75 km southwest) found $^{87}\text{Sr}/^{86}\text{Sr}$ ratios statistically indistinguishable from our samples of the Flagstaff Member (mean of 0.709995 ± 0.000262 ; $n=38$, $p<0.05$), and concluded that the primary catchments feeding Lake Flagstaff at all times drained areas in the fold-thrust to the west (Gierlowski-Kordesch et al., 2008). The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of these rocks reflects (1) the dominant flux of dissolved Sr from Paleozoic and Mesozoic carbonates exposed in the fold-thrust belt (Blum et al., 1998; Jacobsen and Blum, 2000; Gierlowski-Kordesch et al., 2008) and (2) the fact that few Precambrian basement rocks, which might have imparted a more radiogenic signature, were ever exposed south of the Uinta Basin except for the Front Range, which lay more than 300 km to the southeast (Foster et al., 2006).

We interpret the increase in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in carbonate samples from Lake Uinta at ~53 Ma as the result of a large-scale reorganization

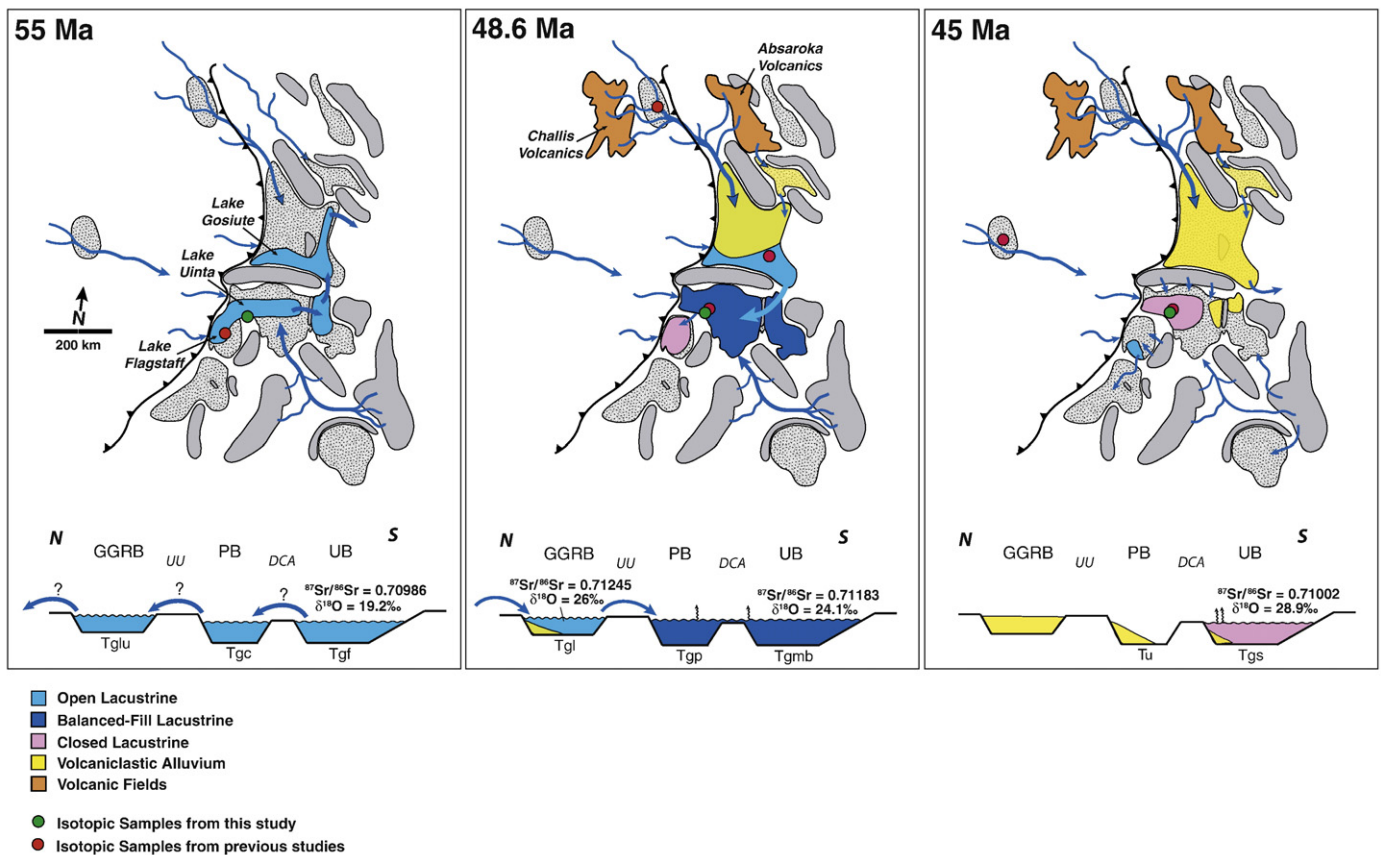


Fig. 5. Inferred development of foreland lakes and Cordilleran drainage patterns at three key times during the Paleogene (refer to Fig. 1 for names of major structures and basins). Schematized cross-sections at bottom of each panel show the hydrology and isotopic compositions of the Greater Green River Basin (GGRB), Piceance Creek Basin (PCB) and Uinta Basin (UB), as separated by sills of the Uinta Uplift (UU) and the Douglas Creek Arch (DCA). Members of the Green River Formation deposited in each basin are abbreviated as follows: Tglu, Luman Tongue; Tgc, Cow Ridge Member; Tgf, Flagstaff Member; Tgl, Laney Member; Tgp, Parachute Creek Member; Tgmb, Main Body; Tgs, Saline Facies. Tu denotes deposition of the Uinta Formation.

of the lake's drainage system with new and substantial inflows from Lake Gosiute and the catchments of the Greater Green River Basin that eventually extended into the Challis Volcanic Field at ~49 Ma (Kent-Corson et al., 2006; Carroll et al., 2008). Three lines of evidence support this interpretation. First, coeval lacustrine carbonates deposited in Lake Gosiute are themselves quite radiogenic. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of samples from the Laney Member of the Green River Formation (~50 Ma) in the Greater Green River Basin (~285 km from our sampled section over the Uinta Uplift) give a mean of 0.71245 ± 0.00014 ($n=22$, $p<0.05$) (Rhodes et al., 2002). The more radiogenic Sr isotope composition of these samples reflects the radiogenic composition of Sr in adjacent, craton-cored Laramide structures (e.g., cores of the Wind River, Granite, Owl Creek, Laramie and Sierra Madre Uplifts were exposed in the Eocene Carroll et al., 2006), where whole rock $^{87}\text{Sr}/^{86}\text{Sr}$ ratios can be in excess of 1.0 (Divis, 1977; Peterman and Hildreth, 