Jason A. Lillegraven and
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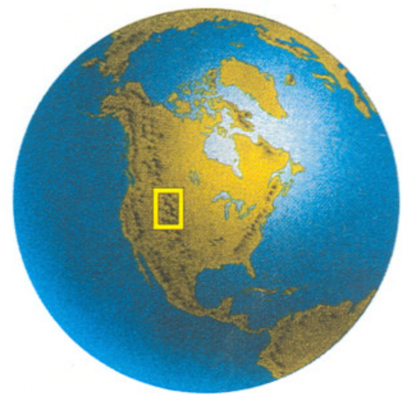
Evolution of Wyoming's Early Cenozoic Topography and Drainage Patterns



A series of nine pairs of paleogeographic maps of the state of Wyoming that begins in the Late Cretaceous and ends in the early Oligocene is presented. One map of each pair indicates relative topography, including inferred fluvial/lacustrine drainage patterns, and is shown in a perspective view; its complement indicates probable limits of hydrographic basins for each of the major river systems and is shown planimetrically. Drainage patterns and areas of hydrographic basins changed profoundly through the 30-million-year interval in sequential (and partly overlapping) response to: Laramide tectonic events; Absaroka–Gallatin–Challis volcanism; major erosion; and massive, distant volcanism. The area of a hydrographic basin affects, or is related to, virtually all hydrologic and geomorphologic processes that occur within the watershed. In turn, these watershed characteristics directly and importantly influence biotic factors and the accumulation of economically important minerals. Thus reconstructions of paleolandscapes and ancient drainage patterns have implications for the study of the evolution of life, in addition to their economic applications.

Wyoming's Paleogene (Paleocene through Oligocene) topographic evolution was dramatic and complex. Major changes were wrought by the successive (and partly overlapping; Figures 1 & 2) influences of Laramide tectonism, Absaroka–Gallatin–Challis volcanism, widespread erosion, and massive influxes of volcaniclastic debris from regions outside the state. The resulting fluvial and lacustrine drainage patterns reflect this topographic evolutionary sequence. These patterns of drainage, in turn, allow recognition of regional uplifts that previously were not discerned from more detailed, geographically localized investigations. Previous reconstructions of Wyoming paleolandscapes and drainage patterns have tended to focus on rather limited geographic areas and temporal intervals.

The series of nine reconstructions for Wyoming presented here begins with the latest Cretaceous and ends with the early Oligocene (Figure 1; see Berggren et al. 1985). A three-dimensional, topographic perspective map (views are due north, as seen from 25° above the horizon, with sun azimuth at 290° set 15° above the horizon) plus a fluvial pattern map (planimetric view, emphasizing major drainage-divides) were prepared for each of nine intervals. The perspective maps include considerable vertical exaggeration (probably about sixfold); an exact value cannot be established because only relative, not absolute, elevations can be surmised for the paleolandscapes. Differences in relief (associated

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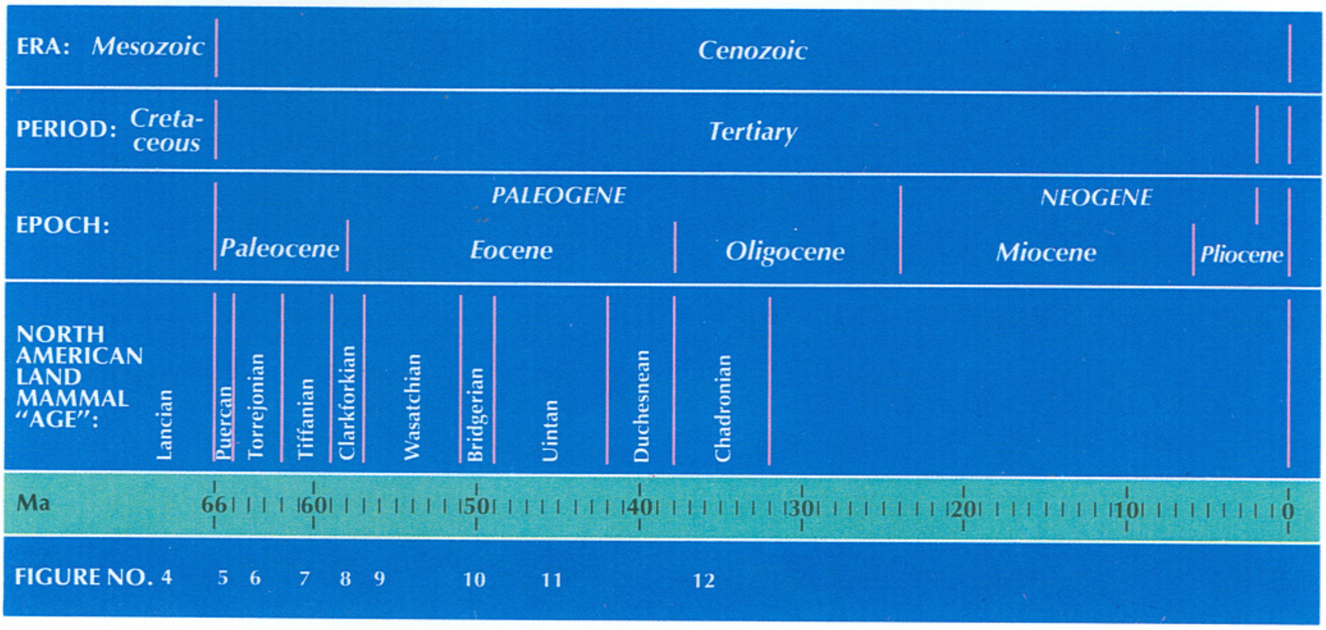


Figure 1. Geological time scale (calibrations are approximated from Berggren et al. 1985 and Flynn 1986). The positions of the figure numbers relative to the time scale indicate the approximate temporal settings of the paleogeographic maps.

with color changes) are intended to show relative degrees of elevation of the various uplifts, basins, and alluvial plains for each reconstruction. The maps suggest relative amounts of uplift and erosion, but as currently conceived cannot indicate the amount of basin subsidence, an important element of Laramide-style deformation in Wyoming during the Late Cretaceous and early Paleogene (Hagen et al. 1985). Also, although crustal shortening across Wyoming during Laramide deformation was significant (Gries 1983), uncertainties of magnitude for specific areas are great; thus shortening was not included in these reconstructions. The data upon which the maps are based are derived from hundreds of published references, only the most pertinent of which are cited.

The study is restricted to Wyoming plus small parts of adjacent Montana, Idaho, and Utah, even though the geological events of Wyoming are not fully representative of the Paleogene for the whole Rocky Mountain region. Nevertheless, the latest Cretaceous through the early Oligocene is better known overall in Wyoming than in neighboring states, and development during this time directly impinges upon interpretations of regional geological development. A stratigraphic record for the latest Eocene ("Duchesnean") of Wyoming is virtually nonexistent (Savage & Russell 1983), so no maps are presented for that interval. The sequence of reconstructions ends at the early Oligocene because much of the subsequent stratigraphic record has been removed by the present cycle of erosion. Wyoming's later Oligocene through Pliocene can better be determined indirectly by studying surrounding areas.

Most Paleogene fluvial systems leaving Wyoming flowed across what is now the Great Plains. The Paleogene sedimentary record of the Plains states is so incomplete, however, that knowledge of their ancient drainage patterns is equivocal at best. Thus no attempt was made to determine the fate of Paleogene watercourses once they left Wyoming.

Because available radioisotopic dates are few and widely scattered, mammalian paleontology has been used to provide relative dates of nonmarine Paleogene strata in the Rocky Mountain region. Thus terms (Figure 1) of the provincial "North American Land Mammal 'Ages'" (Lillegraven & McKenna 1986, Wood et al. 1941, Woodburne in press) are used for the latest Mesozoic and Cenozoic. These local (North American) terms are preferred because they allow biochronological refine-

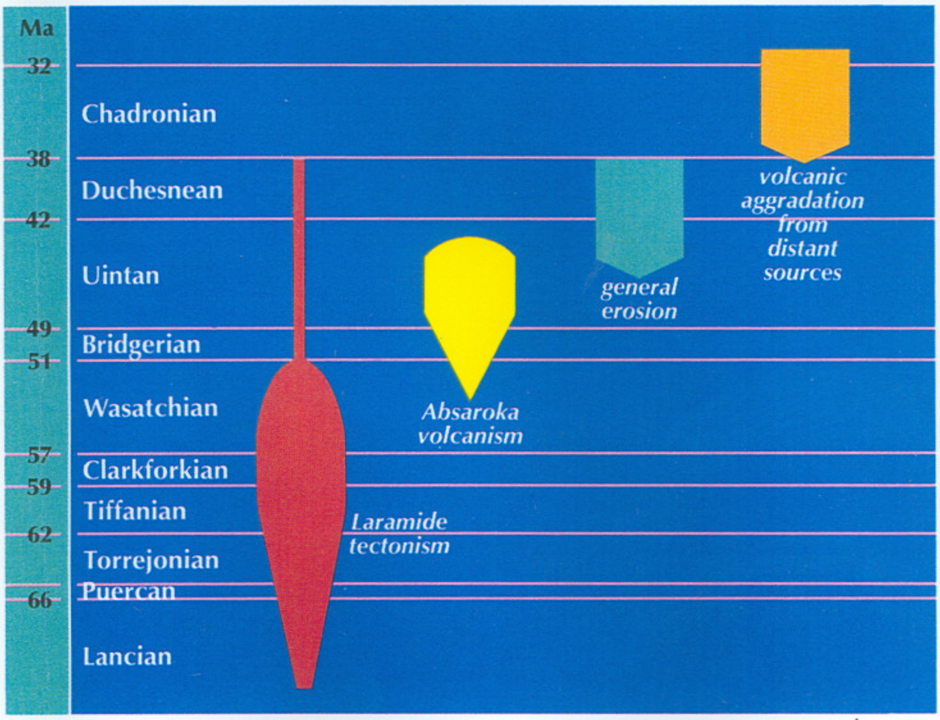


Figure 2. Relative timing of major geological events that influenced Wyoming during latest Cretaceous and Paleogene times. Widths of the balloons suggest relative magnitudes of activity through time (within Wyoming only). Aggradation of distantly derived volcaniclastic sediments continued well into the Miocene.

ment, in contrast to uncertainties associated with correlation of epochal (i.e., Paleocene through Oligocene) boundaries in North America to their areas of original definition in dominantly marine strata of Europe.

Wyoming today (Love & Christiansen 1985) is a high, semiarid plateau (mean elevation, 1975 m, with two thirds of its area within 507 m of that value). But it is a plateau complicated by a series of mountains, generally northwest-trending, separated by broad, sparsely vegetated basins (Figure 3). Most of the state's primary physiographic features were in place by the Clarkforkian (latest Paleocene–earliest Eocene). Thus Wyoming's present physiography is in large part relict from the late Eocene, and was preserved until quite recently by extensive Oligo–Miocene infillings of the state's basins with debris from distant volcanic sources. Evidence from western Nebraska (Swinehart et al. 1985) suggests that the present cycle of erosion in Wyoming and in the adjacent High Plains began sometime during the latter half of the Miocene. The relatively less resistant Oligo–Miocene volcaniclastic debris was largely scoured from Wyoming's basins, exhuming the more resistant rocks of the mountains which defined the Eocene landscape.

Methods

The technical procedures used to develop the following paleogeographic reconstructions are new. All programs used were created by Ostresh and are summarized in Table 1. Computations were performed on a Control Data Corporation Cyber 760 at the University of Wyoming. The figures were created on 35-mm color slides by the University of Wyoming's III FR80/A Computer Output to Microfilm recorder (COM).

