# Eocene Climates, Depositional Environments, and Geography, Greater Green River Basin, Wyoming, Utah, and Colorado

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*By* HENRY W. ROEHLER

GEOLOGY OF THE EOCENE WASATCH, GREEN RIVER, AND BRIDGER (WASHAKIE) FORMATIONS, GREATER GREEN RIVER BASIN, WYOMING, UTAH, AND COLORADO

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*Depositional history of continental Eocene rocks in an intermontane basin of the Central Rocky Mountains*

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# EOCENE CLIMATES, DEPOSITIONAL ENVIRONMENTS, AND GEOGRAPHY, GREATER GREEN RIVER BASIN, WYOMING, UTAH, AND COLORADO

By HENRY W. ROEHLER


ABSTRACT

The climates, depositional environments, and geography of Eocene rocks in the greater Green River basin are investigated to determine the origin, mode of deposition, and areal distribution of the Wasatch, Green River, Bridger, and Washakie Formations. The data indicate that Eocene climates ranged from cool temperate to tropical and were affected by both terrestrial and astronomical factors. The terrestrial factors were mainly latitude, altitude, regional geography, tectonism, and volcanism. The astronomical factors are interpreted from repetitious rock sequences in the Wilkins Peak Member of the Green River Formation that record seasonal changes, 21,000 year precession of the equinox cycles, 100,000 year eccentricity cycles, and an undetermined cycle of 727,000 years.

Eight depositional environments are identified, discussed, and illustrated by diagrams, columnar sections, and photographs. They are: (1) fluvial, (2) paludal, (3) freshwater lacustrine, (4) saltwater lacustrine, (5) pond and playa lake, (6) evaporite (salt pan), (7) mudflat, and (8) volcanic and fluviovolcanic. The areal distribution of the eight depositional environments in the Wasatch, Green River, Bridger, and Washakie Formations is illustrated by photographs and 13 paleogeographic maps.


## INTRODUCTION

In this report lithostratigraphic, biostratigraphic, and chronostratigraphic data are used to define and illustrate the climates, depositional environments, and geography of Eocene formations in the greater Green River basin. The chapter begins with a discussion of previous investigations of the Eocene climates, depositional environments, and geography; it continues with evidence that the Eocene climates underwent progressive changes and that these changes affected the type and distribution of depositional environments; and it ends with graphic portrayals of the areal distribution of depositional environments in relation to Eocene stratigraphic units.

## PREVIOUS INVESTIGATIONS

### CLIMATE

The significance of the Eocene climates and climate changes was first recognized by Bradley in 1925 in a report on the origin of the Green River Formation and its oil shale. He wrote that the geology "is complicated by progressive climatic and, consequently, ecologic changes, upon which were probably also superposed periodic or cyclic phases of shorter duration" (Bradley, 1925, p. 262). By using modern analogs, Bradley (1929, p. 93) estimated that the mean annual precipitation across the floor of the basin during the Eocene ranged between 35 and 38 inches and the mean annual evaporation from the water surface of Lake Gosiute was between 39 and 47 inches. Bradley (1963, table 23.4, p. 635) estimated the mean annual rainfall and temperature for various altitudes across the hydrographic basin of the lake, and he calculated that the annual precipitation on the surface of the lake during its salting stage was about 24 inches. In one of his final papers, Bradley (1973) indicated that oil-shale beds in the Wilkins Peak Member of the Green River Formation were deposited in a "desert environment." A desert environment suggests that much hotter and drier conditions were present during oil shale deposition than the conditions he had described in earlier reports. Bradley's discussions of the Eocene climates indicate that they primarily pertained to the middle Eocene part of the Green River Formation.

The most reliable information concerning the Eocene climates comes from the analysis of megascopic and microscopic plant fossils. Brown (1928, 1934) collected and identified 195 species of plant megafossils in the Green River Formation in southwestern Wyoming. Other species were subsequently added to Brown's list by MacGinitie (1969). The significance of these fossils as paleoclimate indicators was incorporated in a review of Tertiary floras of the Rocky Mountains published by Leopold and MacGinitie (1972).

In 1968, while measuring the Washakie basin reference section (this volume, Chapter D), I collected 28 rock samples for palynological analysis from variously spaced stratigraphic levels between the base and top of Eocene outcrops. Twenty-two of the samples contained identifiable palynomorphs (Chapter D, table 5). Climatic interpretations from study of these palynomorphs were included in the above-mentioned report by Leopold and MacGinitie (1972). According to these authors, the early Eocene floras suggest a humid subtropical to warm temperate climate with summer rainfall and only mild frost. The mean annual temperature may have been above 13 °C and the mean annual range of temperature during the year could have been from about 22 to 28 °C (Leopold and MacGinitie, 1972, p. 169). The rocks in this interval include the main body and Niland Tongue of the Wasatch Formation and the Luman and Tipton Tongues of the Green River Formation. The earliest middle Eocene climate, which pertains to parts of the Cathedral Bluffs Tongue of the Wasatch Formation and the Wilkins Peak Member of the Green River Formation, was described as generally hot and dry (Leopold and MacGinitie, 1972, p. 170). The early middle Eocene climate during deposition of the lower part of the Laney Member of the Green River Formation was characterized as warm and humid with tropical affinities (Leopold and MacGinitie, 1972, p. 171). The middle middle Eocene floras, in the upper part of the Laney Member of the Green River Formation, indicated a climate change to cooler, subhumid conditions (Leopold and MacGinitie, 1972, p. 172). Late Eocene pollen and leaf data from the Washakie Formation indicate that the climate was dry, but temperate (Leopold and MacGinitie, 1972, p. 172).

In correspondence with MacGinitie (written commun., 1976), the temperature and precipitation ranges for Eocene rocks were reinterpreted based on the pollen floras collected in the Washakie basin reference section (Chapter D, this volume). MacGinitie concluded that the average temperature was 18 to 19 °C during early Eocene, 17 to 18 °C during middle Eocene, and 17 °C during late Eocene. The average annual precipitation was probably more than 40 inches during early Eocene, 25 to 35 inches during middle Eocene, and 15 to 20 inches during late Eocene. MacGinitie believed that there was little seasonality in the early Eocene, but that it became more pronounced in the middle and late Eocene.

Axelrod (1968) studied Eocene floras of the Snake River Plain located in Idaho west of the greater Green River basin. He concluded that in the Eocene the Snake River Plain was a volcanic plateau, of which the highest parts, at altitudes of 4,000 to 6,000 ft, were covered with subalpine and conifer-hardwood forests. These forests graded eastward and downward in elevation into Wyoming to the western margins of the greater Green River basin, where deciduous hardwood and then evergreen broadleaved forests were present at altitudes of about 1,500 ft. He interpreted the climates for these zones as cold temperate for the subalpine forest and warm temperate for the broadleaved evergreen forest (Axelrod, 1968, table 1). As these floras and their characterizing climates were present in the mountains along the western margins of the greater Green River basin, they were also probably present in the mountains that bounded the north, east, and south margins of the basin.

The Eocene climate during deposition of the Niland Tongue of the Wasatch Formation was interpreted by Nichols (1987) using palynomorphs collected from core samples in the Vermillion Creek basin in Tps. 12–13 N., Rs. 100–101 W., southwestern Wyoming. Nichols believed that the climate of the floor of the basin during deposition of the Niland Tongue was subtropical without freezing temperatures and humid enough to support luxuriant vegetation.

## DEPOSITIONAL ENVIRONMENTS

Understanding of the depositional history of Eocene rocks in the greater Green River basin has greatly improved since Hayden (1869, p. 190–191) first defined the Green River Formation as a group of shales of "purely fresh-water origin." King (1878, p. 446–447) applied the name Gosiute Lake to the lacustrine basin in which the sediments of the Green River Formation were deposited; he stated that there was "evidence of accumulation in still, rather deep water." The lacustrine origin of the Green River Formation was confirmed in a series of reports subsequently published by Bradley (1926, 1929, 1936, 1948, 1959, and 1964). Bradley also acknowledged the fluvial origin of the Wasatch and Bridger (Washakie) Formations in these reports, but he did not discuss the defining characteristics of the fluvial environment. Studies of depositional environments of Eocene rocks in the greater Green River basin have focused, for example, on the Rock Springs uplift area (Roehler, 1965), on the Green River Formation of Wyoming (Eugster and Surdam, 1973), on playa-lake environments in particular (Wolfbauer, 1973), and on southwestern Wyoming stratigraphy (Sullivan, 1980). Numerous additional papers have focused on the sedimentology, lithofacies, mineralogy, geochemistry, or economics of specific areas or specific stratigraphic units.

The Green River Formation has probably been studied in greater detail than any other stratigraphic unit in the Western Interior United States. These studies have been prompted by the economic importance of the trona, oil shale, and uranium deposits in the formation, and by the scientific interest created by the presence of more than 50 syngenetic and authigenic minerals (mostly carbonates, silicates, and phosphates). A long list of investigations includes important works by Milton and Eugster (1959), Milton and Fahey (1960), Smith (1961), Mannion and Jefferson (1962), Love (1964), Iijima and Hay (1968), Eugster and Hardie (1975), Desborough (1975), Robb and Smith (1976), Hardie, Smoot, and Eugster (1978), Surdam and Stanley (1979, 1980), Mott and Drever (1983), and Sullivan (1985).