1978; Zielinski et al., 1981; Mueller et al., 1985; Frost et al., 1998; Patel et al., 1999). Although the Uinta Uplift bounding the Uinta Basin to the north is also basement-cored, the east-trending axis of the range is beyond the southwestern margin of the Wyoming craton, so that basement rocks at the core of the Uinta Uplift are a mixture of sediments deposited during the Neoproterozoic accretion of terranes (Ball and Farmer, 1998; Condie et al., 2001; Nelson et al., 2002; Foster et al., 2006). The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of these sediments range from 0.774 to 0.793 (Crittenden and Peterman, 1975)—more radiogenic than the rocks of the fold-thrust belt and Tertiary volcanics, but not to the level of the craton-cored uplifts of Wyoming. If catchments draining the Uinta Uplift were responsible for the increase in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios at ~53 Ma, we would expect $^{87}\text{Sr}/^{86}\text{Sr}$ ratios to also be high during the later stages of Lake Uinta's lifespan, when braided streams flowing south from the Uinta Uplift deposited fluvial units along the northern margin of the lake (Anderson and Picard, 1972; Davis et al., in press). To the contrary, $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in lacustrine carbonates formed during that time (Sandstone and Limestone Facies of the Green River Formation) remain low and may even decline slightly over time.

Second, the increase in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios at ~53 Ma coincides with an increase in $\delta^{18}\text{O}_{\text{calcite}}$ values by ~6‰ between the Colton Formation and the Main Body Green River Formation. Prior to ~49 Ma, lacustrine carbonates of the lower LaCede Bed (Laney Member) of the Green River Formation of the Greater Green River Basin have a mean $\delta^{18}\text{O}_{\text{calcite}}$ value of 26‰ (Carroll et al., 2008). Following the shift in Sr isotope composition at ~53 Ma, the mean $\delta^{18}\text{O}_{\text{calcite}}$ value of coeval carbonates in the lower Main Body of the Uinta Basin's Green River Formation is similar: 24.9‰ ($1\sigma=3.5$, $n=47$). The contemporaneous expansion of Lake Uinta and increase in $\delta^{18}\text{O}_{\text{calcite}}$ values of the Uinta Basin to values that correspond with those of carbonates forming in Lake Gosiute reflects the isotopic influence of water from Lake Gosiute, where the water had previously been enriched by evaporation. After ~49 Ma, when — despite low- $\delta^{18}\text{O}$ waters sourced in the Challis and Absaroka Volcanic Fields flooding into Lake Gosiute at 48.9 Ma (Kent-Corson et al., 2006; Carroll et al., 2008) — mean $\delta^{18}\text{O}_{\text{calcite}}$ values of carbonate forming ~1000 km downstream at the Mahogany highstand of Lake Uinta increase ~2‰ further and variability decreases (mean=26.6‰, $1\sigma=1.1$, $n=14$).