RASTER is the name of the program that communicates with the COM, via an intermediary set of driver routines developed by James Kirkpatrick (University of Wyoming Computer Services). RASTER requires three types of input: a matrix of elevations; a co-registered matrix of color indices; and a set of control commands that provides informa-

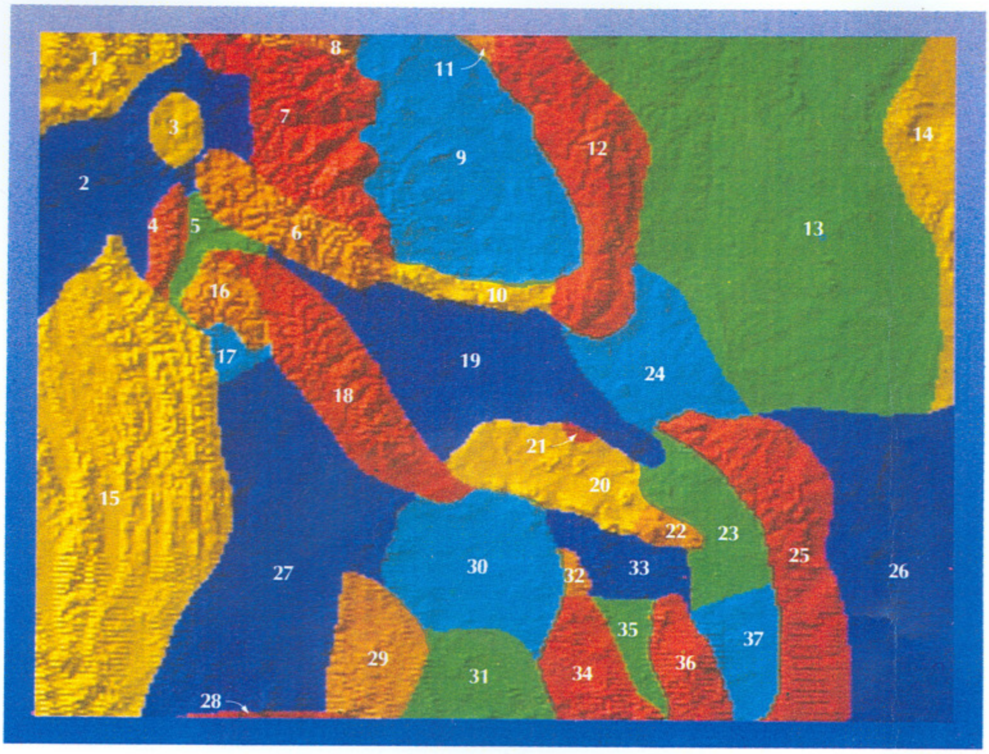


Figure **3.** *Dominant physiographic features of the study area (names from* Webster's New Geographical Dictionary *[1984] and U. S. Geological Survey,* Geographic Names Information System, State of Wyoming *[1981]):* **1,** *complex mountainous terrain of southwestern Montana;* **2,** *combination of Snake River Plain, Teton Basin (Pierre's Hole), and Yellowstone National Park;* **3,** *Basin Creek Uplift;* **4,** *Teton Range;* **5,** *Jackson Hole;* **6,** *Washakie Range (largely buried by Absaroka volcanic sequences);* **7,** *Absaroka Range;* **8,** *Beartooth Mountains;* **9,** *Bighorn Basin;* **10,** *Owl Creek Mountains;* **11,** *Pryor Mountains;* **12,** *Bighorn Mountains;* **13,** *Powder River Basin;* **14,** *Black Hills;* **15,** *Wyoming–Idaho Overthrust Belt;* **16,** *Gros Ventre Range;* **17,** *Hoback Basin;* **18,** *Wind River Range;* **19,** *Wind River Basin;* **20,** *Granite Mountains (Sweetwater Arch or Uplift);* **21,** *Rattlesnake Hills volcanic field;* **22,** *Shirley and Freezeout Mountains;* **23,** *Shirley Basin and Bates Hole;* **24,** *Casper Arch;* **25,** *Laramie Mountains;* **26,** *Hartville Uplift, Goshen Hole, and Denver–Julesburg Basin;* **27,** *Green River Basin proper and Bridger Basin;* **28,** *Uinta Mountains;* **29,** *Rock Springs Uplift;* **30,** *Great Divide (Red Desert) Basin and Bison Basin;* **31,** *Wamsutter Arch and Washakie Basin;* **32,** *Rawlins Uplift;* **33,** *Hanna Basin and Carbon Basin;* **34,** *Sierra Madre;* **35,** *Saratoga Basin;* **36,** *Medicine Bow Mountains (including Snowy Range);* **37,** *Laramie Basin.*

tion such as title, vertical exaggeration, and viewer and sun positions relative to the landscape. The matrix of elevations is a series of numerical values organized as a matrix whose row and column indices represent the northings and eastings (or in some cases, latitudes and longitudes) of a given elevation. The matrix of color indices defines special toning rules for each of the elevations: an index of 0 means that RASTER's default color scheme applies, forming shades of green in the lowlands, yellows and oranges in the uplands; an index of 1 paints an elevation blue to represent lakes or streams. For the perspective views, these two indices sufficed, but for the planimetric views as many as six color indices were used. Color indices affect hue (red, green, yellow, etc.) and saturation (vividness) of the colors; lightness is computed within RASTER as a function of the sun's angle plus surface slope and aspect, using an equation derived from Lambert's law (Newman & Sproull 1979).

Creation of the paleogeographic reconstructions began with sketches of major topographic contour lines plus a superposed drainage network, both developed by Lillegraven by interpretation from best available geological information. These drawings were digitized, using a graphic input program called GRFNPUT, and modified with a graphic editing program called GRFEDIT. At this initial stage, the digitized topographic contours consisted of polylines (ordered sequences of X,Y coordinates), plus an elevation associated with each contour. The digitized and co-registered drainage network consisted only of polylines. For some of the figures, lake boundaries also were digitized as polylines.

Seven programs were used to create and modify matrices of elevation and color indices from the polyline data. CON2MAT first converted the contour polylines and elevations into a co-registered matrix of elevations. The matrix was then smoothed by the program called SMOOTHE which, at each iteration, replaces each elevation by a weighted average of itself and its surrounding eight elevations. SMOOTHE was iterated 10 times to produce a "structure matrix" of elevations.

To simulate texture to an otherwise smooth landscape surface, each

Table 1. Programs Used to Create the Figures (listed in order of occurrence in the text)

RASTER

Input:
Matrix of elevations.
Matrix of color indices (optional).
Control commands.

Output:
Perspective views of the matrix of elevations, reproduced as 35-mm color slides.

Remarks:
The program divides the slide into 1000 scan lines with 1500 pixels per scan line. It features hidden surface elimination, Gouraud color smoothings, and a shading model based upon Lambert's law (Newman & Sproull 1979). The viewer and sun positions, vertical exaggeration, and several other parameters can be controlled by the user. In the absence of a matrix of color indices, the surface hue is a function of elevation. Can handle input matrices of as many as 1000 rows and 1000 columns.

GRFNPUT

Input:
Initializing control coordinates.
Individual points or streams of points from a digitizing pad.

Output:
X,Y coordinates of points or streams of points in a coordinate system of the user's choice, as defined by initializing controls.

Remarks:
Initializing control coordinates make the digitizing process "relocatable"; i.e., one can tape down a drawing, digitize parts of it, remove it from the digitizing pad, tape it down again in a subsequent session in a different position and orientation, then continue to digitize the drawing; the first and second parts digitized will co-register.

GRFEDIT

Input:
A set of polylines or polygons.
User editing commands.

Output:
An edited set of polylines or polygons.

Remarks:
This is an interactive graphics editor currently implemented on a Tektronix 4207 color graphics terminal, which uses routines in the Tektronix IGL Plot 10 Interactive Graphics Library. The input data are first displayed on the screen, then the user can zoom and pan to particular locations for editing. The editing commands include changing the location of a point, inserting and deleting points, and dumping selected polylines or polygons to an output file.

CON2MAT

Input:
Contour elevation and polylines.

Output:
Matrix of elevations of as many as 300 rows and 300 columns, specified by user.

SMOOTHE

Input:
Matrix of elevations.

Output:
Smoothed matrix of elevations.

Remarks:
The number of smoothing iterations is controllable by the user. Each iteration replaces each input elevation by the weighted average of itself and as many as eight adjacent elevations.

FRACTAL

Input:
A random number generator seed.
A fractal dimension.

Output:
A 257-row by 257-column matrix of elevations.

Remarks:
The fractal dimension varies between 2.0 and 3.0. A dimension of 2.0 gives a smooth surface, while a dimension of 3.0 produces a chaotic, essentially random matrix of elevations. The authors used a value of 2.7.

BLEND

Input:
Two or more matrices of same order.
User-supplied computer code that defines the way the two matrices are to be combined, element by element.

Output:
A new matrix of the same order as the input matrices, each element of which is a combination of the input matrices, following computational rules specified by user.

LIN2MAT

Input:
A set of polylines.
An associated set of color indices or values (optional).

Output:
A matrix of as many as 300 rows and 300 columns, as specified by user. If no indices or values are supplied, matrix has a value of 0 except in positions crossed by polylines, where it has a value of 1. Otherwise, it has a user-supplied background value except in positions crossed by polylines, where it has the polyline index or value.

LIN2POL

Input:
A set of polylines.

Output:
A set of closed, coherent polygons ("closed" means that the first point and the last point are the same; "coherent" means that the boundary of the polygon does not cross itself or any other polygon or polyline).

POL2MAT

Input:
A set of closed, coherent polygons.
An associated set of color indices or values (optional).

Output:
A matrix of as many as 300 rows by 300 columns, as specified by the user. Locations inside or on the border of the polygon have the value 1 (or the index or value of the polygon, if this is supplied). Other locations have the value 0 (or a user-supplied background value).

AREA

Input:
A set of closed, coherent polygons.

Output:
The area of each polygon.

structure matrix was "crumpled" slightly by blending it with a fractal (Mandelbrot 1983) matrix of elevations. The fractal program itself (called FRACTAL) is a generalization of a routine by Dewdney (1986). The blending in effect superimposes a fractal zone upon the structure matrix; the blended elevation will be somewhere between the original structure elevation and a certain percentage (the authors used 50%) of that elevation, depending upon the value of the fractal elevation.

The polylines for drainage patterns were input to the program called LIN2MAT to create a 1/0 matrix indicating the presence or absence of rivers and streams. Lake polylines were converted into lake polygons by the program LIN2POL, then these polygons were input to the program POL2MAT to create a 1/0 matrix indicating the presence or absence of lakes. BLEND then lowered the elevations (by 30.5 m) at locations where rivers and lakes were present. The lake 1/0 matrix was also input to RASTER as a color index matrix to paint the lakes blue. In constructing lake polygons from polylines, LIN2POL simply ensured that the beginning and ending points of polygons forming the lake boundaries were the same. More generally, LIN2POL is a program that creates a set of closed polygons from any set of intersecting polylines. Here it was used to create color index polygons for Figure 3 and for the planimetric views of the hydrographic basins. These polygons were then input to POL2MAT to create color index matrices for processing by RASTER.

An additional program (called AREA) was used to compute the areas of drainage basins (Table 1). The algorithm is derived from Simpson's rule (ITTC 1963), and consists of taking the absolute value of the sum of the following terms for I = 2,N:

$$0.5 \cdot [Y(I) + Y(I-1)] \cdot [X(I) - X(I-1)]$$

where X(I),Y(I) is the coordinate of the Ith point of N in the perimeter.

Paleogeographic Reconstructions

Late Lancian (Latest Cretaceous) (Figure 4)

Through most of the 31-million-year history of the Late Cretaceous, Wyoming repeatedly was transgressed and regressed by the western shoreline of a generally shallow epicontinental sea that extended from the Arctic Sea to the Gulf of Mexico. The body of water is known most commonly as the Western Interior Cretaceous Seaway. Throughout most of the Late Cretaceous, emergent parts of Wyoming formed part of a vast, heavily vegetated coastal plain that separated the western shoreline from zones of major deformation and volcanism farther to the west (McGookey et al. 1972). Great volumes of erosional debris were carried eastward from the uplands by major rivers, and deposited on the subsiding coastal plains and in shallow seas. Also, huge volumes of volcanic ash periodically settled on the terrestrial and marine landscape.

The latest Cretaceous (Lancian) was a time of withdrawal of the epeiric sea from the North American western interior. In spite of significant local uplifts subject to subaerial erosion that existed across various parts of Wyoming prior to the Lancian, the major events of the generally eastwardly migrating Laramide orogeny (Hamilton 1981) did not reach Wyoming until about that time. Several of the modern mountain ranges and their intervening, subsiding basins (Figure 3) first became defined during the Lancian. Included within these are the Granite Mountains (Love 1970), Wind River Range (Steidtmann et al. 1986), Gros Ventre Range (Dorr et al. 1977), Washakie Range (Love 1973), Uinta Uplift (Bruhn et al. 1986, W. Hansen 1984), greater Green River Basin, and Wind River Basin (Keefer 1965, 1970). More localized uplifts included parts of the Medicine Bow Range (Blackstone 1975, 1983) and probably the Beartooth Uplift. All of these tectonic elements, however, had ill-defined borders during the Lancian, and were expressed as elongated, somewhat asymmetric dome-like structures. No evidence indicates the existence during Lancian time of the Owl Creek, Bighorn, Sierra Madre, Laramie, or Black Hills uplifts.

The southwest corner of Wyoming experienced active, mostly west-to-east thrusting during the Lancian, with synorogenic deposition of debris eroded from the various thrust sheets (Kraig et al. 1987, Lamerson 1982, Oriel & Tracey 1970, Royse et al. 1975). The authors' reconstructions of the Wyoming Overthrust Belt (Figures 4–9), though developed from Wiltschko & Dorr's (1983) models, are generalized, designed merely to suggest broad evolutionary patterns.