Eocene environments of deposition were classified by Roehler (1965). The environments were listed as: (1) non-red-bed fluviatile, (2) red-bed fluviatile, (3) paludal, (4) recurrent lacustrine, (5) shallow lacustrine, (6) deep lacustrine, (7) evaporitic, and (8) mudflat. These depositional environments were later modified and expanded by Roehler (1974) to 10 environments consisting of: (1) mountain front, (2) red-bed fluviatile, (3) non-red-bed fluviatile, (4) freshwater lacustrine, (5) pond, (6) swamp (paludal), (7) saline lacustrine, (8) shoreline, (9) mudflat, and (10) evaporite. Further discussion and refinement of this classification system appear later in this chapter. The classification system may not be applicable to rocks of other geologic ages in other geographic areas, but it is useful for studying Eocene rocks in the greater Green River basin.

### PALEOGEOGRAPHY

The first maps that show the geographic distribution of Eocene rocks in the greater Green River basin were published in 1964 (Bradley, 1964). In 1965, Roehler (fig. 2, p. 146) illustrated the areal extent of the Ramsey Ranch Member of the Wasatch Formation and the Luman Tongue and Wilkins Peak Member of the Green River Formation on a map of the basin compiled on a cadastral base. Generalized paleogeographic maps of poorly identified stratigraphic levels in the Green River Formation were later published by Wolfbauer (1973), Surdam and Wolfbauer (1975), and Stanley and Surdam (1978). The first definitive investigation of the Eocene geography was by Sullivan (1980), who prepared isopach and lithofacies maps for all of the major stratigraphic units. The areal distribution and thickness of stratigraphic units in the Wasatch and Green River Formations are illustrated by isopach maps in Chapter E of this volume and by paleogeographic maps later in this chapter.

## TERRESTRIAL FACTORS AFFECTING EOCENE CLIMATE

Extremes of temperature, precipitation, and evaporation determined the greater Green River basin's Eocene weather, the weather determined the basin's climate, and the climate was a major factor in determining the basin's depositional environments and geography. The terrestrial elements that affected the basin's climate were principally latitude, altitude, regional geography, tectonism, and volcanism.

### LATITUDE

The latitude of the greater Green River basin during the Eocene was about 35° N., based on the secular path of the rotational axis of the Earth in relation to the present position of the north pole (Milankovitch, 1941, fig. 32). This location is 5°–8° of latitude south of the present location of the basin. In terms of climate, the more southerly position of the basin during the Eocene is probably unimportant, if considerations are given to other factors, such as its mid-continent location and the prevailing regional weather patterns. Temperatures normally decrease with increasing latitudes, but the decreases are not necessarily accompanied by uniform changes in precipitation and evaporation.

The latitude of 35° N. lies near the juncture of the Hadley and Ferrel atmospheric circulation cells, where high pressures dominate, prevailing winds are westerly, and climates are commonly arid (Perlmutter and Matthews, 1989). That prevailing winds during the Eocene were westerly is indicated by the eastward and southeastward thinning of a number of regionally correlatable air-laid volcanic ash beds (tuffs) that are preserved in lacustrine rocks of the

Green River Formation. Less reliable evidence for a northwesterly wind direction is found in the orientation of sedimentary structures in sandstone beds of the Cottonwood Creek delta, which was located on the eastern shores of Lake Gosiute (Roehler and others, 1988, p. A6).

## ALTITUDE

The altitude of the floor of the greater Green River basin during the Eocene is believed to have been about 1,000 ft above sea level (Bradley, 1929, p. 89). The tops of the surrounding mountains were about 3,000 to 4,000 ft higher (MacGinitie, 1969, p. 57). The mean annual temperature of the floor of the basin is estimated to have been about 66.5 °F (Bradley, 1929, p. 93–95), and it presumably fluctuated seasonally. The mean annual temperature near the crests of the mountains surrounding the basin may have been as low as 43 °F (Bradley, 1963, p. 634). Using these data, the average lapse rate per 1,000 ft of elevation would have ranged between 5.9 and 7.8 °F.

## REGIONAL GEOGRAPHY

Ocean currents and (or) prevailing storm tracks control the climates of most geographic areas. The general configuration of the North American continent has not changed appreciably since the Eocene, when the greater Green River basin was an intermontane area located hundreds of miles from the closest ocean. This inland location placed the basin far beyond the influence of circulating warm and cold ocean currents. The prevailing storm tracks across the basin are presently directed eastward. There is no reason to believe that storm tracks during the Eocene varied much from those of today. The basin is presently an arid, windy desert with annual precipitation ranges of 7 to 14 inches; temperatures range from about –30 °F to more than 100 °F (Root and others, 1973). The present basin climate, however, is much different than the Eocene climate because the floor of the basin is now about 5,000 ft higher in elevation.

The prevailing westerly winds that crossed the basin during the Eocene undoubtedly cooled and lost moisture as they rose over the mountains that bordered the basin to the west. As these winds continued down the east side of these mountains into the basin, they would have been compressed and warmed and the remaining moisture would have been considerably reduced. Such drying winds could have contributed to the extremely arid conditions that are known to have been present during deposition of parts of the Wilkins Peak Member of the Green River Formation.

Axelrod (1968, p. 729–730) believed that the volcanic plateau located west of the greater Green River basin during the Eocene (discussed following) trended north-south for several hundred miles and rose 3,000 to 6,000 ft above the west margins of the basin. A topographic feature of this magnitude would certainly have created a barrier (rain shadow) to moisture that could have entered the basin from the west.

## TECTONISM

Eocene rocks in the greater Green River basin were deposited during the waning stages of the Laramide orogeny. The Laramide orogeny involved intermittent uplift in the mountains surrounding the basin, which was accompanied by thrust faulting along the mountain flanks. Changes in the physical configurations of the basin and mountain terranes brought about by the Laramide orogeny would have affected the climate as a result of temperature fluctuations.

Major mountain uplifts are generally accompanied by the downwarping of parts of adjoining basins. The location and trends of thickening of Eocene rocks indicate that such downwarpings occurred along the north flank of the Uinta Mountains at the south margin of the basin and along the southwest flank of the Wind River Mountains at the north margin of the basin (this volume, Chapter E, fig. 15). These downwarpings created synclinal depressions, or troughs. The major depositional axis (a line connecting the deepest parts of the basin) was situated along the Uinta Mountain trough. As much as 10,000 ft of lacustrine, fluvial, paludal, and volcanic sediments was deposited in this trough.

The Darby, Wind River, and Sparks Ranch thrust faults, at the west, north, and south margins of the basin, were active during the Eocene. Some of the movements along these faults involved hundreds of feet of throw. The effects of such movements have been largely obliterated by postfault erosion and deposition, but one can speculate on their consequences. Large scarps would have formed along the fault planes, drainage systems would have been severely disrupted, and major earthquakes would have occurred. In this setting, blocked or dammed drainages would have created ephemeral closed lakes, which would have significantly affected evaporation and precipitation within the basin. The earthquakes would have caused tidal waves on Lake Gosiute, which would have had devastating effects on the plant and animal life and sedimentary deposits located along its shorelines.

#### SPARKS RANCH THRUST FAULT

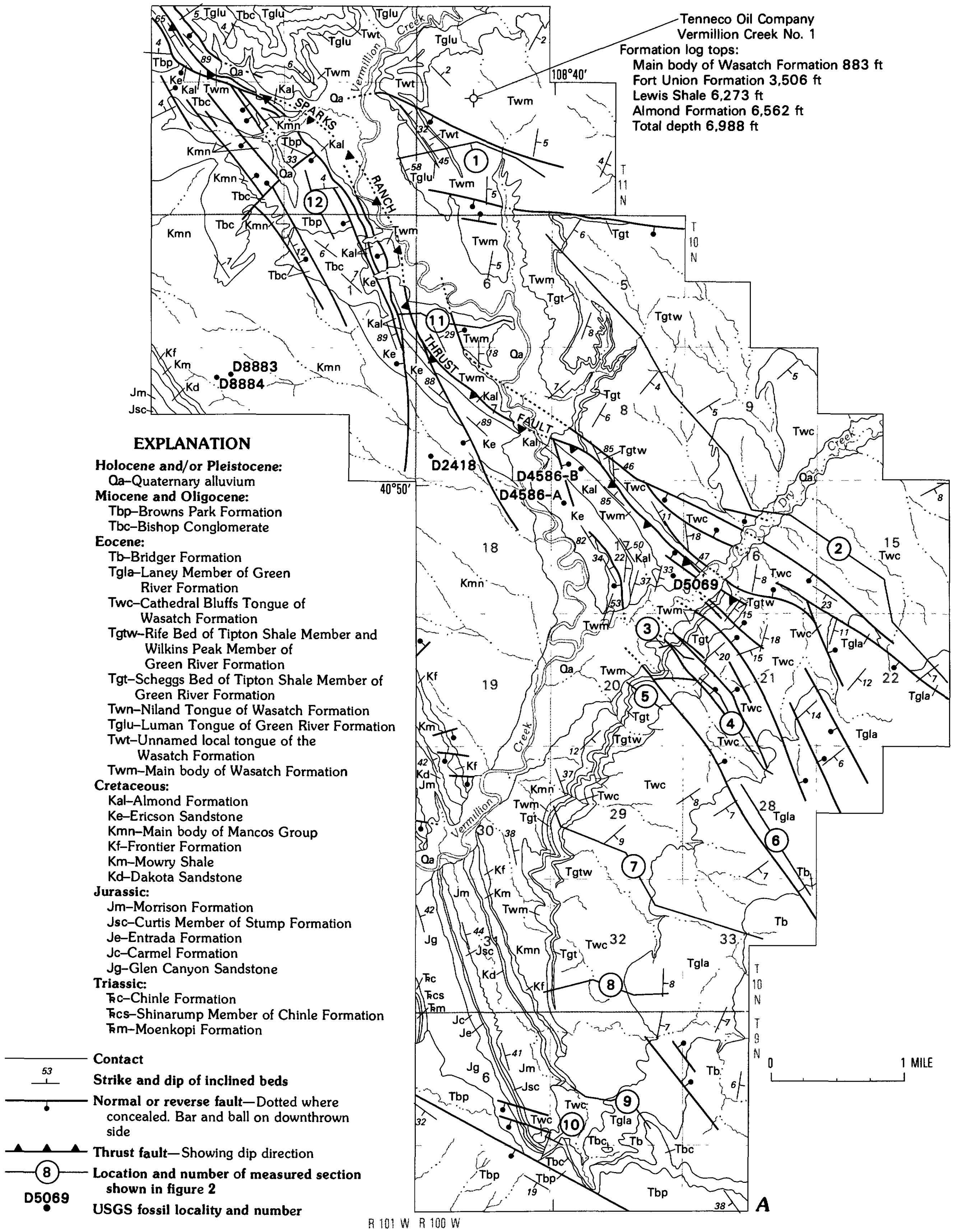
An example of faulting that severely disrupted Eocene sedimentation is visible along the Sparks Ranch thrust in Tps. 9–11 N., Rs. 100–101 W. in northwest Colorado (fig. 1). The Wasatch, Green River, and Bridger Formations are well exposed there along Vermillion Creek, where they were mapped and measured by the author (unpublished data). The formations have a combined total thickness of nearly 5,000 ft on the downthrown northeast limb of the thrust (note the thickness of lower Eocene rocks in the Tenneco Oil and Gas Company Vermillion Creek Well No. 1, fig. 1). The total thickness of the formations decreases rapidly to less than 1,500 ft along 6 mi of southwest-trending outcrops that cross the fault (between measured sections 1 and 10, fig. 2). The thinning is due to (1) onlapping and wedgeout of lacustrine sediments toward shorelines of Lake Gosiute, (2) thinning of fluvial rocks onto elevated northeast margins of the Uinta Mountains, and (3) penecontemporaneous erosion and (or) nondeposition of sediments across the upthrown limb of the thrust.