Third, previous sedimentological studies have proposed a period of hydrologic linkage between the Greater Green River and Uinta Basins via the Piceance Creek Basin (Surdam and Stanley, 1980; Smith et al., 2008). Evidence for this linkage is found in: (1) the southward and interbasinal progradation of volcanoclastic sands from sources in the Absaroka and Challis Volcanic Fields into the Wind River, Greater Green River, Piceance Creek and then eastern Uinta Basins (Surdam and Stanley, 1980; Smith et al., 2008) and (2) the time equivalence of the Mahogany highstand in Lake Uinta at 48.6 Ma and a sequence boundary “fill-to-spill” surface in Lake Gosiute (Smith et al., 2008; Carroll et al., 2008).

At ~46 Ma, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of carbonate samples indicate that inflows from the Greater Green River Basin to Lake Uinta ceased,

resulting in contraction of the lake and intense evaporation of its waters. This interpretation is supported by the return of Sr isotopic values to values similar to those prior to ~53 Ma (Fig. 2), indicating a loss of inflows draining basement-cored uplift. Evidence for closure and intense evaporation is given by high and increasing O isotope values, high Sr/Ca ratios, covariation of C and O isotopes of carbonate [Figs. 2 and 3], and the presence of evaporite minerals (Dyoni et al., 1985).

Although we believe that the Sr isotope data provide the strongest evidence for large-scale drainage reorganization, we recognize that the isotopic shift could be due to other factors that can influence the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of lake water, in particular input of volcanic ash from distal eruptions or windblown carbonate. We do not think that either of these possible inputs significantly influenced the Sr isotopic results discussed here for the following two reasons. First, the Sr isotopic composition of possible sources for airfall ashes is too low to cause the positive Sr isotopic excursion at ~53 Ma. During the Early Eocene and early Middle Eocene, the Absaroka and Challis Volcanic Fields were emplaced in the northern Cordillera. However, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of Tertiary volcanics in the North American Cordillera nowhere exceed 0.709 (Peterman et al., 1970; Meen, 1987; Cunningham et al., 1998; Dostal et al., 2001; Vogel et al., 2001), and thus cannot explain the Early Eocene increase in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of Uinta Basin carbonates to >0.711.

Second, if windblown carbonate were the cause of the change in Sr isotope values at ~53 Ma, the amount of carbonate deposited from the air would have to change at this time, which is unlikely. Eolian inputs of carbonate would presumably have come from the same marine carbonates of Paleozoic or Mesozoic age that were exposed in the drainage basin of Lake Uinta (either in the fold-thrust belt to the west or on the flanks of nearby Laramide block uplifts). Increased input of windblown carbonate from such Paleozoic and Mesozoic limestones could not have caused the observed increase as seawater $^{87}\text{Sr}/^{86}\text{Sr}$ ratios have not exceeded 0.7096 during the Phanerozoic (Burke et al., 1982). It could also be argued that the increase in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios could result from a decrease in windblown carbonate at ~53 Ma. However, such a decrease is inconsistent with the roughly coeval decrease in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios observed in Lake Gosiute (Carroll et al., 2008), which would require an increase in windblown carbonate to that lake. This seems implausible.

6. Discussion

6.1. Tectonic controls on drainage reorganization

Stable isotopic results from intermontane basins within the Sevier hinterland and the Laramide intraforeland basins along its margin have recently been used to suggest a pattern of developing topography and drainage reorganization related to the sweep of magmatism from northeast to southwest through the western U.S. Cordillera (e.g., Davis et al., in press). Though coincident magmatism implies tectonic control of surficial processes, stable isotope data require only that hypsometric mean elevation of basin catchments increased. As such, permissible explanations include one or more of: (1) increasing mean elevations in the hinterland region (Horton et al., 2004), (2) expansion of basin catchments into areas previously at high-elevation (Carroll et al., 2008), and (3) the dissection of a low relief plateau (DeCelles, 2004) into a more rugged landscape of high peaks and deep valleys, but with mean elevation of the plateau remaining near the same or less (Kent-Corson et al., 2006; Davis et al., in press). We suggest that some combination of these topographic scenarios may have occurred and migrated south over time, beginning first in the area of British Columbia and Montana at ~49 Ma (Mulch et al., 2004; Kent-Corson et al., 2006; Mulch et al., 2007), later at ~40 Ma in northern Nevada and Utah (Horton et al., 2004; Mulch and Chamberlain, 2007), and by ~20 Ma in southern Nevada (Horton and Chamberlain, 2006). Accompanying the migration of altered