The northwest corner of Wyoming was buried by vast packages of

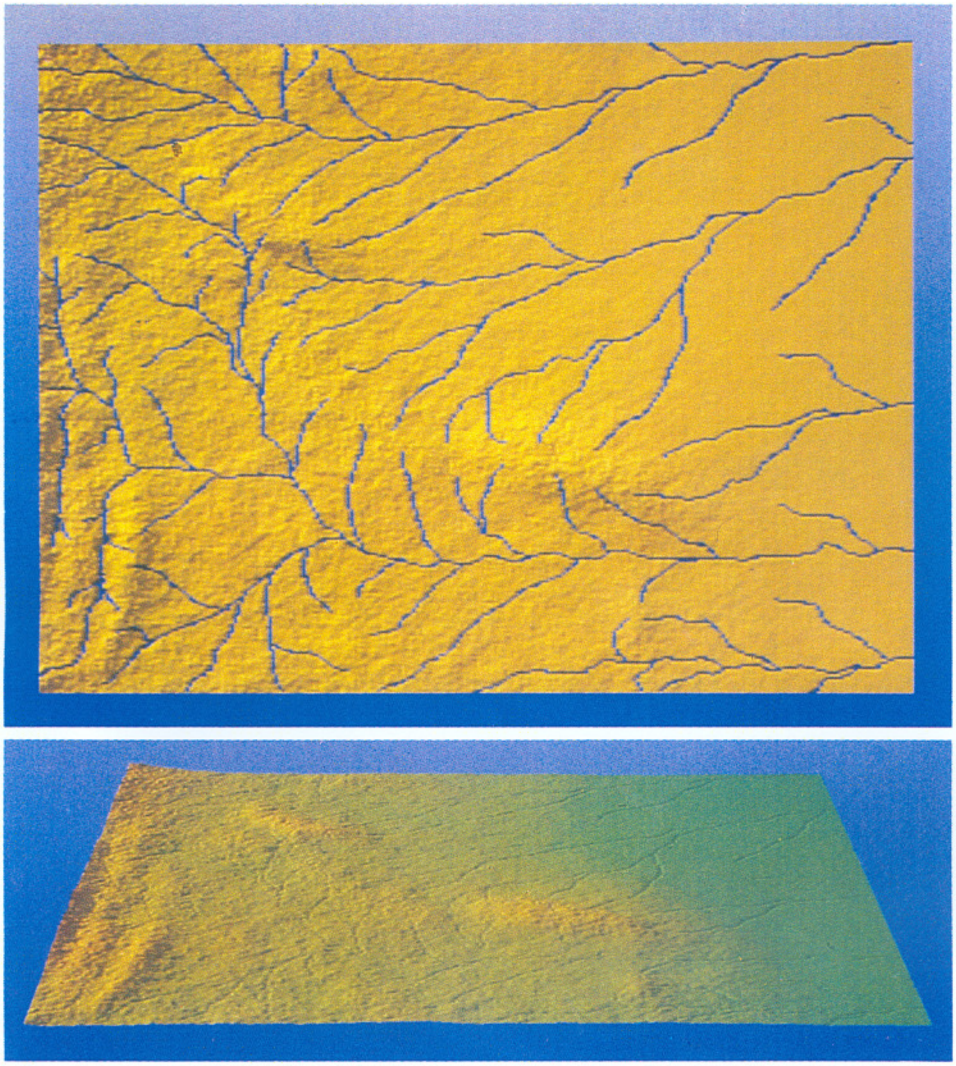


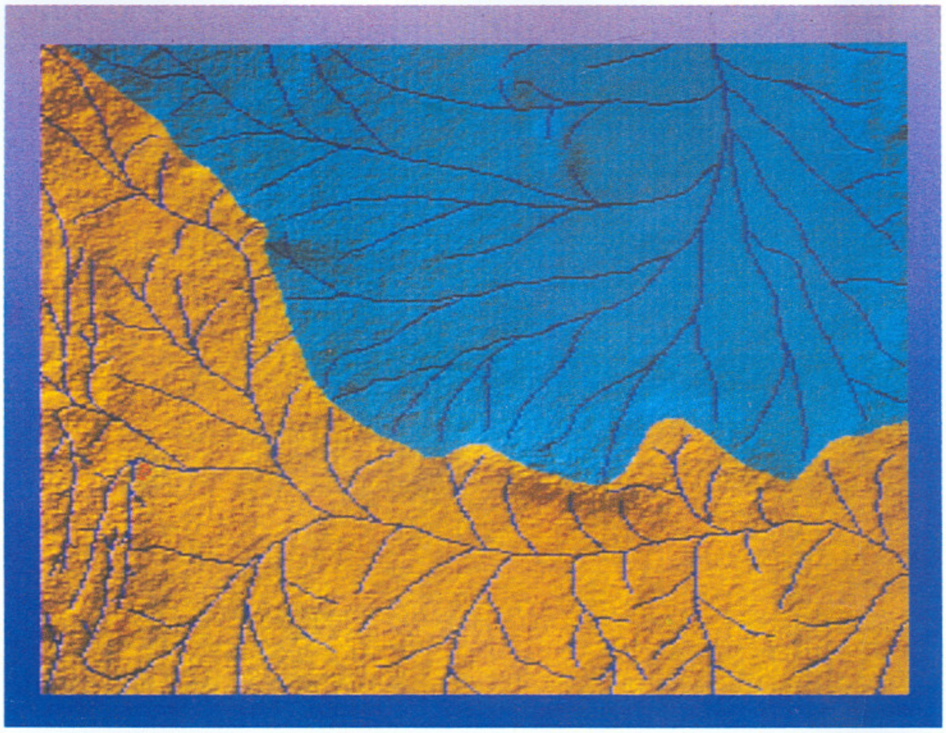
*Figure 4. The Lancian (latest Cretaceous): **top,** hydrographic basins; **bottom,** interpretive paleotopography. See Table 2 for comparisons of the evolving areas of the hydrographic basins.*

coarse, largely quartzitic debris derived from major uplifts (mostly thrust sheets; Kraus 1985) in central and eastern Idaho (the "Targhee Uplift" of Love 1973). Within the sedimentary deposits the volcanic debris—derived from important centers of Late Cretaceous volcanism in southwestern Montana (Lindsey 1972)—increases northward.

The overall grain of drainage across Wyoming during Lancian time was dendritic and generally eastward, with minor divides caused by the various gentle uplifts that existed across the southwestern half of the state. Because of a persistent connection between the northern Wind River Range and southern Washakie Range, the present-day area of Jackson Hole drained into the northern Green River Basin (present Hoback Basin), rather than more directly eastward into the Wind River Basin. That peculiarity of drainage seems to have persisted until early in the Eocene (perhaps as late as late Wasatchian; McKenna 1980a). The drainage pattern in the Overthrust Belt is shown (Figures 4–10) as having been trellislike, but detailed fluvial connections are hypothetical.

Puercan (Earliest Paleocene) (Figure 5)

The earliest Paleocene landscape heralded significant changes from that of the Lancian. Most important were continued eastward migration and increased complexity of the Overthrust Belt, origin of the Basin Creek Uplift (Love 1973), gentle doming of the Rock Springs Uplift (Winterfeld



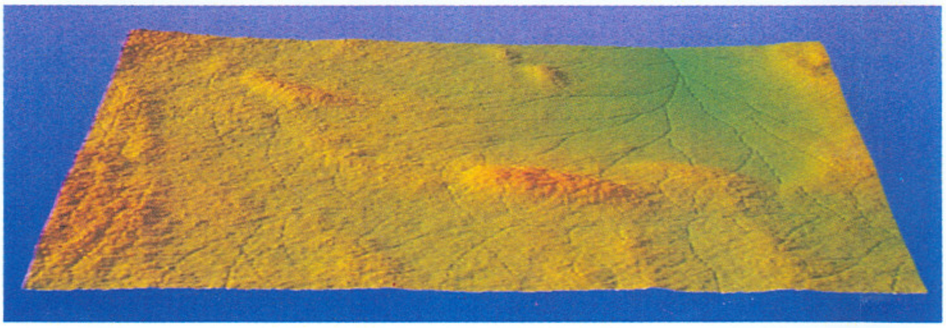


*Figure 5. The Puercan (earliest Paleocene): **top,** hydrographic basins; **bottom,** interpretive paleotopography. Note deflection of drainage in the northern area by uplift of the Black Hills.*

1982), and an early broad upwarp of the Black Hills (Flores & Ethridge 1985). Additionally, each of the previously mentioned Lancian uplifts except the Beartooth block became more elevated in response to increasing intensity of Laramide tectonism. Local indications exist for initial uplifts of minor parts of the ancestral Bighorn Mountains. The timing of initial uplift of the Laramie Mountains is unknown, but because the range was stripped of any preexisting sedimentary cover down to its Precambrian core by early Eocene time (Blackstone 1975), the authors suggest minor uplift early in the Paleocene. The currently exposed core of the Laramie Mountains was at a depth of about 4 km prior to uplift (Johnson & Smithson 1985). No Paleocene or early Eocene strata have been preserved in Wyoming east of the Laramie Mountains. Ahlbrandt & Groen (1987) suggest that such absence can be explained by periodic middle Tertiary uplift of parts of southeastern Wyoming, and erosion of any earlier Cenozoic sedimentary accumulations.

Increased definition of the Rock Springs Uplift further split the greater Green River Basin into its present western component (Green River Basin proper and Bridger Basin) and eastern component (Great Divide and Washakie Basins). Similarly—assuming a Puercan origin of the Laramie Mountains—the Laramie and Shirley Basins appeared. But little evidence suggests separation of the Bighorn and Powder River Basins.

According to these restorations of the drainage pattern, the southwestern half of the state directly inherited most of the fluvial system characteristic of the Lancian. But because of the onset of the Black Hills upwarp, drainage of the northeastern quarter of the state changed markedly; the earliest version of the Powder River came into existence, probably draining northward across what is now southeastern Montana. Though Ayers (1986) suggested that early Paleocene fluvial systems drained to the southwest out of the present area of the Powder River Basin, the authors consider that unlikely. Instead, Figure 5 was constructed using paleocurrent data presented by Flores & Ethridge (1985).

Torrejonian (Late Early Paleocene) (Figure 6)

The Beartooth Uplift remained minor until Clarkforkian time. The Rock Springs Uplift was essentially buried during the Torrejonian. Most of the Lancian–Puercan positive areas, however, continued their relative elevations during the Torrejonian. Uplift of the Washakie Range became particularly important. These various orogenic events (and concomitant active subsidence of adjacent basins) were accompanied until the end of the Wasatchian by continued eastward development of younger thrust plates of the Overthrust Belt. Beginning at about Torrejonian time the eastward convexity (as seen in map view) of the leading edge of the Overthrust Belt became obvious; the northern end of the Wyoming thrust sheets had met the structural impediment of the ancestral Gros Ventre Range (Dorr et al. 1977).

The most important single event in Wyoming associated with Torrejonian time was definitive uplift of the ancestral Bighorn Mountains. This event delineated the Bighorn versus Powder River Basins, and was associated with the earliest marked subsidence of the Powder River Basin along a definite basinal axis. Major uplift of the Casper Arch postdated the Torrejonian and, in agreement with Ayers (1986), the authors suggest in Figure 6 that extensive lake deposits of the northeastern Wind River Basin (Waltman Lake of Keefer 1961, Phillips 1983) and the western Powder River Basin (Lake Lebo) may have been contiguous for part of that time. In any case, active middle Paleocene subsidence in the two basins led to extensive lakes and deposition of lacustrine strata. Farther to the south, other lakes persisted through much of Paleocene time within the present area of the Hanna Basin (Glass 1975).

Uplift of the Laramie Mountains likely became substantial enough by Torrejonian time to deflect drainage patterns from the southwestern half of Wyoming northward into the Wind River and Powder River Basins. If true, the Lancian–Puercan major eastward drainage out of southeastern Wyoming would have been severely restricted areally, probably being limited to the area immediately east of the crest of the Laramie Mountains. Ayers (1986) suggested that drainage from Lake Lebo was to the southeast, as based on interpretation of ancient paleoslope. But in light of evidence for significant westward input of sands (Ayers 1986, Flores & Ethridge 1985) in southern reaches of the Powder River Basin, the authors interpret the lake's outlet to have been northward. If true, most of the northeastern half of Wyoming contributed surface waters to the monumental delta system of western North Dakota (Cherven & Jacob 1985) that drained into the shallow Cannonball Sea. Marine waters of the Cannonball Sea persisted across the northern Great Plains through much of the early Paleocene, with connection northward to the Arctic Sea (Marincovich et al. 1985).