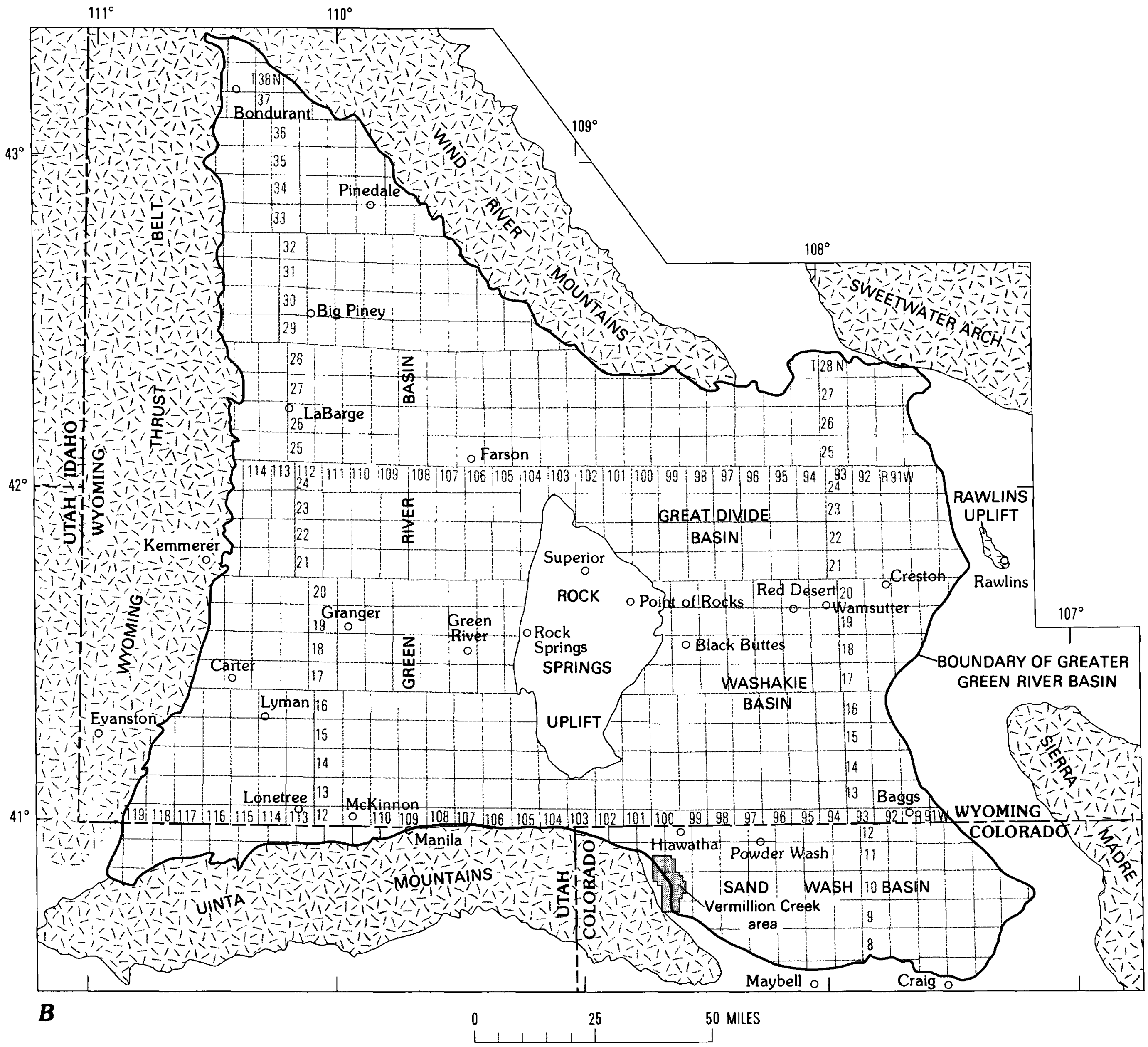
As shown in figure 2, the final movement of the Sparks Ranch thrust fault took place in late early Eocene during deposition of the Cathedral Bluffs Tongue of the Wasatch Formation. On the geologic map of the Vermillion Creek area (fig. 1), the southernmost surface expression of the thrust fault is located in SE¼SW¼ sec. 16, T. 10 N., R. 100 W. At that location (between sections 2 and 3, fig. 2), the fault displaces the Wilkins Peak Member of the Green River Formation and the lower part of the Cathedral Bluffs Tongue of the Wasatch Formation. The upper part of the Cathedral Bluffs Tongue and the overlying Laney Member of the Green River Formation are not displaced, but were deposited without interruption across the older faulted rocks. These relationships are discernible in figure 3. The amount of thinning in the Cathedral Bluffs Tongue across the fault indicates that displacement during the final fault movement amounted to about 500 ft.

The final movement of the Sparks Ranch thrust fault had far-reaching effects on the depositional history of Lake Gosiute and on the Eocene geography of the greater Green River basin. The final movement coincides with a westward tilting of the greater Green River basin and the withdrawal of the lake from a 3,000 $mi^2$ area east of the Rock Springs uplift. The movement marks the end of deposition of the Wilkins Peak Member in the Great Divide, Washakie, and Sand Wash basins. The final fault movement and the basin tilting took place shortly after deposition of bed 11 at the boundary of the lower and middle parts of the Wilkins Peak Member (Chapter E, figs. 23–25). The thrust faulting and basin tilting apparently had little or no effect on the deposition of bedded evaporites, as trona and halite continued to be deposited at the lake basin center, which was located in the southern part of the Green River basin.

## VOLCANISM

Volcanic dust that enters the atmosphere from great volcanic eruptions is known to have major effects on the Earth's climate. The presence of the dust causes a scattering and reflection of solar radiation before it reaches the Earth, thereby reducing surface temperatures. According to Brooks (1926, p. 135) cold years followed the great volcanic eruptions of Asama in 1783, Tomboro in 1815, Krakatoa in 1883, and Katmai in 1912. The Krakatoa eruption ejected an estimated 18 $km^3$ of material into the atmosphere, and much of it stayed there for nearly 2½ years (Alvarez and others, 1980, p. 1105). During the Eocene, a volcanic field extended westward from the Yellowstone Park area in northwest Wyoming across southern Idaho and northern Nevada into northern California, Oregon, and southern Washington (Axelrod, 1968, fig. 1). During the early and early middle Eocene, airborne volcanic ash from intermittent eruptions in this volcanic field drifted eastward across the greater Green River basin, settled out of the atmosphere, and accumulated in beds that range in thickness from a few inches to a few feet. The intensity and frequency of these eruptions increased during the middle Eocene during deposition of the Sand Butte Bed of the Laney Member of the Green River Formation (Chapter D, table 3), and from then until the end of the Eocene Epoch tuffaceous sediments composed most of the rocks deposited in the greater Green River basin area. The Eocene volcanism also had far-reaching effects on sedimentation within the basin. It not only contributed to the infilling and extinction of Lake Gosiute, but also caused a cooling of the late middle and late Eocene climates, which is reflected in the paleoflora (Chapter D, table 5).


