Feast to famine: Sediment supply control on Laramide basin fill

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ABSTRACT
Erosion of Laramide-style uplifts in the western United States exerted an important first-order influence on Paleogene sedimentation by controlling sediment supply rates to adjacent closed basins. During the latest Cretaceous through Paleocene, these uplifts exposed thick intervals of mud-rich Upper Cretaceous foreland basin fill, which was quickly eroded and redeposited. Cretaceous sedimentary lithologies dominate Paleocene conglomerate clast compositions, and the volume of eroded foreland basin strata is approximately twice the volume of preserved Paleocene basin fill. As a result of this sediment oversupply, clastic alluvial and paludal facies dominate Paleocene strata, and are associated with relatively shallow and ephemeral freshwater lake facies. In contrast, large, long-lived, carbonate-producing lakes occupied several of the basins during the Eocene. Basement-derived clasts (granite, quartzite, and other metamorphic rocks) simultaneously became abundant in lower Eocene conglomerate. We propose that Eocene lakes developed primarily due to exposure of erosion-resistant lithologies within cores of Laramide uplifts. The resultant decrease in erosion rate starved adjacent basins of sediment, allowing the widespread and prolonged deposition of organic-rich lacustrine mudstone. These observations suggest that geomorphic evolution of the surrounding landscape should be considered as a potentially important influence on sedimentation in many other interior basins, in addition to more conventionally interpreted tectonic and climatic controls.

Keywords: Fort Union Formation, Green River Formation, Paleocene, Eocene, lacustrine.

INTRODUCTION
Deposition of geologically significant lake deposits is commonly assumed to be controlled by a combination of tectonic controls on basin accommodation and climatic controls on their hydrology (Carroll and Bohacs, 1999). However, geomorphic modification of the surrounding landscape has exerted an additional and well-documented control on sedimentation in many Quaternary lake basins (e.g., Bouchard et al., 1998; Waythomas, 2001). Lacustrine and other associated closed-basin deposits fundamentally represent the preserved downstream record of larger drainage systems, and thus it is likely that older lake deposits also contain a significant record of landscape evolution that has not yet been fully appreciated (e.g., Sáez et al., 1999; Pietras et al., 2003).

The nonmarine early Tertiary sedimentary basins east of the Cretaceous–Tertiary Sevier orogenic belt of the western U.S. are economically important for their resources of soda ash, oil shale, lignite, and natural gas (Dygi, 1996; Pitman et al., 1989; Flores et al., 1999). They also hold a unique archive of the coevolution of mammals and plant landscapes, and a record of an episode of dramatic global warming near the Paleocene-Eocene boundary (Koch et al., 1995). These basins occupy a segmented foreland, divided by a number of basement-cored Laramide uplifts (e.g., Dickinson et al., 1988). Laramide uplift began during the Maastrichtian and continued until the middle Eocene. Paleocene basin fills are typically dominated by relatively fine grained fluvial and flood-plain deposits (notably the Fort Union Formation), which include commercially important lignite deposits. Lake deposits are generally sand rich and represent relatively shallow freshwater systems (Yuretich, 1989). In contrast, large, long-lived, and often hypersaline lakes of the Green River Formation occurred in several basins during the early to middle Eocene (Johnson, 1985; Roehlher, 1992).

A potential explanation for the fundamentally different character of Paleocene versus Eocene basin fill is in the heterogeneous pre-Laramide geology of the Cretaceous foreland basin and its substrate. Precambrian crystalline and metasedimentary rocks exposed in the core of various Laramide uplifts are relatively resistant to erosion, as are a number of late Paleozoic to early Mesozoic carbonate and well-cemented eolian sandstone units. In contrast, Cretaceous foreland basin fill consists largely of mudstone and poorly cemented sandstone lithologies that are much more likely to generate fine-grained sediment (Graham et al., 1986; DeCelles et al., 1991). In this study we examine the hypothesis that changes in sediment supply due to progressive erosion (unroofing) of Laramide uplifts exerted a first-order control on the nature of Paleogene sedimentation in adjacent basins.