topography, drainages feeding Laramide basins were rearranged causing stable isotopic shifts that roughly coincide with isotopic shifts that are observed to the west within the Sevier hinterland (Davis et al., in press).

One of the most pronounced rearrangements has been observed in Lake Gosiute at 48.9 Ma, where $^{87}\text{Sr}/^{86}\text{Sr}$ ratios decreased from 0.71234 ± 0.00042 to 0.71163 ± 0.00026 ($p < 0.05$) while $\delta^{18}\text{O}_{\text{calcite}}$ values decreased by roughly 6‰ (Carroll et al., 2008). Based on this evidence and similar isotopic shifts observed in the Sage Creek Basin in the Sevier hinterland ~500 km northwest of Lake Gosiute (Kent-Corson et al., 2006), that study suggested that Lake Gosiute's hydrology was affected by stream capture of catchments draining the rising volcanic topography of the Challis Volcanic Field (~51–47 Ma (Fisher et al., 1992; Carroll et al., 2008)). Moreover, these isotopic shifts occurred quickly, in less than 200,000 yr (between 48.9 and 48.7 Ma) (Carroll et al., 2008).

Although our age constraints are not as tight, the Sr and O isotopic data from the Uinta Basin are consistent with this interpretation, and we now show that the integration of Cordilleran drainages occurred at a larger-scale in two stages: A hydrologic linkage between Lakes Gosiute and Uinta first existed beginning at ~53 Ma. With the rearrangement of catchments feeding Lake Gosiute at 48.9 Ma and until ~46 Ma, the Cordilleran drainage network extended from the Sage Creek Basin in Montana through Lake Gosiute and into Lake Uinta, nearly 1000 km.

Exactly what caused Lake Gosiute to first overflow into Lake Uinta at ~53 Ma and then cease at ~46 Ma is unknown. However, lake hydrology is a function of potential accommodation space and sediment/water input (Carroll and Bohacs, 1999), so that the overspilling of Lake Gosiute resulted from an excess of inputs relative to accommodation space in its basin. Prior to ~49 Ma, sedimentary facies successions in Lake Gosiute indicate cyclic fluctuation of lake levels, suggesting that outflows to Lake Uinta would have been periodic (Ball and Farmer, 1998). Periodic flows are consistent with the highly variable, and somewhat lower $\delta^{18}\text{O}_{\text{calcite}}$ values of samples in Lake Uinta between ~53 Ma and the Mahogany highstand at 48.6 Ma. However, the isotopic shifts observed in Lake Gosiute at 48.9 Ma coincide with a fill-to-spill surface marking a hydrologic transition of the lake to permanently overfilled as a result of drainage reorganization which captured water and sediment from new catchments draining the volcanic edifices to the north (Ball and Farmer, 1998). This hydrologic transition in Lake Gosiute is again consistent with the decreased variability of $\delta^{18}\text{O}_{\text{calcite}}$ values from Lake Uinta samples, though the observed decrease in $\delta^{18}\text{O}_{\text{calcite}}$ values of Lake Gosiute samples (Carroll et al., 2008) was apparently attenuated during its travel to the Uinta Basin. Such attenuation probably occurred as a result of direct evaporative enrichment of the water as well as by its mixing with saline waters of the still discrete lake in the Piceance Creek Basin.

The end of this interconnected drainage network we attribute to more proximal causes. Based on growth structures in synorogenic clastic sediments shed south off of the Uinta Uplift, Late Laramide tectonism was ongoing as late as ~40 Ma (Anderson and Picard, 1974). We thus favor an explanation whereby topographic growth of the Uinta Uplift diverted southerly outflows from the Greater Green River Basin at ~46 Ma. However, another possibility is that the infilling of the Piceance Creek Basin with sediments at ~46 Ma (Smith et al., 2008) led to rearrangement of drainage patterns such that waters flowing south from the Greater Green River Basin were no longer directed west across the Douglas Creek Arch. Careful isotopic study of Piceance Creek Basin carbonates might resolve this question.