Although the western end of the Owl Creek Mountains probably was a positive area, the eastern parts of the future range remained a lowland. Streams from at least the southern half of the newly defined Bighorn Ba-

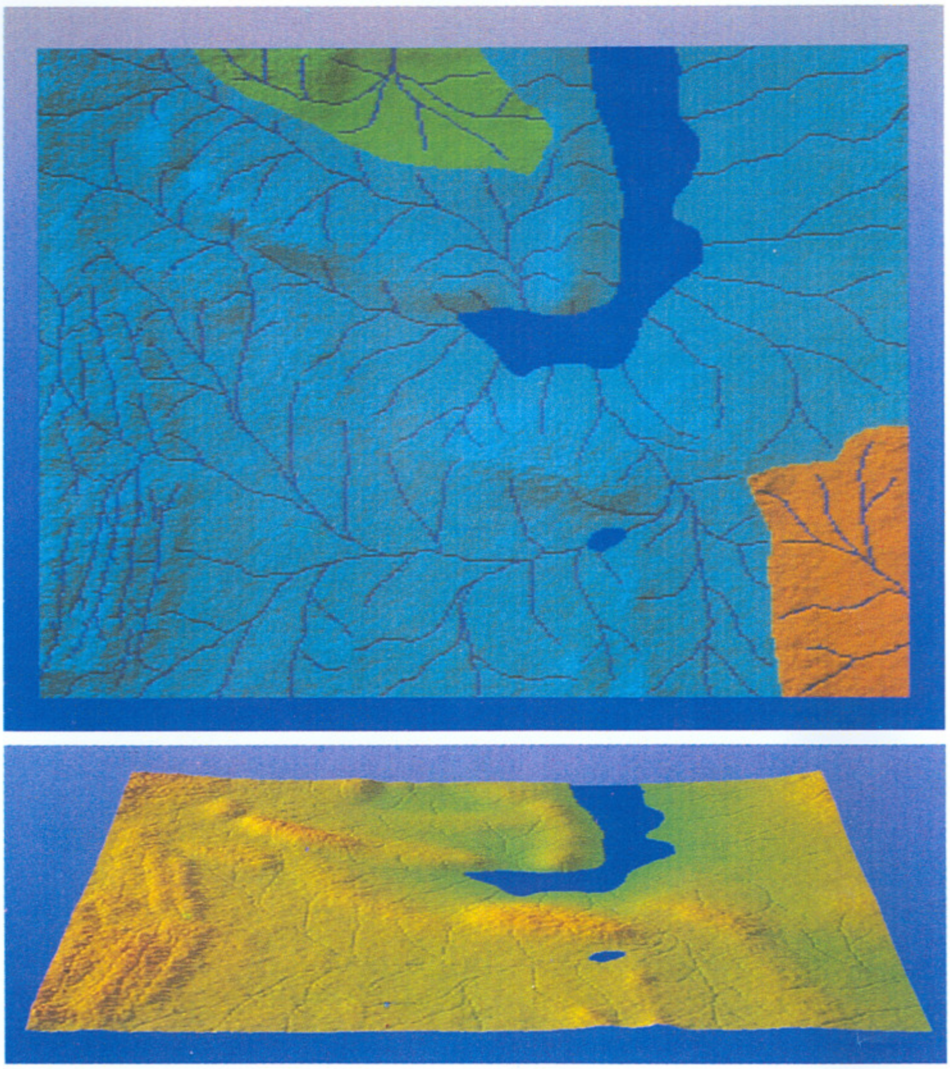


*Figure **6.** The Torrejonian (late early Paleocene): **top,** hydrographic basins; **bottom,** interpretive paleotopography. The large lake system probably drained northward into ancient Montana. The authors conjecture that the rising Laramie Mountains deflected drainage in the south toward the north. According to interpretations expressed in this pair of maps, most of the area of study drained northward.*

sin probably drained southward into Waltman Lake. Thus it appears that, during Torrejonian time, most of the area of Wyoming fed into the lacustrine systems of the Wind River and Powder River Basins. Because of the extensive, persistent, and occasional foul-water nature of Waltman Lake, that drainage was probably internal for part of its existence.

Paleocene drainage patterns within the Bighorn Basin are in need of general review. Although northward drainage of the more northerly half of the basin during the Torrejonian (and for the entirety of the basin thereafter) has been suggested here, field evidence for such patterns is equivocal, or in some places contradictory, until late in the Clarkforkian (Kraus 1980). As proposed by Bown (1980), southward drainage out of the Bighorn Basin may well have been more general and more persistent during the Paleocene than here hypothesized. Influx of coarse clastic sediments during closing phases of deposition of Waltman Lake, however, suggests that marginal uplifts were well established (Phillips 1983).

Tiffanian (Later Paleocene) (Figure 7)

The magnitude of Laramide orogenesis suggested in Figure 1 increased during the Tiffanian beyond that of the Torrejonian, and approached culmination in the Clarkforkian–Wasatchian. The Bighorn Mountains continued broad upwarping, and the Black Hills achieved maximum uplift. New data from northern parts of the Powder River Basin (Merin

& Lindholm 1986) suggest that the ranges surrounding the basin were locally eroded to their Precambrian cores during late phases of the Paleocene. Particularly important uplifts occurred in the northern Laramie, Medicine Bow, Sierra Madre, and northern Uinta Mountains, and Wind River and Gros Ventre Ranges. The Casper Arch apparently began to rise at about this time. In contrast, uplands that seemingly became reduced in elevation (through curtailed tectonism or extensive erosion) include the Basin Creek Uplift, the Washakie Range, and the Rock Springs Uplift; the last probably was covered by sediments during the Tiffanian. There is little evidence for significant uplift of the eastern Owl Creek Mountains or Beartooth block.

Paleocene history of the Shirley and Freezeout Mountains area north of the Hanna and Carbon Basins is largely unknown. Nevertheless, for purposes of discussion, the authors suggest major uplift of areas of the Shirley and Freezeout Mountains during the Tiffanian. Analysis of conglomerates across the Hanna and Carbon Basins (D. Hansen 1986), however, suggests that some uplift of the northern basin rim occurred as early as the latest Cretaceous.

Minor volcanism occurred near the northeastern corner of Wyoming beginning in the late Paleocene, continuing into the late Eocene (Chadwick 1985). Because of uncertainties of timing, however, the various small centers have not been plotted on the maps herein.

Much of Wyoming's drainage pattern for the Tiffanian was directly inherited from that of the Torrejonian; principal differences involve the Wind River, Powder River, and, probably, the Bighorn Basins. Waltman Lake was greatly reduced in area from its Torrejonian maximum, and probably experienced external drainage via streams that were eroding eastward across the gently elevating Casper Arch. The previously extensive lacustrine systems of the western Powder River Basin also were greatly curtailed, and were replaced by coal swamps with generally northward, external drainage.

Drainage patterns of the medial Paleocene in the Bighorn Basin are uncertain. The hypothesis here is that low-magnitude upwarping of the eastern Owl Creek Mountains began in the Tiffanian in association with early stages in development of the South Owl Creek Fault System (which also influenced early tectonism of the Casper Arch). Even quite limited uplift of the eastern Owl Creeks would have diverted drainages in the southern Bighorn Basin northward, presaging the more definite Clarkforkian pattern. Minor lake deposits are described within the Tiffanian section of the northern Bighorn Basin, with influxes of clastic sediments from the Beartooth and Bighorn Mountains (Yuretich et al. 1984). The western margin of the Bighorn Basin remained open and continued to receive gravels derived by river systems from far-western source areas (Kraus 1985). The source was established in the latest Cretaceous, and intermittent influxes of western gravels continued into Wasatchian time.

Clarkforkian (Latest Paleocene–Earliest Eocene) (Figure 8)

The Clarkforkian and early Wasatchian represent the interval of most intensive crustal deformation in Wyoming during the Laramide Orogeny. Intensive tectonism was neither universal nor equal, and influenced some mountain ranges much more than others. The Clarkforkian (and early Wasatchian) was the time of principal uplift of the Beartooth, Wind River, Gros Ventre, and Granite Mountains positive areas. Important uplift continued in the Medicine Bow, Sierra Madre, Uinta, and Bighorn Mountains, Casper Arch, and even along the southern margin of the Wind River Basin. Gentle elevation probably continued along the

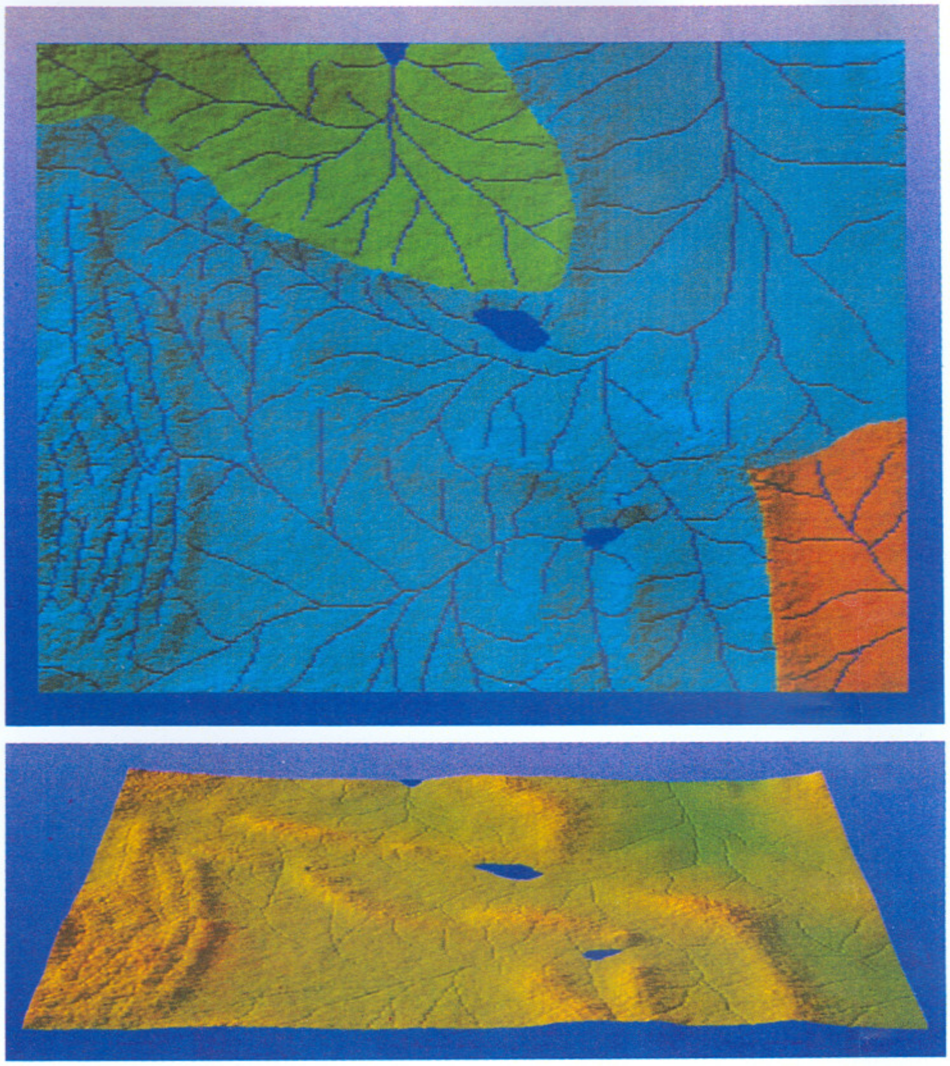


*Figure 7. The Tiffanian (later Paleocene): **top,** hydrographic basins; **bottom,** interpretive paleotopography. Development of Lake Belfry suggests increasing importance of northward drainage from the Bighorn Basin.*

length of the Laramie Mountains. As was the case earlier, the Basin Creek Uplift and Washakie Range were reduced by erosion; the Washakie Range also experienced important downfaulting (Winterfeld & Conard 1983). The Rock Springs Uplift probably remained buried by sedimentary debris. Though field evidence is scant, the eastern Owl Creek Mountains probably were undergoing upwarping; however, major faulting and dominant uplift occurred during the Wasatchian. The Clarkforkian drainage pattern was inherited directly, with few significant alterations, from that of the Tiffanian.

Early Wasatchian (Early Eocene) (Figure 9)

Intensive erosion accompanied the final important pulses of the Laramide Orogeny, supplying tremendous volumes of sediments from uplands into all of Wyoming's basins. The uplands were deeply dissected and eventually subdued in topography as compared with elevations characteristic of the Clarkforkian and earliest Wasatchian. By Wasatchian time, Paleozoic and Mesozoic strata had been eroded from the crests of all of Wyoming's ranges, broadly exposing their ancient Precambrian cores. As a result, prodigious volumes of granitic debris were shed from the mountainous cores into Wasatchian basins of Wyoming, and deep canyons and generally complex topographies were developed on the very crests of the mountains. Many of these high-level Wasatchian

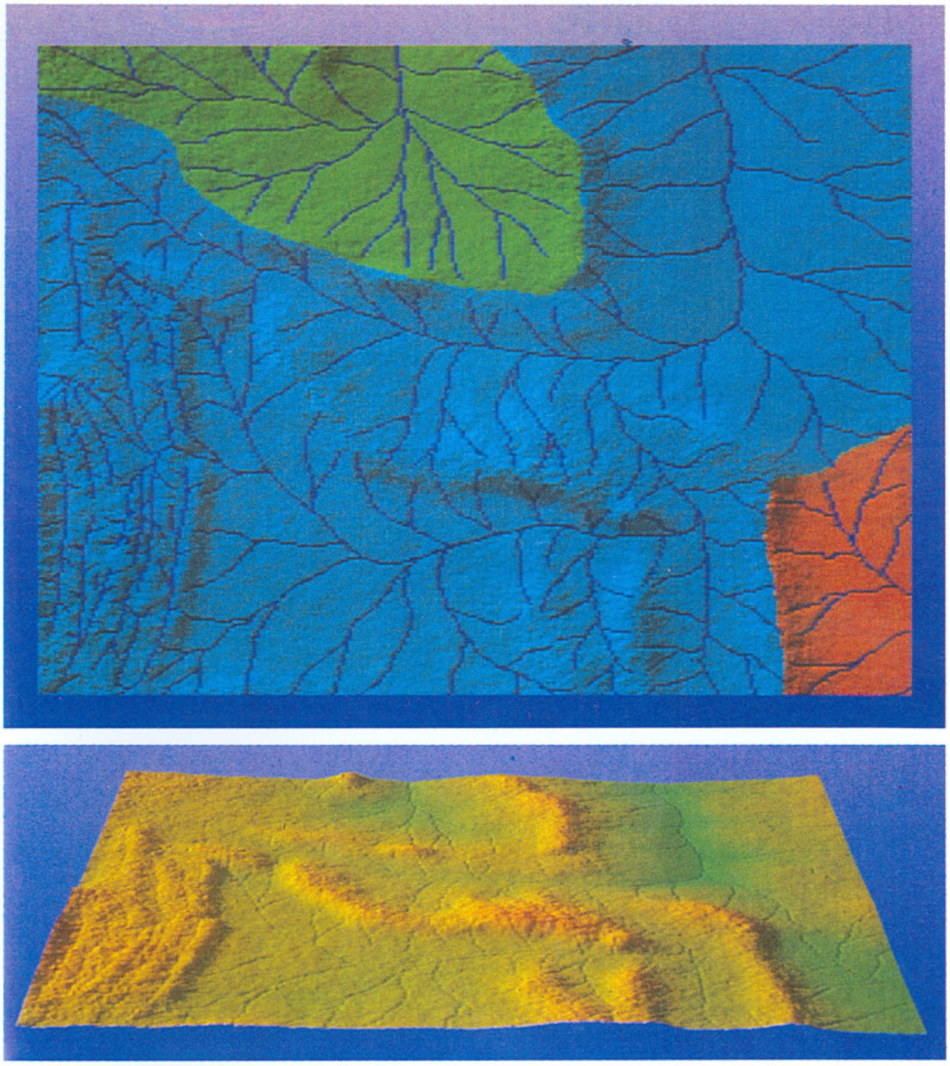


Figure ***8.*** *The Clarkforkian (latest Paleocene–earliest Eocene):* ***top,*** *hydrographic basins;* ***bottom,*** *interpretive paleotopography. Although Laramide tectonism was beginning to culminate, the observed drainage pattern was inherited without major change from the one that characterized the Tiffanian.*

canyons were to be secondarily filled by sediments during various younger intervals of Wyoming's Tertiary history.