Tenneco Oil Company
Vermillion Creek No. 1
Formation log tops:
Main body of Wasatch Formation 883 ft
Fort Union Formation 3,506 ft
Lewis Shale 6,273 ft
Almond Formation 6,562 ft
Total depth 6,988 ft
108°40'
40°50'
SPARKS RANCH THRUST FAULT
Vermillion Creek
Dry Creek
T 11 N
T 10 N
T 9 N
R 101 W
R 100 W
0
1 MILE
EXPLANATION
Holocene and/or Pleistocene:
Qa–Quaternary alluvium
Miocene and Oligocene:
Tbp–Browns Park Formation
Tbc–Bishop Conglomerate
Eocene:
Tb–Bridger Formation
Tgla–Laney Member of Green River Formation
Twc–Cathedral Bluffs Tongue of Wasatch Formation
Tgtw–Rife Bed of Tipton Shale Member and Wilkins Peak Member of Green River Formation
Tgt–Scheggs Bed of Tipton Shale Member of Green River Formation
Twn–Niland Tongue of Wasatch Formation
Tglu–Luman Tongue of Green River Formation
Twt–Unnamed local tongue of the Wasatch Formation
Twm–Main body of Wasatch Formation
Cretaceous:
Kal–Almond Formation
Ke–Ericson Sandstone
Kmn–Main body of Mancos Group
Kf–Frontier Formation
Km–Mowry Shale
Kd–Dakota Sandstone
Jurassic:
Jm–Morrison Formation
Jsc–Curtis Member of Stump Formation
Je–Entrada Formation
Jc–Carmel Formation
Jg–Glen Canyon Sandstone
Triassic:
Ћc–Chinle Formation
Ћcs–Shinarump Member of Chinle Formation
Ћm–Moenkopi Formation
Contact
53
Strike and dip of inclined beds
Normal or reverse fault—Dotted where concealed. Bar and ball on downthrown side
Thrust fault—Showing dip direction
8
Location and number of measured section shown in figure 2
D5069
USGS fossil locality and number
A




***B***

FIGURE 1 (above and facing page).—Vermillion Creek area, northwest Colorado. *A*, geologic map; *B*, generalized index map of greater Green River basin showing location of Vermillion Creek area (shaded), major structural features, towns, and townships and ranges.

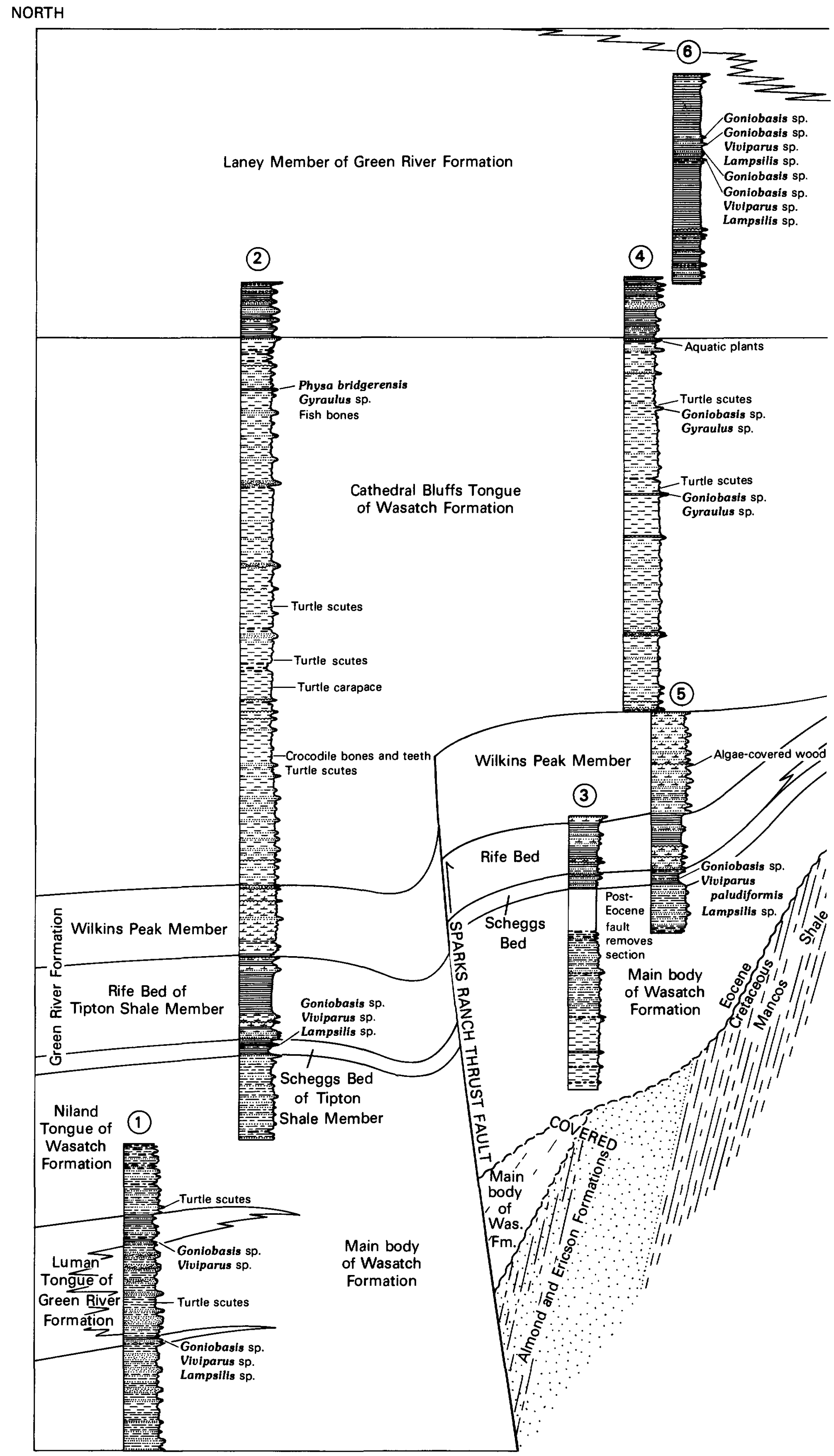
## ASTRONOMICAL FACTORS AFFECTING EOCENE CLIMATE

Astronomical factors affecting deposition of the Green River Formation were investigated at length by Bradley (1929). Bradley discussed the origin, composition, and rates of accumulation of varves, the presence of sunspot cycles in varved rocks, and the cycle of the precession of the equinoxes. Bradley's observations were expanded in a paper published by Fischer (1986). My investigations supplement the data and support the conclusions of Bradley and Fischer.

### RECORD OF THE SEASONS

#### VARVES

Varve deposition occurs in lakes where sediment supply or productivity varies seasonally, and where the bottom sediments are not mixed by wave action, currents, bottom-dwelling organisms, or overturn. Most


NORTH
Laney Member of Green River Formation
Goniobasis sp.
Goniobasis sp.
Viviparus sp.
Lampsilis sp.
Goniobasis sp.
Goniobasis sp.
Viviparus sp.
Lampsilis sp.
Aquatic plants
Physa bridgerensis
Gyraulus sp.
Fish bones
Turtle scutes
Goniobasis sp.
Gyraulus sp.
Cathedral Bluffs Tongue of Wasatch Formation
Turtle scutes
Goniobasis sp.
Gyraulus sp.
Turtle scutes
Turtle scutes
Turtle carapace
Crocodile bones and teeth
Turtle scutes
Wilkins Peak Member
Algae-covered wood
Rife Bed
Goniobasis sp.
Viviparus paludiformis
Lampsilis sp.
Post-Eocene fault removes section
Scheggs Bed
Main body of Wasatch Formation
Green River Formation
Wilkins Peak Member
Rife Bed of Tipton Shale Member
Goniobasis sp.
Viviparus sp.
Lampsilis sp.
Scheggs Bed of Tipton Shale Member
SPARKS RANCH THRUST FAULT
Eocene
Cretaceous
Mancos
Shale
COVERED
Niland Tongue of Wasatch Formation
Turtle scutes
Goniobasis sp.
Viviparus sp.
Luman Tongue of Green River Formation
Turtle scutes
Goniobasis sp.
Viviparus sp.
Lampsilis sp.
Main body of Wasatch Formation
Main body of Was. Fm.
Almond and Ericson Formations