6.2. Implications with regard to stable isotope paleoaltimetry studies

With the advent of stable isotope paleoaltimetry (Chamberlain and Poage, 2000; Garzzone et al., 2000; Rowley et al., 2001), it is now

possible to reconstruct the past topographic history of many mountain belts. These studies are based upon the premise that as an air mass rises over an orographic barrier the precipitation becomes progressively depleted in the heavy isotopes of O and H in a predictable fashion. While this method is effective in simple climatic regimes involving one air mass that intersects mountain ranges at high angles, it becomes increasingly difficult to apply such an approach to mountain belts with more complicated climate and drainage patterns.

Our study underscores some of these complications. By using both Sr and O isotopes, we recognize that the increase in $\delta^{18}\text{O}_{\text{calcite}}$ values of Lake Uinta carbonates records the isotopic influence of a large flux of water from Lake Gosiute, where the water had previously been enriched by evaporation. Even though the continuous overspilling of Lake Gosiute at ~49 Ma was prompted by capture of low- $\delta^{18}\text{O}$ waters sourced in the Challis and Absaroka Volcanic Fields (Kent-Corson et al., 2006; Carroll et al., 2008), the isotopic effect observed ~1000 km downstream in Lake Uinta was a modest increase in $\delta^{18}\text{O}_{\text{calcite}}$. If we relied only on the O isotope values of Lake Uinta, any interpretation concerning the changing hypsometry of the basin would have been incorrect. The O isotope data alone suggests that the basin became closed and strongly evaporative and/or the hypsometric mean elevation of basin catchments was reduced. However, the data presented here when placed in context of other studies (Kent-Corson et al., 2006; Carroll et al., 2008) suggest that the hypsometric mean elevation of Uinta Basin catchments increased at ~49 Ma, even during a time when O isotope values were increasing in the lake.

The results from this study suggest that determining of paleoelevation using isotopic lapse rates in complicated climatic and hydrologic settings will be, at best, difficult. That said, however, it is possible to understand how topography and drainage patterns evolve in response to tectonism by examining and comparing isotopic records of multiple basins spread over a large geographic region and using several isotopic proxies in well-dated sections.

7. Conclusions

Here we present geochemical data from carbonates formed in the southwestern Uinta Basin, Utah (Fig. 1) between the Late Cretaceous and late Middle Eocene. Sr isotope composition of lacustrine carbonates indicates a dramatic expansion of Lake Uinta's drainage basin (Fig. 5). We interpret the increase in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios to result from a sudden influx of water from Lake Gosiute in Wyoming via the Piceance Creek Basin of northwestern Colorado in two stages: Between ~53 and 49, prior to the Mahogany highstand, inflows were periodic and correlated with Gosiute's lake levels. Beginning at ~48.9, growing inflows to Lake Gosiute from the Challis and Absaroka Volcanic Fields led to continuous inflows to Lake Uinta and the Mahogany highstand at 48.6 Ma (Fig. 5; Horton et al., 2004). This first influx at ~53 Ma is marked by a significant and rapid increase in the O isotope record of the Uinta Basin by ~6‰ as the waters of Lake Uinta equilibrated isotopically with inflowing waters that had undergone evaporation in the Greater Green River and Piceance Creek Basins. Similarly, despite the low- ^{18}O waters flowing into Lake Gosiute at ~49 Ma (Poage and Chamberlain, 2001; Horton et al., 2004), the waters steadily spilling out into the Uinta Basin were enriched in transit by evaporation and mixing with saline waters of the Piceance Creek Basin so that mean $\delta^{18}\text{O}_{\text{calcite}}$ values of Lake Uinta samples increase by another ~2‰. The contribution of water from Lake Gosiute was suddenly and drastically curtailed at ~46 Ma, quickly leading to the contraction and intense evaporation of Lake Uinta while potential accommodation space outweighed the diminished sediment and water inflows (Carroll and Bohacs, 1999).

Results presented here support the thesis that basin development and lake hydrology in the Laramide foreland were characterized by large-scale changes in Cordilleran drainage patterns tapping distal source areas (DeCelles, 1994). Though drainage from the hinterland

seems to have been the dominant pattern for much of the Paleogene (Fouch et al., 1983; Gierlowski-Kordesch et al., 2008; Henry, 2008), tectonically mediated drainage rearrangements within the foreland in some cases profoundly influenced the developing Laramide basins and their O isotope records. Unrecognized, such drainage rearrangements might easily confound studies of isotope paleoaltimetry.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2008.08.009.

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