The Bighorn and Laramie Mountains continued to uplift, and the Owl Creek Mountains and Casper Arch experienced their most important deformation. Late in the Wasatchian (not shown in Figure 9) the first consequential pulses of volcanism began at the future site of the Absaroka Range (Smedes & Prostka 1972). The main Absaroka volcanic episode, however, was limited to Bridgerian and, especially, Uintan time (Love, Kudo et al. 1976). The drainage pattern of the Wasatchian was inherited without significant change from the Clarkforkian. However, the advent of Absaroka volcanism introduced dramatic alterations in the general patterns of middle Eocene drainage across most of Wyoming.

Late Wasatchian–Bridgerian (Earlier Medial Eocene) (Figure 10)

Laramide orogenesis (Figure 1) was mainly completed in Wyoming by the end of the Wasatchian. Though important eastward motion of the Overthrust Belt persisted late into the Wasatchian, nonvolcanic mountain-building in Wyoming was comparatively minor after that time. Nevertheless, markedly changing paleodrainage patterns suggest that important regional warpings occurred during the Bridgerian and Uintan, followed by extensive erosion across much of the Rocky Moun-

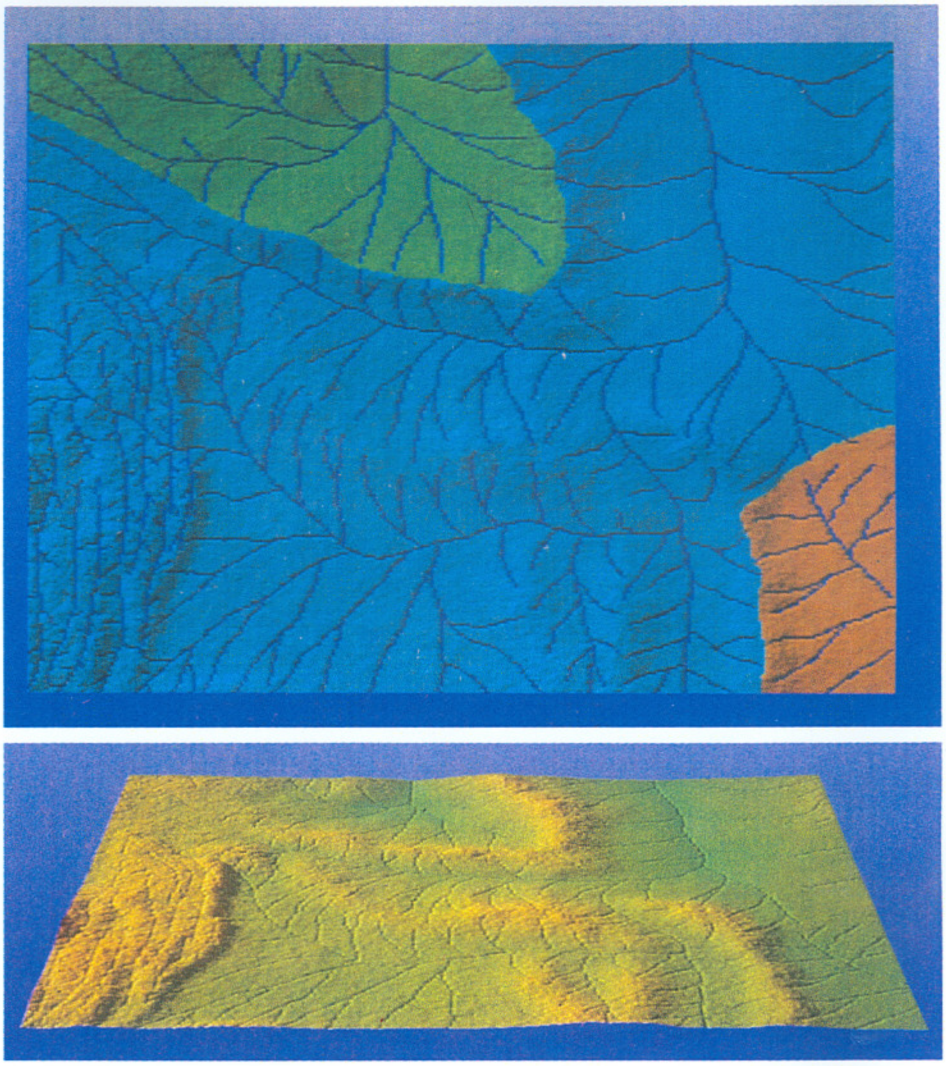


Figure 9. The early Wasatchian (early Eocene): ***top,*** *hydrographic basins;* ***bottom,*** *interpretive paleotopography. Important Laramide tectonism continued through this interval; nevertheless, ancient highlands became deeply dissected by intensive erosion. The early Wasatchian represents the end of the basic drainage patterns established early in the Paleocene.*

tains during the last few million years of the Eocene. Part of the key to understanding these later Eocene events must lie with the onset of volcanism (Chadwick 1985) in central Wyoming (Rattlesnake Hills field) and, on a vastly larger scale, in northwestern Wyoming (Absaroka field), central and eastern Idaho (Challis field), and western Montana (Gallatin field plus various smaller centers). Though the Rattlesnake Hills volcanic field was a comparatively minor contributor to extrusive debris (Pekarek 1978), the Absaroka, Gallatin, and Challis centers ejected great volumes of lava and ash onto the Eocene landscape (Love, Leopold et al. 1978; McKenna 1980a). These volcaniclastic materials were weathered by the warm, humid climate, reworked by the streams, and during Bridgerian time filled much of the Bighorn and Wind River Basins. Even the Wind River Range (Steidtmann et al. 1983) must have been largely buried during the Bridgerian, as Absaroka-derived debris has been recorded southwest of the present southern Wind River in the northern Green River Basin (Groll & Steidtmann 1987).

The late Wasatchian and, especially, the Bridgerian were times of major development of lakes in the western half of Wyoming. Fossil Lake formed during the latter half of the Wasatchian in the eastern Wyoming Overthrust Belt; its duration was comparatively brief and apparently did not persist into the Bridgerian. The lake system of the Green River Basin (Lake Gosiute), in contrast, was much more extensive in space and time.

*Figure **10.** The late Wasatchian and Bridgerian (earlier medial Eocene): **top,** hydrographic basins; **bottom,** interpretive paleotopography. The advent of intensive volcanic activity in northwestern Wyoming, southwestern Montana, and east-central Idaho probably led to thermogenic upwarping of the entire volcanic area. Temporary internal drainage developed Lake Tatman in the southern Bighorn Basin, and major lake systems grew in southwestern Wyoming. Much of the drainage pattern characteristic of the Paleocene through the early Eocene had been disrupted.*

Lake Gosiute began in the medial Wasatchian and persisted late into the Bridgerian. Although direct connection between Fossil Lake and Lake Gosiute would have been ephemeral (W. Hansen 1985), the former probably drained from near its southern end into the latter.

The southern part of the Bighorn Basin also was a center of lacustrine deposition during the Bridgerian. Extant deposits representing various intervals of the history of Tatman Lake (Bown 1982) extend from the southeastern Absaroka Range on the west to the present crest of the eastern Owl Creek Mountains on the east. Wasatchian canyons on flanks of the Owl Creeks were infilled by fluvial and lacustrine strata during the Bridgerian and younger intervals. Because of extensive late Cenozoic erosion, the original southern limits of Tatman Lake (over what is now the northeastern Wind River Basin) probably never will be known; the shoreline drawn in Figure 10 is a conservative estimate, based upon the approximate limits of field evidence. Although most of the record has been removed by erosion, other Bridgerian lakes may well have existed across what is now the Wind River Basin (Love, McGrew et al. 1963). An example is represented by lacustrine sediments in unit 4 of the Wagon Bed Formation as exposed on northwestern flanks of the Granite Mountains (Van Houten 1964). The size of the lake is unknown, but it was persistent enough to allow development of low-grade oil shales (R. C. Surdam personal communication).

Although much is unknown about details of Wyoming's drainage patterns during the late Wasatchian and Bridgerian, dramatic changes from preexisting conditions had clearly developed. By the late Wasatchian, for example, the previous positive connection between the northern Wind River Range and southern Washakie Range (McKenna 1980a) had been eroded so that rivers north of the Gros Ventre Range passed eastward into the northwest corner of the Wind River Basin.

The authors agree with Sklenar & Andersen (1985) that at first Lake Gosiute drained externally, via streams that eventually entered the Powder River system, leaving Wyoming to the north. But rather than draining directly northward across the then tectonically active Granite Mountains, early Lake Gosiute may well have first drained to the east as proposed for the Torrejonian through earlier Wasatchian (Figures 6–9). Later, Lake Gosiute developed internal drainage (Sullivan 1985), with major accumulations of trona in the Green River Basin. Finally, late in its existence, Lake Gosiute developed southerly outlets, thus vastly increasing the hydrographic limits for the complex lacustrine system of the Piceance Basin of northwestern Colorado and the Uinta Basin of northeastern Utah. As proposed by Dickinson et al. (1987), Lake Uinta and its various tributaries (including Wyoming's late Lake Gosiute) probably drained westward into a fluvial system, with other shallow lakes along the way (Emry 1987), leading ultimately to Oregon where it emptied into the Pacific Ocean. The southerly drainage from Wyoming's Green River Basin persisted at least into the early Uintan.

Drainage patterns associated with environs of Tatman Lake are mostly unknown, except at its western shorelines along ancient uplands of the southeastern Absaroka Range. Initial drainage may have been internal. With continued basin-filling by volcaniclastic debris, the lake probably fed streams that flowed southward toward the Green River Basin. Though the authors have not endorsed the idea in the present reconstructions, Love, McGrew et al. (1963) suggested that the entire eastern half of Wyoming tilted westward during the Bridgerian, thus also contributing waters to Lake Gosiute and points south.

In any case, the drainage divides hypothesized in Figures 10 and 11 differ dramatically from those typical of the Paleocene through the early Wasatchian (Figures 6–9). During Bridgerian and early Uintan time all but the northeastern third of Wyoming's surface contributed waters that flowed southward (and probably ultimately to the Pacific Coast) rather than, as was previously the case, northward and eastward (either to Hudson Bay or the Gulf of Mexico). If true, the hydrographic limits of the Green River Basin were markedly larger than those visualized by Bradley (1964). The Continental Divide during the Bridgerian and at least the early Uintan in Wyoming seems to have been parallel to its present counterpart, though the Eocene version was somewhat farther to the northeast. In all probability, drainage patterns of the northern Bighorn and Powder River Basins and southeastern corner of Wyoming fundamentally retained their Paleocene–early Wasatchian distributions.

The advent of extensive volcanism in northwestern Wyoming and in adjacent states may be the key to understanding the medial and late Eocene evolution of paleodrainages. Broad upwarps associated with batholithic and volcanic centers seem to have occurred and probably were caused by differential heat flow to the earth's surface, associated with changing interactions between the lithosphere and the subducting Farallon Plate (Engebretson et al. 1984). These subregional uplifts, probably thermogenic in origin, are geologically recognizable in the gross evolution of drainage patterns (cf. Underwood & Bachman 1986).