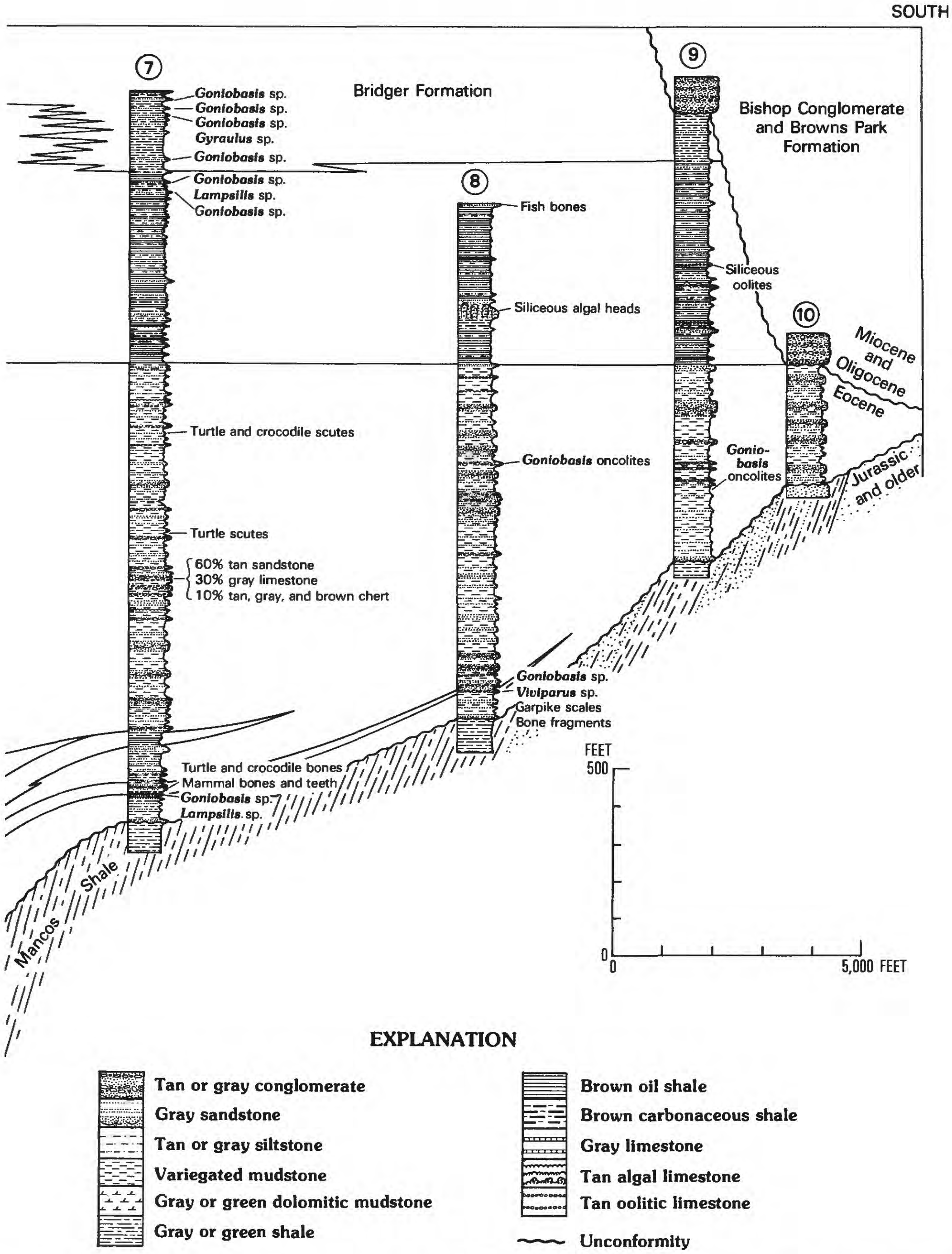



FIGURE 2 (above and facing page).—Correlation of Eocene rocks in surface sections measured along Vermillion Creek in northwest Colorado. Datum is the top of the Cathedral Bluffs Tongue of the Wasatch Formation. Normal faults in a late Tertiary collapse of the Sparks Ranch thrust fault are not shown. Measured section locations shown in figure 1.

oil-shale beds in the Green River Formation exhibit varving. The varves in these beds generally range in thickness from a few micrometers to about 1 millimeter and in color from tan to black. The varve thicknesses are dependent on rates of sedimentation, distances from shorelines, and the composition and texture of the varve material. Varved oil shale in the Green River Formation is mostly composed of clay-size particles of calcite, dolomite, and quartz, with lesser amounts of illite, feldspar, and pyrite (Smith,

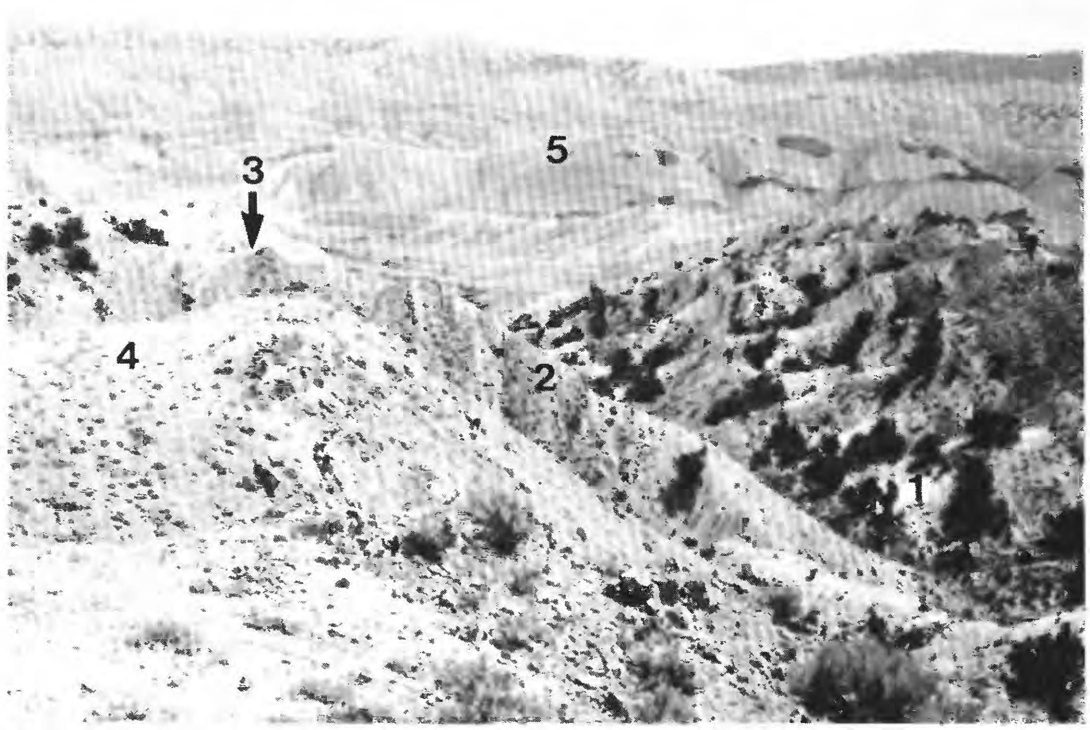



FIGURE 3.—Structural relationships of Eocene and associated rocks along the Sparks Ranch thrust fault in T. 10 N., R. 100 W., northwest Colorado. View is to the southeast from SW¼ sec. 8 along the trend of the thrust fault. 1, upturned Upper Cretaceous Almond Formation; 2, upturned main body of Wasatch Formation; 3, toe of Sparks Ranch thrust fault; 4, upturned and deformed Rife Bed of Tipton Shale Member and Wilkins Peak Member of Green River Formation; and 5, distant outcrops of south-dipping Wasatch, Green River, and Bridger Formations that unconformably overlie upturned beds in foreground. Geology of the area shown in figure 1.

1969, p. 186). The varves are formed by alternating light and dark laminations, or couplets (fig. 4, Nos. 1–3). The dark laminations generally contain more organic matter (kerogen) than the lighter laminations. Some very high grade, black oil shales (fig. 4, No. 4) do not appear to be varved, but this may be a function of the masking of the light laminations by large amounts of dark-colored kerogen.

The organic material in oil shale was derived mostly from autochthonous blue-green algae that thrived in the lake waters and from allochthonous plant material including stems, leaves, wood tissue, spores, and pollen. The dark laminations, being organically rich, are believed to have been deposited during summer and fall seasons when the lake waters were warm, when algal blooms occurred, when nutrients entering the lake were abundant, and when the productivity levels of the lake were at their highest. The light laminations, or organically lean layers, are believed to have been deposited in the winter and spring seasons, when the lake waters were cool and the productivity levels were at their lowest.

Rates of deposition of oil-shale beds can be determined by counting the seasonal (yearly) varves. From varve counts, Bradley (1929, p. 29) determined that the time necessary to accumulate 1 ft of oil shale in the Green River Formation ranged from 2,000 years for moderately good oil shale (15–35 gal/ton) to 8,200 years for rich oil shale (more than 35 gal/ton). For this report, varves were counted in a section of polished core taken from near the base of the Laney Member of the Green River Formation in the U.S. Bureau of Mines Wyoming Corehole No. 1, located in NW¼SW¼NW¼ sec. 30, T. 23 N., R. 107 W. in the eastern part of the Green River basin. A segment of this core is shown in figure 5. The number of varves counted per foot varied between 3,500 and 5,000 and averaged 4,200.

## SUNSPOT CYCLES

Sunspots are dark spots on the Sun's surface that are related to electric-magnetic disturbances. Sunspots occur in groups that vary in number and that

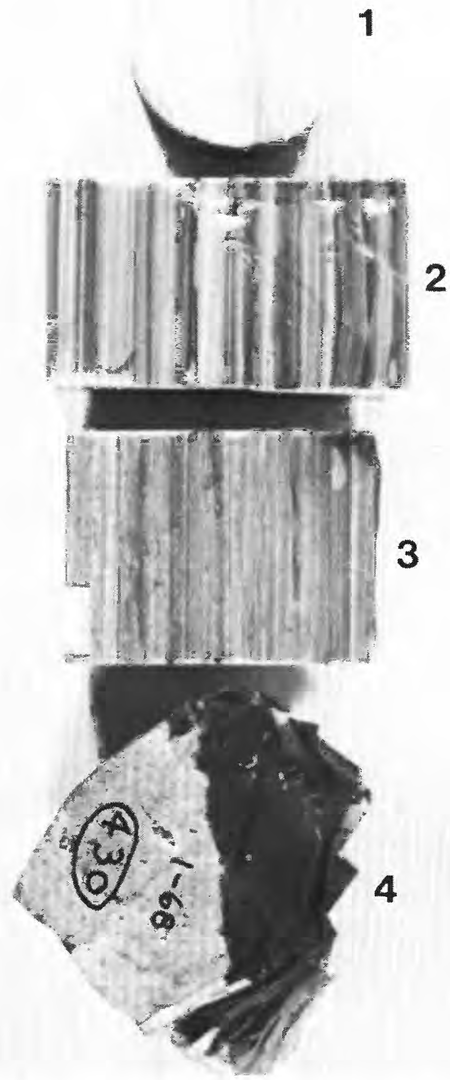



FIGURE 4.—Core and outcrop samples showing varves and grades of oil shale. 1, tan varved oil shale yielding 3 gallons of oil per ton of rock; 2, tan and brown varved oil shale yielding 9 gallons of oil per ton of rock; 3, light to dark-brown varved oil shale yielding 15 gallons of oil per ton of rock; and 4, black unvarved(?) oil shale yielding 46 gallons of oil per ton of rock. Sample 1 is 1½ inches in diameter.

