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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 $^{87}Sr/^{86}Sr$ 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-$\delta^{18}O$ 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.

1. Introduction

During the past decade, numerous stable isotopic studies have reconstructed the paleoaltimetry of mountain belts worldwide (Chamberlain and Poage, 2000; Garzione 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 Garzione 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 km^2) 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 km^2 (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 (Dyni 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 ($\delta^{18}O_{lw}$) 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 $\delta^{13}C$–$\delta^{18}O$ values and Sr/Ca ratios in carbonate samples. If evaporation is relatively high $\delta^{13}C$ and $\delta^{18}O$ values will covary because hydrologically closed lakes have long residence times allowing preferential outgassing of ^{12}C-rich CO_2 accompanied by evaporative enrichment of ^{18}O (Talbot and Kelts, 1990). Sr/Ca ratios will also be high in evaporative lakes as the partitioning of Sr between host water