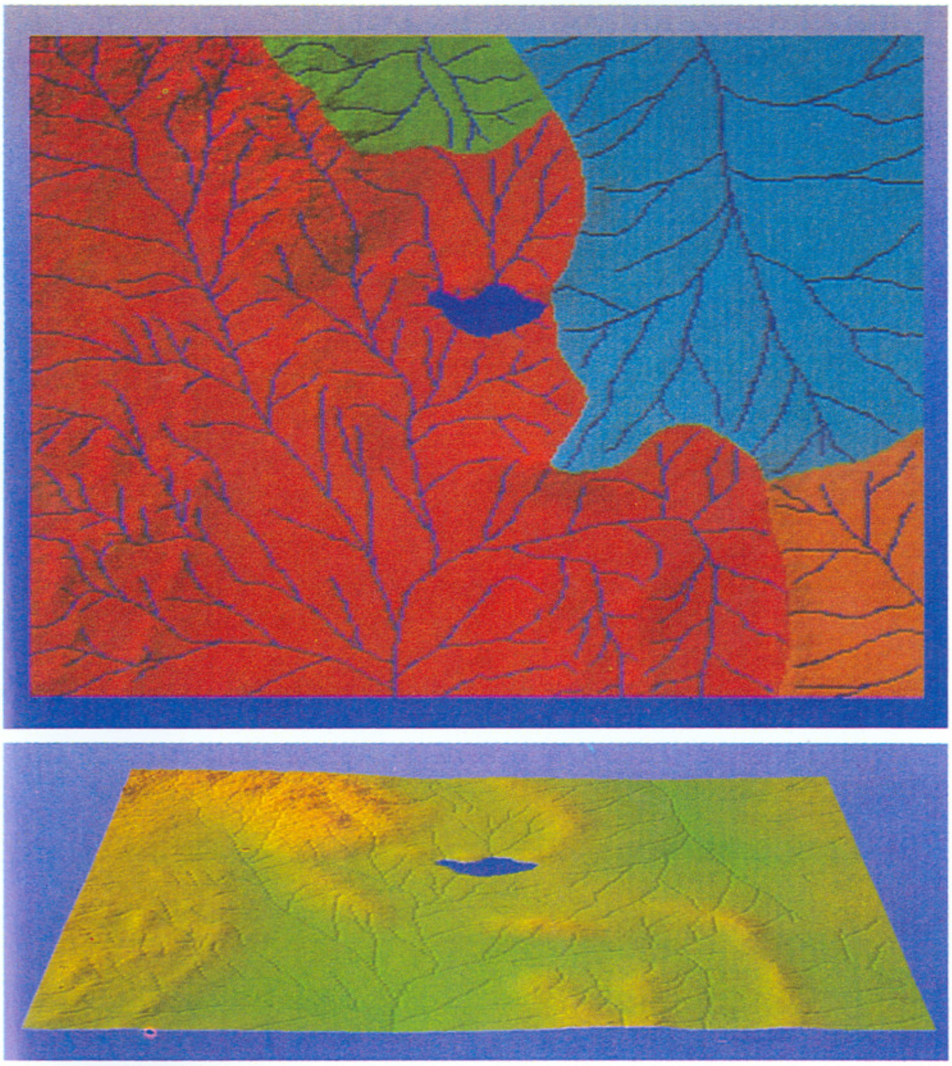


Figure ***11.*** *The early Uintan (later medial Eocene):* ***top,*** *hydrographic basins;* ***bottom,*** *interpretive paleotopography. With intensifying volcanic activity to the northwest, most of the area drained southward into ancient northwestern Colorado.*

Early Uintan (Later Medial Eocene) (Figure 11)

Volcanic activity in northwestern Wyoming, eastern Idaho, and southwestern Montana continued from, and even intensified beyond, conditions during the Bridgerian. The western basins of Wyoming continued to be infilled by volcaniclastic debris, aided by continued erosion of summit crests of the various Laramide mountain ranges. Among the local ranges, only the Uinta Mountains were actively uplifted during Uintan time (W. Hansen 1984). Though in part conjectural, the authors suggest in Figure 11 that basins within the Wyoming Overthrust Belt were largely filled by ash and other volcaniclastic debris (Nelson 1973), contributed in part from the Challis volcanic field. Moreover, major parts of the Owl Creek Mountains and the Washakie, Gros Ventre, and much of the Wind River Ranges probably were essentially buried by debris from the Absaroka field during at least early Uintan time.

A probable effect of local volcanism on the Uintan landscape was a broad upwarping of Wyoming's northwest quarter, and continuation of a general southerly grain to the drainage across most of the state. Thus fine-grained volcaniclastics originating in northwestern Wyoming were carried by surface streams during early Uintan time directly into northwestern Colorado (Johnson 1985, Surdam & Stanley 1980).

Though the limits of lacustrine deposition are wholly unknown, bodies of water persisted along the northeastern border of the Wind River

Basin during at least part of the Uintan (Thaden 1980), probably part of the generally southward drainage pattern into the Green River Basin.

Duchesnean (Late Eocene) (Not Figured)

The last 5 million years of the Eocene of Wyoming are virtually unknown; strata of that age are documented only in patches around the northeastern (Krishtalka & Setoguchi 1977) and southeastern (Emry 1973) Wind River Basin and in a small part of southeastern Wyoming near the Nebraska border (Schlaikjer 1935). The interval also is poorly documented throughout the Rocky Mountains in general and seems to represent an interval dominated by intensive regional, or even continent-wide erosion (Epis et al. 1980, Gresens 1981). Of the mountains in the immediate vicinity of Wyoming, only the Uintas continued their uplift, shedding coarse, clastic debris from their flanks (W. Hansen 1986). Volcanism was greatly reduced in the Absaroka field during this interval, though it persisted in the Challis field of Idaho. Drainage patterns across most of Wyoming during the latest Eocene are quite unknown.

Early Chadronian (Earliest Oligocene) (Figure 12)

Near the end of the Eocene, volcanic events wholly external to Wyoming began to profoundly influence its topography. Colossal volumes of tephra settled across Wyoming, derived from many sources across the Pacific Northwest, Nevada, and western Utah. Additional volcanic centers ranging from southeastern Arizona across central New Mexico into northern Colorado also may have contributed somewhat.

The repetitious blanketings of airborne volcanic ash were washed off the highlands, reworked by fluvial and eolian processes, and redeposited in the basins by periodic flooding of sediment-choked streams of all sizes. All of Wyoming's basins were in large part filled during Chadronian time by distantly derived volcanic ash combined with sediments shed locally by erosion from persistent uplands. Basinal deposition lapped progressively higher onto mountainous flanks through time (Love 1978). Southern divides of the Bighorn Mountains, for example, were covered high enough during the Chadronian that volcanic pebbles eroded from remnant peaks of the Absaroka Range and were carried by rivers directly eastward to nearly the center of the Powder River Basin (McKenna 1980b, McKenna & Love 1972).

Because of the extensive early Oligocene infillings of Wyoming's basins, a basic eastwardly grained drainage pattern reminiscent of that of the latest Cretaceous (Figure 4) was established. Evidence from Wyoming's High Plains (Stanley 1976), however, suggests that the southern Laramie Mountains were not covered until the early Miocene (contra Seeland 1985). Thus, as implied by Harshman (1972), Chadronian streams immediately west of the Laramie Mountains flowed, as most do today, to the north. The Black Hills positive area also served to deflect the otherwise generally eastward drainages at the northeast corner of Wyoming. Seeland (1985) suggested that fluvial systems to the north of the Black Hills ultimately drained toward Hudson Bay, while those to the south of the Black Hills flowed to the Gulf of Mexico.

By late Chadronian time, Wyoming's landscape was one of considerable monotony, dominated by vast savannah shrublands with distantly separated and heavily eroded remnants of Laramide uplifts (Lillegraven & Tabrum 1983). Except for late Oligocene pulses of uplift of the Wind River Range (Steidtmann 1987), the general landscape became evermore planar until about the middle of the Miocene; basinal aggradation of dominantly volcaniclastic sediments continued. Conditions then shift-

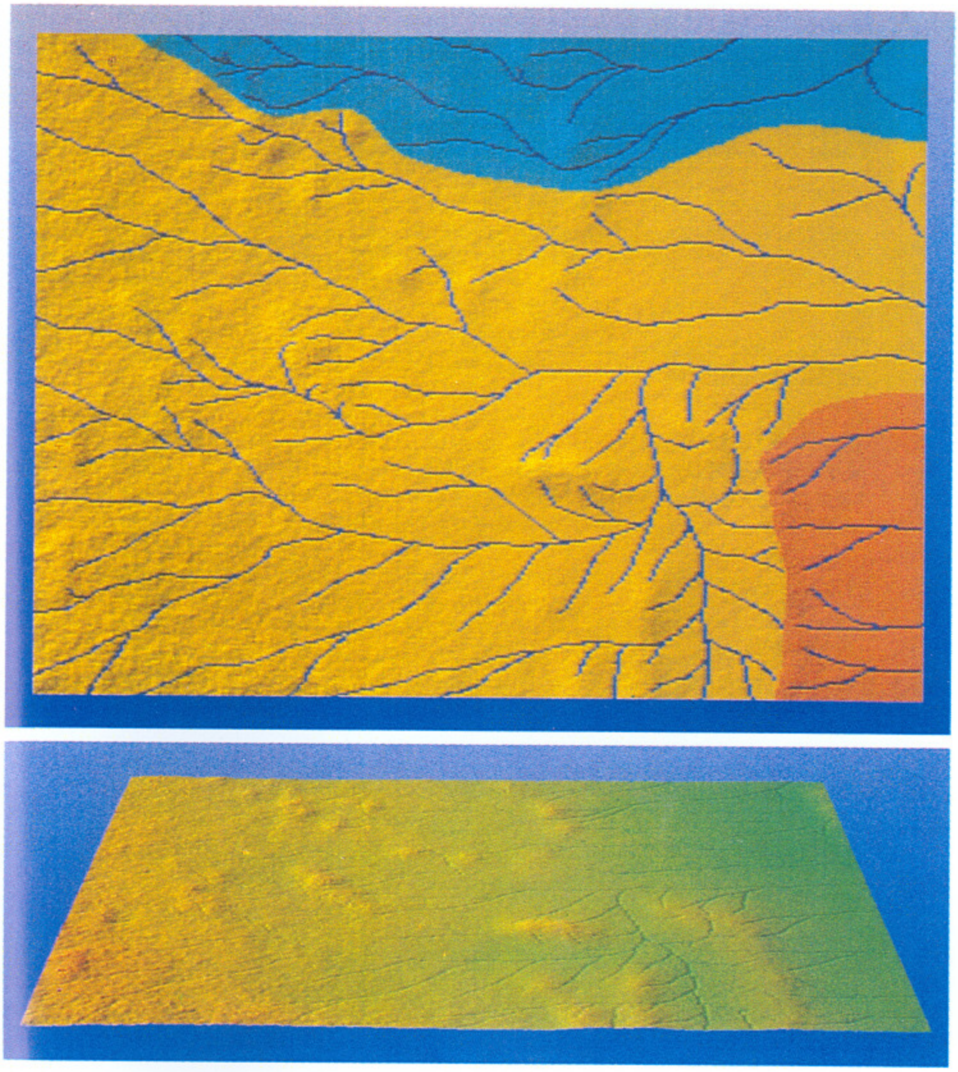


Figure **12.** *The early Chadronian (earliest Oligocene):* ***top,*** *hydrographic basins;* ***bottom,*** *interpretive paleotopography. Massive influxes of air-fall volcaniclastic debris from far-western and southern sources filled most of the Laramide structural basins. Except for persistent barriers in the form of the Laramie Mountains and Black Hills, a principally eastward grain of the drainage pattern was reestablished.*

ed during an interval of several million years that was characterized by alternate cutting and filling (Skinner et al. 1977). Finally, approximately the past 10 million years reflect the dominance of massive erosion (Angevine & Flanagan 1987), exhuming an essentially Eocene topography.

Discussion

Dramatic changes in areas of hydrographic basins occurred across the region of study during the 30-million-year period of interest (Table 2). Clearly, the time scales are much greater than geomorphologists ordinarily study (Lewin 1980). Nevertheless, such researchers long have recognized the crucial importance of areas of drainage basins to virtually all measurable hydrologic and geomorphic elements (e.g., Chorley 1972, Dunne & Leopold 1978, Gardiner & Park 1978, Gregory & Walling 1973, Langbein et al. 1947, Schumm 1977, Zavoianu 1985). In fact, Anderson (1957) referred to the area of hydrographic basins as "the devil's own variable" because of its close interaction with almost every known watershed characteristic. Surface and subsurface flow regimes of watersheds also have direct and important influences upon biotic factors (especially on vegetation and aquatic species) and accumulation of economically important minerals. Thus, although beyond the intended scope of this research, reconstructions of paleolandscapes and ancient drainage patterns have direct implications for studies of the evolution of life, plus potential for economic applications.

Table 2. Changes in Percentage of Map Area for Hydrographic Basins*

	Early Chadronian	Duchesnean	Early Uintan	Late Wasatchian–Bridgerian	Early Wasatchian	Clarkforkian	Tiffanian	Torrejonian	Puercan	Late Lancian
Ancient Powder River drainage	14	?	26	24	78	78	78	89	48	–
Ancient Bighorn River drainage	–	?	4	3	16	16	16	5	–	–
General eastward drainage	79	?	–	–	–	–	–	–	52	100
Drainage to Tatman Lake	–	?	–	10	–	–	–	–	–	–
Ancient Green River drainage	–	?	64	57	–	–	–	–	–	–
Drainage from east of Laramie Mts.	7	?	6	6	6	6	6	6	–	–

**Values rounded from two decimal places, total map area is 288 702 km². Note how relative basin sizes were sequentially influenced by Laramide tectonism, Absaroka–Gallatin–Challis volcanism, and aggradation of volcanic debris from more distant sources (see Figure 2).*

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Bibliography

Ahlbrandt, T. S.; & Groen, W.