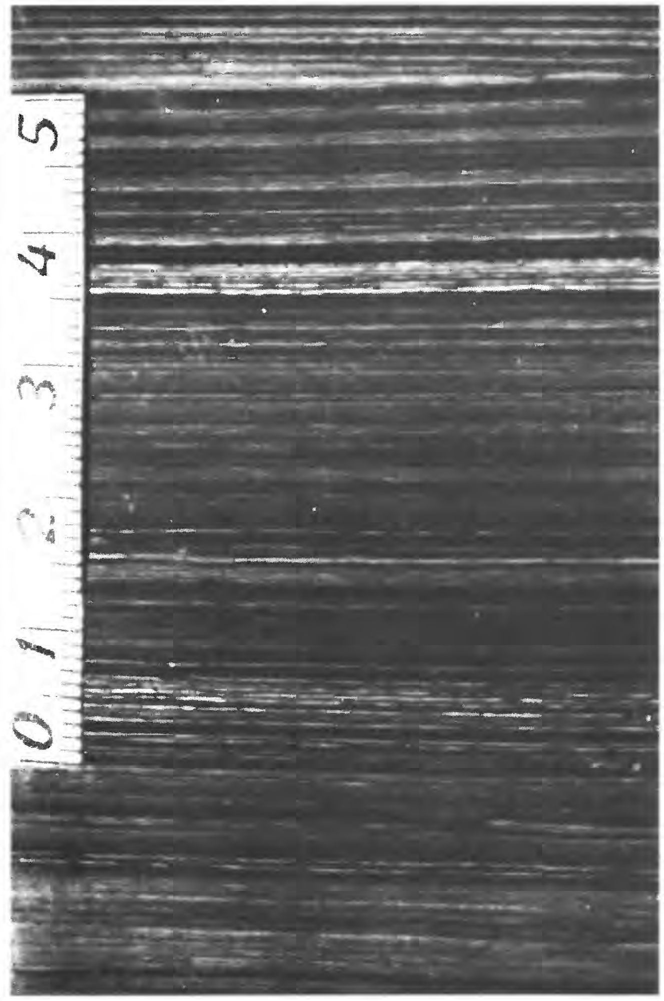



FIGURE 5.—Oil-shale varves in polished core sample from near the base of the Laney Member of the Green River Formation in U.S. Bureau of Mines Wyoming Corehole No. 1. Scale is in centimeters.

appear in a periodic manner. The interval between periods of maximum sunspots averages 11.1 years (Baker, 1961, p. 187). The average temperature of the Earth is higher when sunspots are at a minimum, because the Sun at such times radiates greater energy.

Recurrent groups of unusually thick varves in oil-shale beds in the Green River Formation, which occur in intervals ranging from about 7 to 18 years and averaging a little less than 12 years, were identified as sunspot cycles by Bradley (1929, p. 104). He interpreted the thick varves as occurring during years of sunspot minima, when Lake Gosiute was abnormally low, when the waters were abnormally warm, and when rates of accumulation of carbonates and organic matter were highest. My conclusions concerning sunspot cycles do not agree with those of Bradley (1929). Although thick and thin varves are present in oil-shale beds throughout the Green River Formation, I have not observed that they occur in consistent numbers of years, or regular periods that can clearly be attributed to sunspot minima or maxima.

## SOLAR SYSTEM PERTURBATIONS

Temperature is the most important element that controls the type and location of the Earth's climates.

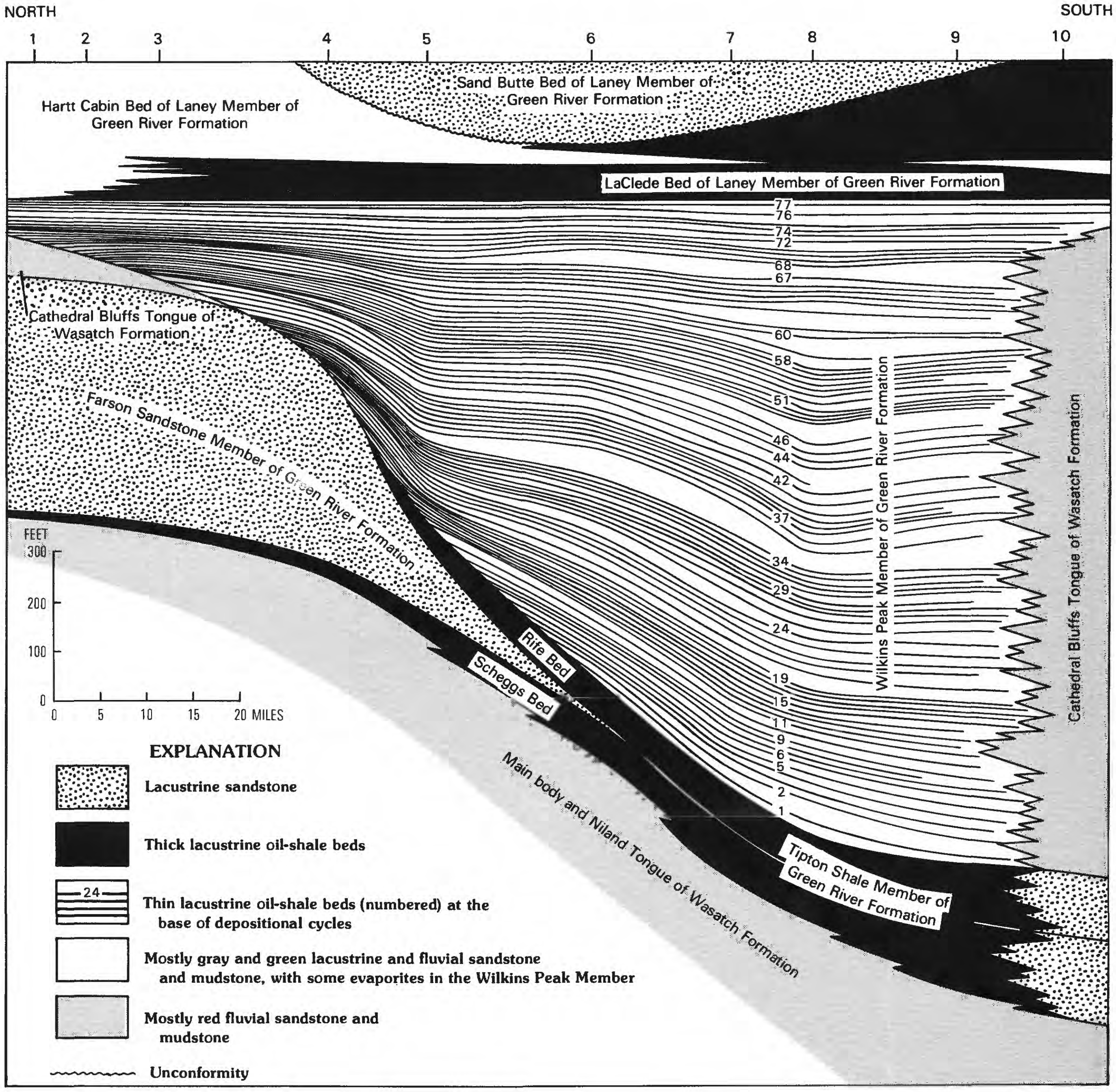
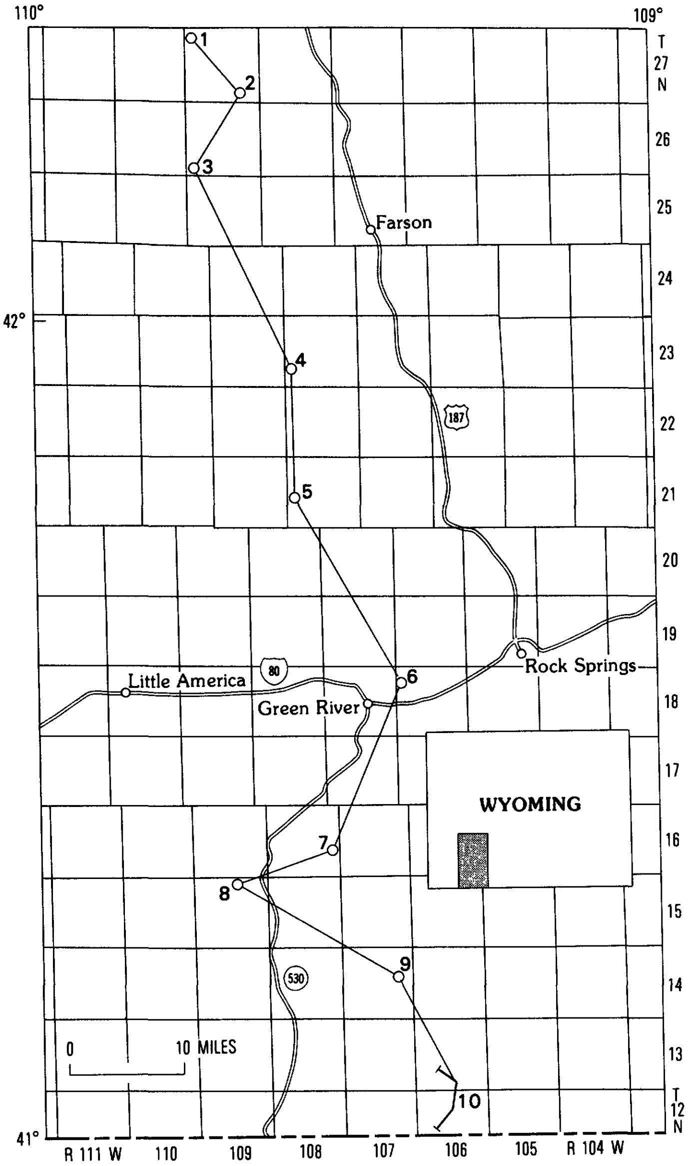



FIGURE 6 (above and facing page).—North-south cross section of the Green River Formation in the Green River basin showing the stratigraphic locations of 77 beds of cyclically deposited oil shale in the Wilkins Peak Member of the Green River Formation. Modified from Roehler (1991b).