UNROOFING HISTORY OF LARAMIDE UPLIFTS
Compositions of conglomerate clasts derived from basement-cored uplifts have been reported in many previous studies (summarized in Fig. 1; references for each locality can be found in the GSA Data Repository1). Clast types have been categorized as Precambrian, Paleozoic, or Mesozoic. Precambrian clasts typically include igneous and metamorphic lithologies, such as granite, gneiss, schist, and quartzite. Paleozoic clasts are derived from lower to middle Paleozoic shallow-marine sandstone and carbonates, and upper Paleozoic carbonates, red beds, and eolian sandstone (Dickinson, 1992). Mesozoic strata in this area are dominated by Upper Cretaceous foreland basin deposits, which consist largely of shallow-marine mudrock and subordinate sandstone (DeCelles, 2004). Major conglomerate units occur near the thrust front (e.g., Lawton, 1986), but are rare farther east. Other Mesozoic strata

1GSA Data Repository item 2006037, Table DR1 and references for localities, is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.
Eocene sites. Paleozoic clasts are present at an additional six sites, glomerate, Precambrian clasts are present at 10 of 18 summarized early formation of the Paleozoic Ancestral Rocky Mountains (Tweto, 1980).

At seven additional sites Paleozoic clasts are the oldest present. All 23 localities are summarized at bottom of figure, in order of oldest clast type present in Paleocene conglomerate. References for each locality can be found in the Data Repository (see footnote 1).

The oldest clast types at 6 of the 20 summarized Paleocene conglomerate sites were derived from Mesozoic sources. The most common Mesozoic clast lithologies are sandstone and chert, with subordinate limestone and mudstone. Due to its durability, chert is an important constituent of Mesozoic-derived conglomerate. However, chert is a problematic indicator of the level of unroofing because it is common in both Paleozoic and Mesozoic strata, and has a high potential for recycling (Graham et al., 1986). Therefore, determinations of the depth of unroofing were not based on the presence of chert alone, but instead are based on interpretation of broader clast assemblages.

At seven additional sites Paleozoic clasts are the oldest present. Precambrian clasts appear at only seven of the summarized sites, and typically are associated with structural culminations in adjacent uplifts. Precambrian clasts occur in conglomerate derived from the southern Wind River uplift, possibly because this area is on trend with a regional N-S structure represented by the Douglas Creek arch and the Rock Springs uplift. Quartzite clasts in the western Uinta Basin are derived from a structural culmination within the Sevier thrust belt. At two other sites (19 and 23; Fig. 1), granitic clasts record the Paleocene exhumation of the Paleozoic Ancestral Rocky Mountains (Tweto, 1980).

In contrast to the prevalence of Mesozoic clasts in Paleocene conglomerate, Precambrian clasts are present at 10 of 18 summarized early Eocene sites. Paleozoic clasts are present at an additional six sites, indicating that Mesozoic cover had been breached on a majority of uplifts by this time (three of these six sites are adjacent to the Sevier thrust belt). Pre-Mesozoic clasts are absent at only one site adjacent to the structural low point of the adjacent uplift. The central Uinta Mountains were producing quartzite clasts in the early Eocene, but Precambrian rocks had not yet been exposed in lower areas of the range to the west. Similarly, Mesozoic clasts were being shed from low-lying areas of the Bighorn Mountains at the same time that Precambrian rocks were exposed at their crest. Several other Laramide-style uplifts, such as the Rock Springs and Douglas Creek arches, have never eroded down through their Cretaceous cover or shed significant conglomerates.

**VOLUMETRIC ESTIMATION OF PALEOCENE EROSION VS. DEPOSITION**

To estimate the impact that erosional stripping of foreland basin strata from the tops of Laramide uplifts had on sediment supply to adjacent basins, we calculated the volume of eroded Mesozoic rocks based on previously published isopach maps and the present areas of pre-Mesozoic exposure. We also compiled a new regional isopach map of Paleocene basin fill, using completion reports from 1252 subsurface wells; thicknesses at basin boundaries were adjusted to account for known fault relationships with basin fill (Fig. 2).

Based on its present erosional limits, the volume of Cretaceous cover that has been removed from uplifts is approximately twice the preserved volume of Paleocene basin fill (Table 1). This ratio increases to approximately three if Triassic and Jurassic strata are also considered. These ratios likely overestimate actual sediment yield from Mesozoic sources because some of the eroded strata were removed after the Paleocene. We assumed that the original thickness of Cretaceous and older rocks remains intact up to its present erosional limit, which underestimates the actual eroded volume. Other sources of potential error come from assumptions regarding the original thickness of eroded Mesozoic rocks, timing of uplift and erosion, removal of Paleocene rocks by later erosion, and possible underreporting of Paleocene sedimentary volume in small but deep basins (such as the Hanna Basin; Fig. 1).