1987. The Goshen Hole Uplift: a brief review of its geologic history and exploration potential. *The Mountain Geologist* 24:33–44.

Anderson, H. W.

1957. Relating sediment yield to watershed variables. *Transactions of the American Geophysical Union* 38:921–924.

Angevine, C. L.; & Flanagan, K. M.

1987. Buoyant sub-surface loading of the lithosphere in the Great Plains foreland basin. *Nature* 327:137–139.

Ayers, W. B. Jr.

1986. Lacustrine and fluvial–deltaic depositional systems, Fort Union Formation (Paleocene), Powder River Basin, Wyoming and Montana. *Bulletin of the American Association of Petroleum Geologists* 70:1651–1673.

Berggren, W. A.; Kent, D. V.; Flynn, J. J.; et al.

1985. Cenozoic geochronology. *Bulletin of the Geological Society of America* 96:1407–1418.

Blackstone, D. L. Jr.

1975. Late Cretaceous and Cenozoic history of the Laramie Basin region, southeast Wyoming. Curtis, B. F., editor: *Cenozoic History of the Southern Rocky Mountains,* Memoir 144. Geological Society of America, Boulder, 249–279.

1983. Laramide compressional tectonics, southeastern Wyoming. *Contributions to Geology, University of Wyoming* 22:1–38.

Bown, T. M.

1980. Summary of latest Cretaceous and Cenozoic sedimentary, tectonic, and ero-

sional events, Bighorn Basin, Wyoming. Gingerich, P. D., editor: *Early Cenozoic Paleontology and Stratigraphy of the Bighorn Basin, Wyoming. Papers on Paleontology* (University of Michigan, Ann Arbor) 24:25–32.
1982. Geology, paleontology, and correlation of Eocene volcaniclastic rocks, southeast Absaroka Range, Hot Springs County, Wyoming. *Professional Paper of the U. S. Geological Survey* 1201A:1–75.

Bradley, W. H.
1964. Geology of Green River Formation and associated Eocene rocks in southwestern Wyoming and adjacent parts of Colorado and Utah. *Professional Paper of the U. S. Geological Survey* 496A:1–86.

Bruhn, R. L.; Picard, M. D.; & Isby, J. S.
1986. Tectonics and sedimentology of Uinta Arch, western Uinta Mountains, and Uinta Basin. Peterson, J. A., editor: *Paleotectonics and Sedimentation in the Rocky Mountain Region, United States,* Memoir 41. American Association of Petroleum Geologists, Tulsa, Okla., 333–352.

Chadwick, R. A.
1985. Overview of Cenozoic volcanism in the west-central United States. Flores, R. M. & Kaplan, S. S., editors: *Cenozoic Paleogeography of the West-central United States,* Rocky Mountain Paleogeography Symposium 3. Society of Economic Paleontologists and Mineralogists, Denver, 359–382.

Cherven, V. B.; & Jacob, A. F.
1985. Evolution of Paleogene depositional systems, Williston Basin, in response to global sea level changes. Flores, R. M. & Kaplan, S. S., editors: *Cenozoic Paleogeography of the West-central United States,* Rocky Mountain Paleogeography Symposium 3. Society of Economic Paleontologists and Mineralogists, Denver, 127–170.

Chorley, R. J. (editor)
1972. *Spatial Analysis in Geomorphology.* Harper & Row, New York.

Dewdney, A. K.
1986. Computer recreations: of fractal mountains, graftal plants and other computer graphics at Pixar. *Scientific American* 255(December):14–20.

Dickinson, W. R.; Klute, M. A.; Hayes, M. J.; et al.
1987. Laramide tectonics and paleogeography inferred from sedimentary record in Laramide basins of central Rocky Mountain region. *Abstracts with Programs of the Geological Society of America* 19:271.

Dorr, J. A. Jr.; Spearing, D. R.; & Steidtmann, J. R.
1977. Deformation and deposition between a foreland uplift and an impinging thrust belt, Hoback Basin, Wyoming. *Special Paper of the Geological Society of America* 177:1–82.

Dunne, T.; & Leopold, L. B.
1978. *Water in Environmental Planning.* W. H. Freeman, San Francisco.

Emry, R. J.
1973. Stratigraphy and preliminary biostratigraphy of the Flagstaff Rim area, Natrona County, Wyoming. *Smithsonian Contributions to Paleobiology* 18:1–43.
1987. Bridgerian (middle Eocene) mammals of Nevada. *Abstracts with Programs of the Geological Society of America* 19:273–274.

Engebretson, D. C.; Cox, A.; & Thompson, G. A.
1984. Correlation of plate motions with continental tectonics: Laramide to Basin Range. *Tectonics* 3:115–119.

Epis, R. C.; Scott, G. R.; Taylor, R. B.; et al.
1980. Summary of Cenozoic geomorphic, volcanic and tectonic features of central Colorado and adjoining areas. Kent, H. C. & Porter, K. W., editors: *Colorado Geology.* Rocky Mountain Association of Geologists, Denver, 135–156.

Flores, R. M.; & Ethridge, F. G.
1985. Evolution of intermontane fluvial systems of Tertiary Powder River Basin, Montana and Wyoming. Flores, R. M. & Kaplan, S. S., editors: *Cenozoic Paleogeography of the West-central United States,* Rocky Mountain Paleogeography Symposium 3. Society of Economic Paleontologists and Mineralogists, Denver, 107–126.

Flynn, J. J.
1986. Correlation and geochronology of middle Eocene strata from the western United States. *Palaeogeography, Palaeoclimatology, Palaeoecology* 55:335–406.

Gardiner, V.; & Park, C. C.
1978. Drainage basin morphometry: review and assessment. *Progress in Physical Geography* 2:1–35.

Glass, G. B.
1975. Analyses and measured sections of 54 Wyoming coal samples (collected in

1974). *Report of Investigations,* no. 11. Geological Survey of Wyoming, Laramie.

Gregory, K. J.; & Walling, D. E.

1973. *Drainage Basin Form and Process: a Geomorphological Approach.* Wiley & Sons, New York.

Gresens, R. L.

1981. Extension of the Telluride erosion surface to Washington State, and its regional and tectonic significance. *Tectonophysics* 79:145–164.

Gries, R.

1983. North–south compression of Rocky Mountain foreland structures. Lowell, J. D. & Gries, R., editors: *Rocky Mountain Foreland Basins and Uplifts.* Rocky Mountain Association of Geologists, Denver, 9–32.

Groll, P. E.; & Steidtmann, J. R.

1987. Fluvial response to Eocene tectonism, the Bridger Formation, southern Wind River Range, Wyoming. Ethridge, F. C. & Flores, R. M., editors: *Recent Developments in Fluvial Sedimentology,* special volume 39. Society of Economic Paleontologists and Mineralogists, Denver, 263–268.

Hagen, E. S.; Shuster, M. W.; & Furlong, K. P.

1985. Tectonic loading and subsidence of intermontane basins: Wyoming foreland province. *Geology* 13:585–588.

Hamilton, W.

1981. Plate-tectonic mechanism of Laramide deformation. *Contributions to Geology, University of Wyoming* 19:87–92.

Hansen, D. E.

1986. Laramide tectonics and deposition of the Ferris and Hanna Formations, south-central Wyoming. Peterson, J. A., editor: *Paleotectonics and Sedimentation in the Rocky Mountain Region, United States,* Memoir 41. American Association of Petroleum Geologists, Tulsa, Okla., 481–495.

Hansen, W. R.

1984. Post-Laramide tectonic history of the eastern Uinta Mountains, Utah, Colorado, and Wyoming. *The Mountain Geologist* 21:5–29.

1985. Drainage development of the Green River Basin in southwestern Wyoming and its bearing on fish biogeography, neotectonics, and paleoclimates. *The Mountain Geologist* 22:192–204.

1986. Neogene tectonics and geomorphology of the eastern Uinta Mountains in Utah, Colorado, and Wyoming. *Professional Paper of the U. S. Geological Survey* 1356:1–78.

Harshman, E. N.

1972. Geology and uranium deposits, Shirley Basin area, Wyoming. *Professional Paper of the U. S. Geological Survey* 745:1–82.

International Telephone and Telegraph Corporation (ITTC)

1963. *Reference Data for Radio Engineers* (4th ed.). American Book–Stratford Press, New York.

Johnson, R. A.; & Smithson, S. B.

1985. Thrust faulting in the Laramie Mountains, Wyoming, from reanalysis of COCORP data. *Geology* 13:534–537.

Johnson, R. C.

1985. Early Cenozoic history of the Uinta and Piceance Creek Basins, Utah and Colorado, with special reference to the development of Eocene Lake Uinta. Flores, R. M. & Kaplan, S. S., editors: *Cenozoic Paleogeography of the West-central United States,* Rocky Mountain Paleogeography Symposium 3. Society of Economic Paleontologists and Mineralogists, Denver, 247–276.

Keefer, W. R.

1961. Waltman Shale and Shotgun members of Fort Union Formation (Paleocene) in Wind River Basin, Wyoming. *Bulletin of the American Association of Petroleum Geologists* 45:1310–1323.

1965. Stratigraphy and geologic history of the uppermost Cretaceous, Paleocene, and lower Eocene rocks in the Wind River Basin, Wyoming. *Professional Paper of the U. S. Geological Survey* 495A:1–77.

1970. Structural geology of the Wind River Basin, Wyoming. *Professional Paper of the U. S. Geological Survey* 495D:1–35.

Kraig, D. H.; Wiltschko, D. V.; & Spang, J. H.

1987. Interaction of basement uplift and thin-skinned thrusting, Moxa arch and the Western Overthrust Belt, Wyoming: a hypothesis. *Bulletin of the Geological Society of America* 99:654–662.

Kraus, M. J.

1980. Genesis of a fluvial sheet sandstone, Willwood Formation, northwest Wyoming. Gingerich, P. D., editor: *Early Cenozoic Paleontology and Stratigra-*

phy of the Bighorn Basin, Wyoming. *Papers on Paleontology* (University of Michigan, Ann Arbor) 24:87–94.

1985. Early Tertiary quartzite conglomerates of the Bighorn Basin and their significance for paleogeographic reconstruction of northwest Wyoming. Flores, R. M. & Kaplan, S. S., editors: *Cenozoic Paleogeography of the West-central United States,* Rocky Mountain Paleogeography Symposium 3. Society of Economic Paleontologists and Mineralogists, Denver, 71–91.

Krishtakla, L.; & Setoguchi, T.

1977. Paleontology and geology of the Badwater Creek area, central Wyoming. Part 13: The late Eocene Insectivora and Dermoptera. *Annals of the Carnegie Museum of Natural History* 46:71–99.

Lamerson, P. R.

1982. The Fossil Basin and its relationship to the Absaroka thrust system, Wyoming and Utah. Powers, R. B., editor: *Geologic Studies of the Cordilleran Thrust Belt,* vol. 1. Rocky Mountain Association of Geologists, Denver, 279–340.

Langbein, W. B.; et al.

1947. Topographic characteristics of drainage basins. *Water Supply Paper of the U. S. Geological Survey* 968C:125–157.

Lewin, J.

1980. Available and appropriate timescales in geomorphology. Cullingford, R. A., Davidson, D. A., & Lewin, J., editors: *Timescales in Geomorphology.* Wiley & Sons, New York, 3–10.

Lillegraven, J. A.; & McKenna, M. C.

1986. Fossil mammals from the "Mesaverde" Formation (Late Cretaceous, Judithian) of the Bighorn and Wind River Basins, Wyoming, with definitions of Late Cretaceous North American land-mammal "ages." *American Museum Novitates* 2840:1–68.

Lillegraven, J. A.; & Tabrum, A. R.

1983. A new species of *Centetodon* (Mammalia, Insectivora, Geolabididae) from southwestern Montana and its biogeographical implications. *Contributions to Geology, University of Wyoming* 22:57–73.

Lindsey, D. A.

1972. Sedimentary petrology and paleocurrents of the Harebell Formation, Pinyon Conglomerate, and associated coarse clastic deposits, northwestern Wyoming. *Professional Paper of the U. S. Geological Survey* 734B:1–68.

Love, J. D.

1970. Cenozoic geology of the Granite Mountains area, central Wyoming. *Professional Paper of the U. S. Geological Survey* 495C:1–154.

1973. Harebell Formation (Upper Cretaceous) and Pinyon Conglomerate (uppermost Cretaceous and Paleocene), northwestern Wyoming. *Professional Paper of the U. S. Geological Survey* 734A:1–54.

1978. Cenozoic thrust and normal faulting, and tectonic history of the Badwater area, northeastern margin of Wind River Basin, Wyoming. Boyd, R. G., Olson, G. M., & Boberg, W. W., editors: *Resources of the Wind River Basin,* 30th Annual Field Conference Guidebook. Wyoming Geological Association, Casper, 234–238.

Love, J. D.; & Christiansen, A. C.

1985. *Geologic Map of Wyoming,* scale 1:500,000. U. S. Geological Survey.