The amount of total heat received by the Earth from the Sun is constant, but the distribution of the heat across the Earth's surface is determined by three periodic variables: (1) precession of the equinoxes, (2) obliquity of the ecliptic, and (3) orbit eccentricity. The precession of the equinoxes varies from about 14,000 to 23,000 years, but has an average period of about 21,000 years (Fischer, 1980, 1986). The obliquity of the ecliptic varies between 22° and 24½° in a period of 40,400 years (Milankovitch, 1920). The eccentricity of the Earth's orbit has a period of about 100,000 years (Brooks, 1926).




**SOURCE OF DATA**

1. U.S. Department of Energy, Wyoming No. 13, sec. 6, T. 27 N., R. 108 W.
2. U.S. Department of Energy, Wyoming No. 12, sec. 35, T. 27 N., R. 108 W.
3. U.S. Department of Energy, Wyoming No. 11, sec. 31, T. 26 N., R. 108 W.
4. U.S. Bureau of Mines, Wyoming No. 1, sec. 30, T. 23 N., R. 107 W.
5. Union Pacific Railroad Company, Blue Rim 44–19, sec. 19, T. 21 N., R. 107 W.
6. Energy Research and Development Administration, White Mountain No. 1, sec. 7, T. 18 N., R. 106 W.
7. Energy Research and Development Administration, Blacks Fork No. 1, sec. 24, T. 16 N., R. 108 W.
8. Union Pacific Railroad Company, El Paso No. 44–3, sec. 3, T. 15 N., R. 109 W.
9. U.S. Department of Energy, Currant Creek Ridge No. 1, sec. 14, T. 14 N., R. 107 W.
10. U.S. Geological Survey, Measured section No. 1 (Roehler, 1981), T. 12–13 N., R. 106 W.

## CYCLOSTRATIGRAPHY IN WILKINS PEAK MEMBER OF GREEN RIVER FORMATION

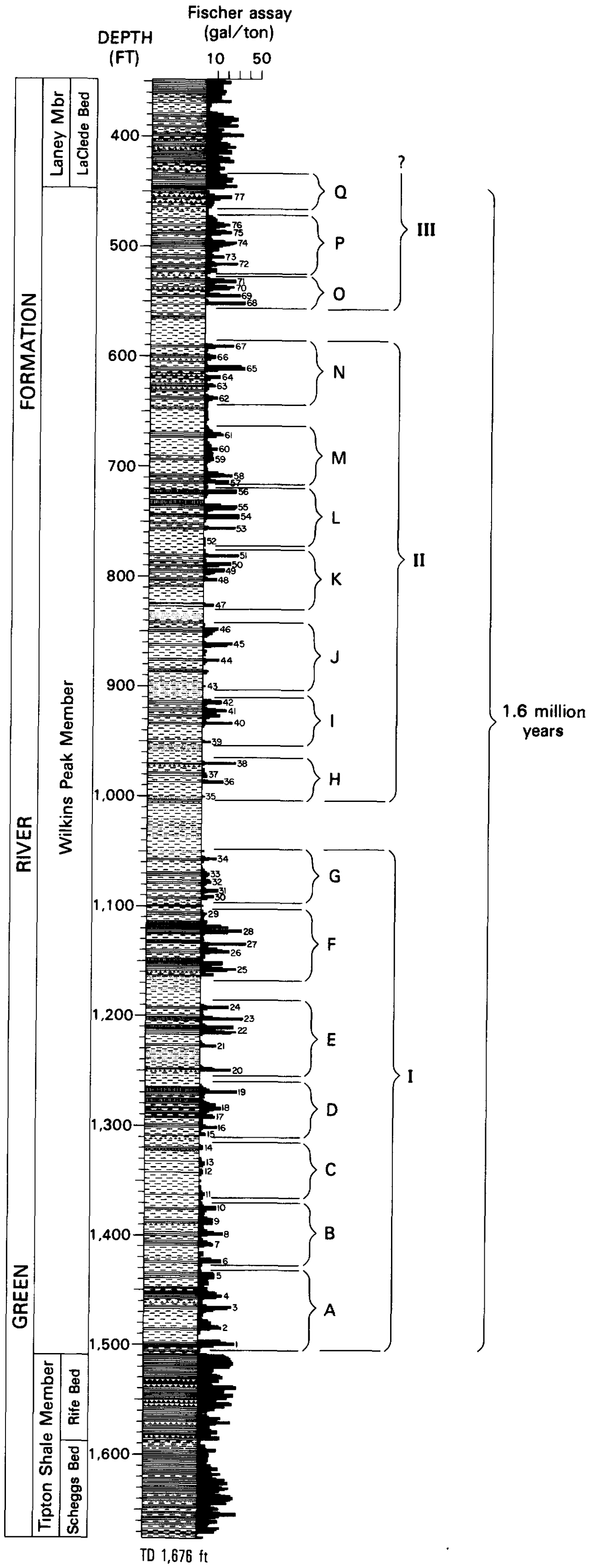
Astronomical time rarely agrees with geologic time. An exception to this rule is found in the cyclostratigraphy of the Wilkins Peak Member of the Green River Formation, where eccentricity and precessional cycles form clearly defined time increments. The obliquity cycle was not identified in the Wilkins Peak Member, but an undetermined cycle with a period of about 727,000 years is present.

### PRECESSION OF THE EQUINOXES

The polar axis of the Earth revolves around the ecliptic pole in a nonconcentric manner with a period that averages 21,000 years. This motion, which causes the equinoxes to slide westward along the ecliptic at the rate of 50 seconds per year, is called the precession of the equinoxes (Baker, 1961, p. 45).

The stratigraphy of the Wilkins Peak Member is distinguished by 77 depositional cycles, each of which is composed of repetitive lithologies that reflect periodic climate changes during the late early and early middle Eocene (Roehler, 1991b). At the depositional centers of the basin of Lake Gosiute, the lithologies of each of the cycles consist of dark-brown oil shale at the base, white to brown bedded evaporites (trona or halite) in the middle, and dark-green dolomitic mudstone at the top (Roehler, 1982). The oil-shale beds were deposited in large saltwater lakes, when the climate was warm and humid; the bedded evaporites were deposited in salt pans as the lakes shrank in size and eventually dried up, when the climate was hot and arid; and the mudstones were deposited on mudflats that covered the floor of the basin after the lakes had dried up, also when the climate was hot and arid. Thin-bedded dolomites and varved mudstones of playa lake origin are commonly present in the mudflat mudstones. Partial cycles occasionally are present where one of the three lithologies in the cycles is missing by erosion, nondeposition, or dissolution. The 77 cycles are easily correlated across the Green River basin in drill holes and outcrop sections using the oil-shale beds that form the base of the cycles (fig. 6).

I have selected the Energy Research and Development Administration Blacks Fork Corehole No. 1 in sec. 24, T. 16 N., R. 108 W. (fig. 6, point 7) to illustrate the lithologic and chronologic relationships of the 77 depositional cycles. The core from this hole has been preserved and is available for inspection at the U.S. Geological Survey Core Research Center, Building 810, Denver Federal Center, Denver, Colo.



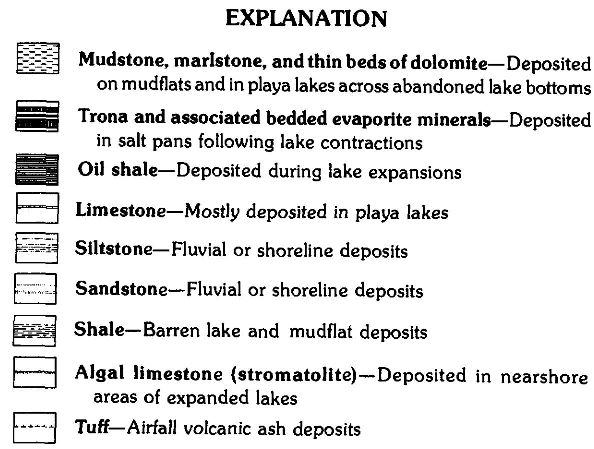




FIGURE 7.—Energy Research and Development Administration Blacks Fork Corehole No. 1 showing lithologies, histograms of Fischer assays of oil-shale beds, depositional cycles 1–77, bundles of depositional cycles A–Q, and superbundles I–III (top of III undetermined).

The stratigraphic positions of the 77 depositional cycles are indicated in figure 6 and shown in detail on the right side of the Blacks Fork No. 1 core in figure 7. The numbers identify the oil-shale beds at the base of each depositional cycle utilizing histograms of oil yields determined by Fischer assay. Each cycle, however, includes not only the numbered oil-shale beds but also the beds composed of evaporites, mudstones, and other lithologies that overlie and separate the oil-shale beds.