The foregoing analysis disregards potential changes in sediment flux from the Sevier thrust belt into Laramide basins. Rocks in the thrust belt contributed sediment to immediately adjacent areas, but sediment dispersal and provenance studies indicate that erosion of Laramide uplifts was the principal source of sediment elsewhere (Dickinson et al., 1988; DeCelles, 2004). Furthermore, there is no evidence for any systematic change in regional-scale sediment flux from the Sevier belt between the Paleocene and Eocene; DeCelles (2004) argued that shortening was generally continuous and progressive from west to east within the combined Sevier-Laramide system throughout that time.

We have also neglected the volume of material that was shed from the eastern extremity of Laramide uplifts and transported either into perimeter basins such as the Denver Basin (Dickinson et al., 1988) or into the Gulf of Mexico.

**DISCUSSION AND CONCLUSIONS**

Although the detailed temporal patterns of erosion within the Laramide foreland are complex, clast compositions in Laramide basins show that widespread exposure of erosion-resistant rocks (Precambrian or Paleozoic) in basement-cored uplifts first occurred during the early Eocene. Prior to that time, Cretaceous and other Mesozoic units that originally mantled the uplifts constituted the primary source of source of basin fill. The volume of Mesozoic rocks removed from the uplifts is subject to various uncertainties, but it clearly exceeded the preserved volume of Paleocene nonmarine strata. Laramide basins therefore were oversupplied with sediment during the Paleocene, resulting in predominantly siliciclastic deposition and alluvial to paludal sedimentary facies.
Eocene basin starvation cannot be as easily tested using a volume-balance approach. However, erosion experiments and studies of modern erosion rates for different lithologies provide an alternative means to evaluate how sediment supply rates may have changed during the Eocene. For example, Sklar and Dietrich (2001) reported experimental data showing that mudstone, and some sandstone, abrades at rates as much as two to three orders of magnitude faster than granite or quartzite. Taking a different approach, Schaller et al. (2001) showed that erosion rates for sedimentary rocks can be as much as four times those for crystalline rocks, based on 10 Be in bedload in the Neckar and Regen Rivers in central Europe. Gauging records of sediment load in the same rivers show a similar relationship. Many other factors also influence these rates, such as sediment mantling of channels and erosion of hillslopes by debris flows (e.g., Stock et al., 2005). However, it is reasonable to expect that Cretaceous and other Mesozoic strata eroded much more quickly than the more resistant underlying lithologies, and therefore that regional sediment supply rates dropped dramatically during the Eocene.

We propose that the expansion of the Green River Formation lakes during the Eocene occurred principally due to reduction of clastic sediment supply, resulting from exposure of erosion resistant lithologies in surrounding uplifts. These lakes, which occupied the Uinta, Piceance Creek, and greater Green River Basins, persisted for at least 5 m.y. (Smith et al., 2003), during which time extensive organic-rich carbonate mudstone (oil shale) and nonmarine evaporite were deposited. Surviving remnants of middle Eocene strata suggest that major lakes occupied the Bighorn and Wind River Basins (Bay, 1969; Boles and Surdam, 1979; Bown, 1982). The eventual infill of several of these basins resulted not from erosion of the rocky uplifts dividing them, but from an influx of juvenile volcaniclastic sediments from the Absaroka Volcanic Province or other sources (Surdam and Stanley, 1980; Groll and Steidtmann, 1987; Buchheim et al., 2000).

In addition to the major changes noted here, many local shifts between alluvial and lacustrine sedimentation were also influenced by changes in sediment supply rate, the precise timing of which may deviate from regional trends. Local patterns and timing of basin accommodation might also influence the predominant style of sedimentation; for example, several smaller basins (Hanna, North Park, Laramie) have thin alluvial Eocene sections or lack Eocene strata (Lillegraven, 1993). Additional higher-resolution studies are therefore needed to fully explore these possibilities and to better understand the relationships between bedrock exposure and basin fill.

This study highlights the first-order control that sediment supply can exert on lake basin evolution, and the potential for sediment supply rates to change independently of paleoclimatic or paleotectonic events. Foreland deformation is commonly preceded by the deposition of relatively fine grained, easily erodable sediments in the foredeep. The rapid unroofing of such deposits from the tops of incipient foreland uplifts may therefore be a common feature of the early history of segmented foreland basins, delaying the development of major lake systems in such settings. The results of this study suggest that lake de-
posits in general may be more sensitive to the geomorphic evolution of the surrounding landscape than previously suspected.

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