Love, J. D.; Leopold, E. B.; & Love, D. W.

1978. Eocene rocks, fossils, and geologic history, Teton Range, northwestern Wyoming. *Professional Paper of the U. S. Geological Survey* 932B:1–40.

Love, J. D.; McGrew, P. O.; & Thomas, H. D.

1963. Relationship of latest Cretaceous and Tertiary deposition and deformation to oil and gas in Wyoming. Childs, O. E., editor: *The Backbone of the Americas—Tectonic History from Pole to Pole; a Symposium,* Memoir 2. American Association of Petroleum Geologists, Tulsa, Okla., 196–208.

Love, L. L.; Kudo, A. M.; & Love, D. W.

1976. Dacites of Bunsen Creek, the Birch Hills, and the Washakie Needles, northwestern Wyoming, and their relationship to the Absaroka volcanic field, Wyoming and Montana. *Bulletin of the Geological Society of America* 87:1455–1462.

Mandelbrot, B. B.

1983. *The Fractal Geometry of Nature: Updated and Augmented.* W. H. Freeman, San Francisco.

Marincovich, L. Jr.; Brouwers, E. M.; & Carter, L. D.

1985. Early Tertiary marine fossils from northern Alaska: implications for Arctic Ocean paleogeography and faunal evolution. *Geology* 13:770–773.

McGookey, D. P.; Haun, J. D.; Hale, L . A.; et al.

1972. Cretaceous system. Mallory, W. W., Mudge, M. R., Swanson, V. E., et al., editors: *Geologic Atlas of the Rocky Mountain Region.* Rocky Mountain Association of Geologists, Denver, 190–228.

McKenna, M. C.

1980a. Late Cretaceous and early Tertiary vertebrate paleontological reconnaissance, Togwotee Pass area, northwestern Wyoming. Jacobs, L. L., editor: *Aspects of Vertebrate History.* Museum of Northern Arizona Press, Flagstaff, 321–343.

1980b. Remaining evidence of Oligocene sedimentary rocks previously present across the Bighorn Basin, Wyoming. Gingerich, P. D., editor: *Early Cenozoic Paleontology and Stratigraphy of the Bighorn Basin, Wyoming. Papers on Paleontology* (University of Michigan, Ann Arbor) 24:143–146.

McKenna, M. C.; & Love, J. D.

1972. High-level strata containing early Miocene mammals in the Bighorn Mountains, Wyoming. *American Museum Novitates* 2490:1–31.

Merin, I. S.; & Lindholm, R. C.

1986. Evidence that the crystalline cores of uplifts adjacent to the Powder River Basin were breached during Paleocene time. *The Mountain Geologist* 23:128–131.

Nelson, M. E.

1973. Age and stratigraphic relations of the Fowkes Formation, Eocene, of southwestern Wyoming and northeastern Utah. *Contributions to Geology, University of Wyoming* 12:27–31.

Newman, W. M.; & Sproull, R. F.

1979. *Principles of Interactive Computer Graphics* (2nd ed.). McGraw-Hill, St. Louis.

Oriel, S. S.; & Tracey, J. I. Jr.

1970. Uppermost Cretaceous and Tertiary stratigraphy of Fossil Basin, southwestern Wyoming. *Professional Paper of the U. S. Geological Survey* 635:1–53.

Pekarek, A. H.

1978. Stratigraphy and structural geology of the Rattlesnake Hills, Wyoming. Boyd, R. G., Olson, G. M., & Boberg, W. W., editors: *Resources of the Wind River Basin,* 30th Annual Field Conference Guidebook. Wyoming Geological Association, Casper, 239–253.

Phillips, S. T.

1983. Tectonic influence on sedimentation, Waltman Member, Fort Union Formation, Wind River Basin, Wyoming. Lowell, J. D. & Gries, R., editors: *Rocky Mountain Foreland Basins and Uplifts.* Rocky Mountain Association of Petroleum Geologists, Denver, 149–160.

Royse, F. Jr.; Warner, M. A.; & Reese, D. L.

1975. Thrust belt structural geometry and related stratigraphic problems Wyoming–Idaho–northern Utah. Bolyard, D. W., editor: *Deep Drilling Frontiers of the Central Rocky Mountains.* Rocky Mountain Association of Geologists, Denver, 41–54.

Savage, D. E.; & Russell, D. E.

1983. *Mammalian Paleofaunas of the World.* Addison-Wesley, London.

Schlaikjer, E. M.

1935. Contributions to the stratigraphy and palaeontology of the Goshen Hole area, Wyoming. III. A new basal Oligocene formation. *Bulletin of the Museum of Comparative Zoology at Harvard College* 76:69–93.

Schumm, S. A. (editor)

1977. *Drainage Basin Morphology. Benchmark Papers in Geology* 41. Dowden, Hutchinson & Ross, Stroudsberg, Penna.

Seeland, D.

1985. Oligocene paleogeography of the northern Great Plains and adjacent mountains. Flores, R. M. & Kaplan, S. S., editors: *Cenozoic Paleogeography of the West-central United States,* Rocky Mountain Paleogeography Symposium 3. Society of Economic Paleontologists and Mineralogists, Denver, 187–205.

Skinner, M. F.; Skinner, S. M.; & Gooris, R. J.

1977. Stratigraphy and biostratigraphy of late Cenozoic deposits in central Sioux County, western Nebraska. *Bulletin of the American Museum of Natural History* 158:263–371.

Sklenar, S. E.; & Andersen, D. W.

1985. Origin and early evolution of an Eocene lake system within the Washakie Basin of southwestern Wyoming. Flores, R. M. & Kaplan, S. S., editors: *Cenozoic Paleogeography of the West-central United States,* Rocky Mountain Paleogeography Symposium 3. Society of Economic Paleontologists and Mineralogists, Denver, 231–245.

Smedes, H. W.; & Prostka, H.

1972. Stratigraphic framework of the Absaroka Volcanic Supergroup in the Yel-

lowstone National Park region. *Professional Paper of the U. S. Geological Survey* 729C:1–33.
Stanley, K. O.
1976. Sandstone petrofacies in the Cenozoic High Plains sequence, eastern Wyoming and Nebraska. *Bulletin of the Geological Society of America* 87:297–309.
Steidtmann, J. R.
1987. The "Wyomide Event": Oligocene deformation in the Rocky Mountain foreland of Wyoming. *Abstracts with Programs of the Geological Society of America* 19(7):855.
Steidtmann, J. R.; McGee, L. C.; & Middleton, L. T.
1983. Laramide sedimentation, folding, and faulting in the southern Wind River Range, Wyoming. Lowell, J. D. & Gries, R., editors: *Rocky Mountain Foreland Basins and Uplifts.* Rocky Mountain Association of Geologists, Denver, 161–167.
Steidtmann, J. R.; Middleton, L. T.; Bottjer, R. J.; et al.
1986. Geometry, distribution, and provenance of tectogenic conglomerates along the southern margin of the Wind River Range, Wyoming. Peterson, J. A., editor: *Paleotectonics and Sedimentation in the Rocky Mountain Region, United States,* Memoir 41. American Association of Petroleum Geologists, Tulsa, Okla., 321–332.
Sullivan, R.
1985. Origin of lacustrine rocks of Wilkins Peak Member, Wyoming. *Bulletin of the American Association of Petroleum Geologists* 69:913–922.
Surdam, R. C.; & Stanley, K. O.
1980. Effects of changes in drainage-basin boundaries on sedimentation in Eocene Lakes Gosiute and Uinta of Wyoming, Utah, and Colorado. *Geology* 8: 135–139.
Swinehart, J. B.; Souders, V. L.; DeGraw, H. M.; et al.
1985. Cenozoic paleogeography of western Nebraska. Flores, R. M. & Kaplan, S. S., editors: *Cenozoic Paleogeography of the West-central United States,* Rocky Mountain Paleogeography Symposium 3. Society of Economic Paleontologists and Mineralogists, Denver, 209–229.
Thaden, R. E.
1980. Geologic map of the Picard Ranch Quadrangle, showing chromolithofacies and coal beds in the Wind River Formation, Fremont County, Wyoming, scale 1:24 000. *Geologic Quadrangle Map of the U. S. Geological Survey* GQ-1539.
Underwood, M. B.; & Bachman, S. B.
1986. Sandstone petrofacies of the Yager complex and the Franciscan Coastal belt, Paleogene of northern California. *Bulletin of the Geological Society of America* 97:809–817.
Van Houten, F. B.
1964. Tertiary geology of the Beaver Rim area, Fremont and Natrona Counties, Wyoming. *Bulletin of the U. S. Geological Survey* 1164:1–99.
Wiltschko, D. V.; & Dorr, J. A. Jr.
1983. Timing of deformation in Overthrust belt and foreland of Idaho, Wyoming, and Utah. *Bulletin of the American Association of Petroleum Geologists* 67: 1304–1322.
Winterfeld, G. F.
1982. Mammalian paleontology of the Fort Union Formation (Paleocene), eastern Rock Springs Uplift, Sweetwater County, Wyoming. *Contributions to Geology, University of Wyoming* 21:73–111.
Winterfeld, G. F.; & Conard, J. B.
1983. Laramide tectonics and deposition, Washakie Range and northwestern Wind River Basin, Wyoming. Lowell, J. D. & Gries, R., editors: *Rocky Mountain Foreland Basins and Uplifts.* Rocky Mountain Association of Geologists, Denver, 137–148.
Wood, H. E. 2nd; Chaney, R. W.; Clark, J.; et al.
1941. Nomenclature and correlation of the North American continental Tertiary. *Bulletin of the Geological Society of America* 52:1–48.
Woodburne, M. O. (editor)
In press. *Vertebrate Paleontology as a Discipline in Geochronology.* University of California Press, Berkeley.
Yuretich, R. F.; Hickey, L. J.; Gregson, B. J.; et al.
1984. Lacustrine deposits in the Paleocene Fort Union Formation, northern Bighorn Basin, Montana. *Journal of Sedimentary Petrology* 54:836–852.
Zavoianu, I.
1985. *Morphometry of Drainage Basins. Developments in Water Science* 20. Elsevier, Amsterdam.

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Adobe Town Presentation — Public Hearing

October 24, 2007 — BLM Hdqtrs., Rock Springs, WY
(Sponsored *by State of Wyoming Environmental Quality Council*)

Greetings/thanks

Name — Jason A. Lillegraven

Presentation will be in the spirit of your needs — provision of facts

Background qualifications
- UW Geology/Zoology faculty — 3 decades (teaching/research/service) — with focus on
  - Systematic paleo of vertebrates (fish through mammals)
  - Principles of paleontology
  - Paleogeographic evolution of WY within geological contexts of Rocky Mtns. and High Plains
- Past-President Society of Vertebrate Paleontology
- National Science Foundation Program Director in Systematic Biology
- NSF proposal review panel in Geology/Paleontology
- In 4th year of retirement but continuing as
  - Co-editor of *Rocky Mountain Geology*
  - Field mapping of NW Bighorn Basin, E Wind River Basin, and E Hanna Basin
- State of Wyoming Professional Geologist (# 24)

Representing only myself

< SLIDES >

SLIDE 1 — Why important?
- Focus today is on unique aspects of Washakie Basin (in general) and Adobe Town (in particular)
- Just one geological/paleontological perspective of many possible

SLIDE 2 — Principal physiographic features
- Locate Washakie Basin and surrounding features
- Most features across WY (except Yellowstone and Tetons) are relict from c. 45 Ma — preserved since then by ashfall cover from NV volcanoes

SLIDE 3 — Relevant geologic time scale
- "Ma"
- Assemblages of fossil mammals form the main means of dating WY Cenozoic strata — Used as standards across western North America to date nonmarine rocks

SLIDE 4 — Relative timing

Go through components — late in Cretaceous through Eocene

Washakie Basin *uniquely* contains the entire pile (through the Uintan)

This is the *only* place in WY, and one of only *two* places in the entire Rockies

SLIDE 5 — End of the Cretaceous (65 Ma)

Extinction of dinosaurs

Explain the two views

All one drainage basin — into retreating mid-continental seaway

SLIDE 6 — End of the Paleocene (55 Ma)

Crustal contraction (c. 20%) led to rugged topography and drainage subdivisions (to Gulf of Mexico and maybe Hudson Bay)

SLIDE 7 — Late in early Eocene (48 Ma)

Advent of Absaroka (and Challis/Gallatin) volcanism

General internal drainage into Lake Gosiute and Fossil Lake

Lake Tatman in S Bighorn Basin

SLIDE 8 — Early in late Eocene (45 Ma)

Lake Gosiute became filled and drained to S — and maybe into *Pacific* Basin

Geologic story closely tied to volcanism in NW Wyoming, SW Montana, and E-central Idaho — Huge drainage basin

SLIDE 9 — Late in Eocene (33 Ma)

Dominance of distant volcanism — prodigious ashfall across the continent

Filled the basins, subdued the topography, and restored the E-ward drainage — "Nebraska with lumps"

Preserved the middle Eocene landscape from erosion — until the last 10 my years or so — entire continent now under unrelenting erosion

SLIDE 10 — Principal physiographic features [again]

Refer to stack of plates — explain erosional relationships — unique preservation at Adobe Town — "unique" goes beyond "rare"

QUESTIONS?