The lithologies of the depositional environments in depositional cycle 23 in the Blacks Fork No. 1 core are described in figure 8. Cycle 23 is considered to be representative of the depositional cycles, although none of the 77 cycles is precisely like any other in thickness or composition. The basal oil shale in the cycle, between 1,204.5 ft and 1,203.4 ft, is composed of black, varved shale and one thin layer of tan-brown, lenticular dolomite. The salt pan in the cycle is located between 1,203.4 ft and 1,201.0 ft. The brown trona deposited in the salt pan contains thin interbedded black oil shale, which suggests that deposition in the pan was at times interrupted by lacustrine flooding. The dark-olive-green mudflat mudstone, from 1,198.9 ft to 1,193.6 ft, is characteristically massive, or

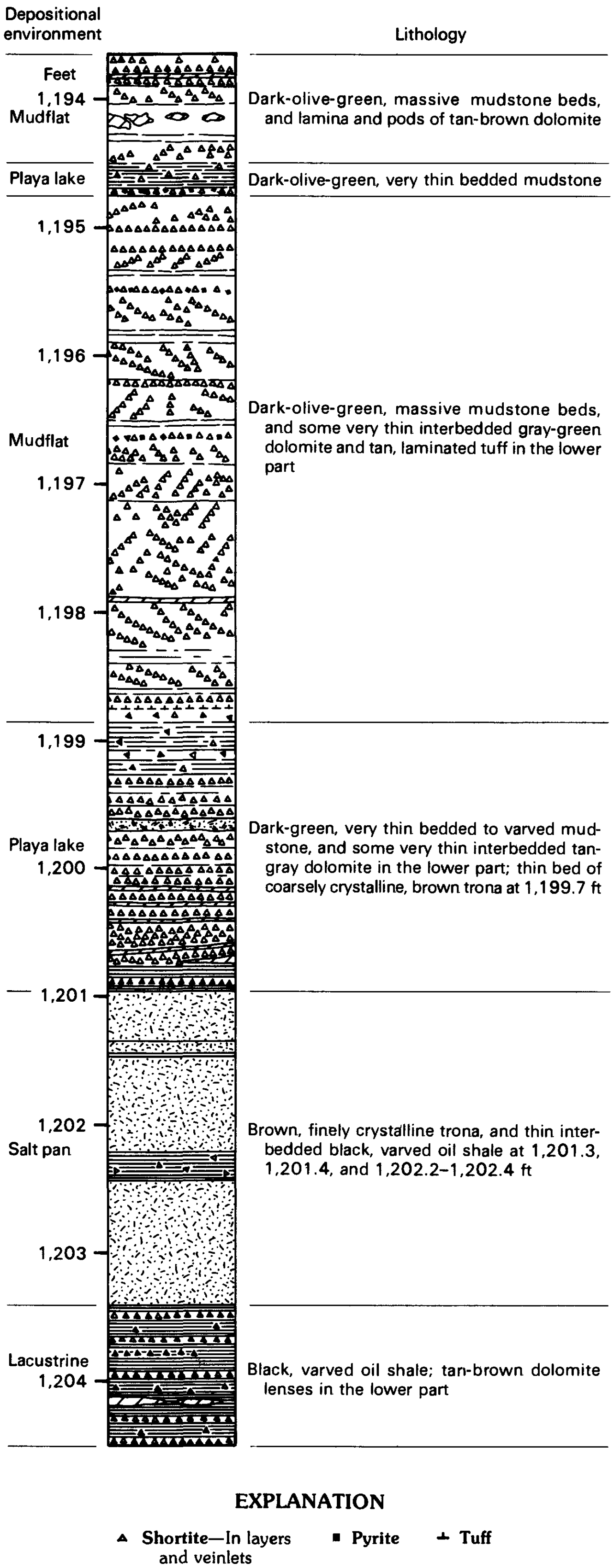



FIGURE 8 (facing column).—Depositional environments and lithologies of depositional cycle 23 in the Wilkins Peak Member in the Blacks Fork No. 1 core shown in figure 7. Corehole depths in feet.

unbedded, but contains some very thin beds of gray-green dolomite and a thin layer of tuff near the base. At the base of (from 1,201.0 ft to 1,198.9 ft) and interbedded with the mudflat mudstones are playa lake deposits that consist of varved or very thin bedded, dark-green, or dark-olive-green mudstone containing thin beds of tan-gray dolomite. Veinlets and thin layers of shortite crystals are abundant and are believed to have formed from saline pore waters during diagenesis. Pyrite is present in a few mudstones.

The Wilkins Peak Member in the Blacks Fork Corehole No. 1 is 1,063 ft thick (rounded to the nearest whole foot). The member is composed of 262 ft of oil shale in beds that range from less than 1 ft to more than 16 ft but average 3.4 ft thick. Using the observed average rate of deposition of 4,200 years per foot (discussed previously), the time required to deposit the oil shale in the member was about 1.1 million years.

Deposition of the entire Wilkins Peak Member is believed to have taken about 1.6 million years. This length of time has been estimated from the stratigraphic thickness of the member, from varve counts, and from potassium-argon dates of biotites in air-fall tuffs determined by Evernden and others (1964), Mauger (1977), O'Neill (1980), and Krishtalka and others (1987). O'Neill (1980, p. 51) calculated a date of about 46.6 Ma for a tuff bed located a few feet below the top of the Wilkins Peak Member. No accurate ages have been established for tuff beds located in the lower part of the member, but the base of the member should date at about 48.2 Ma. The 48.2 Ma date for the base of the member may or may not agree with wide-ranging radiometric ages listed for the upper lower Eocene by Krishtalka and others (1987, table 4.1). If the total time required to deposit the Wilkins Peak Member was 1.6 million years, the 77 depositional cycles in the member have an average period of 20,779 years. This number conforms closely to the average period of 21,000 years for the cycle of the precession of the equinoxes. Each of the 77 depositional cycles in the Wilkins Peak Member thus appears to represent one precessional cycle.

During each precessional cycle, the obliquity of the ecliptic affects climate changes. The greater the obliquity, the farther the distance of the Sun is to the equator, the quantity of heat received at the equator decreases, and the quantity of heat received at the polar and temperate regions increases. Conversely, as the obliquity of the ecliptic decreases, the heat received at the equator increases and at the polar and temperate regions it decreases. The oil shale beds in the 77 depositional cycles of the Wilkins Peak Member are believed to have been deposited during periods of lesser obliquity, when the climate was warm and humid, and the evaporites and mudflats in the cycles are believed to have been deposited during periods of greater obliquity, when the climate was hot and arid. These Eocene climate changes mimic those of the Pleistocene glacial-interglacial periods described by Milankovitch (1941).

### ECCENTRICITY CYCLES

The Earth's orbit around the Sun is elliptical. Its distance from the Sun in this elliptical orbit varies from 91,300,000 miles (perihelion) to 94,500,000 (aphelion), with an eccentricity of 0.017 or 1/60 (Baker, 1961, p. 39–49). The period of the cycle of this eccentricity is about 100,000 years. When the Earth is at perihelion it travels in its orbit more rapidly than it does at aphelion. As stated by Brooks (1926, p. 116), "the season which coincides with perihelion will be short and relatively warm, that which coincides with aphelion will be long and relatively cold."

The 77 depositional cycles, or cycles of precession of the equinoxes, in the Wilkins Peak Member are grouped into bundles that range from 4 to 6 but average 5. These bundles are discernible from the grouping of oil-shale beds in the Blacks Fork Corehole No. 1 (fig. 7), where they are labelled A to Q. If the precessional cycles had a period of 20,779 years (discussed previously) and they generally form bundles of five, then each bundle represents about 103,895 years, which conforms to the 100,000 year eccentricity cycle.

The cause for the precessional bundling was explained by Fischer (1980, p. 101), who wrote that because the eccentricity orbit is cyclic "with a mean period about four or five times that of the precessional cycle, it follows that precessionally induced climate fluctuations should wax and wane in a rhythmic pattern *** in bundles or sets." Precessional cycles 1 to 5 that compose eccentricity cycle A and precessional cycles 6 to 10 that compose eccentricity cycle B in figure 7 are enlarged in figure 9 to illustrate details of the oil-shale histograms. Each of the oil-shale peaks in the histograms in figure 9 corresponds to a relatively cooler and wetter climatic period that resulted in expansions of Lake Gosiute. These were followed by lake contractions, salt-pan development, and lake extinctions that occurred during hot and dry periods in the intervals between the oil-shale peaks. The cooler and wetter periods are believed to correspond to the aphelia of the precessional cycles (times of minimum insolation) and the hotter and drier periods to the perihelia of the precessional cycles (times of maximum insolation). The intervals, or breaks, between the bundles probably occurred during the perihelia of eccentricity cycles.

### UNDETERMINED ASTRONOMICAL(?) CYCLES

The groups of five eccentricity cycles in the Wilkins Peak Member in the Blacks Fork Corehole No. 1 can be grouped into superbundles of seven each. These superbundles are labelled I–III in figure 7. Note that only the basal part of superbundle III is present in the upper part of the Wilkins Peak Member. The interval that separates superbundles I and II is about 50 ft thick and the interval that separates superbundles II and III is about 38 ft thick. The time represented by these intervals is roughly estimated to be about 31,000 and 23,500 years, respectively, which corresponds to a period equal to one precessional cycle for each interval. These "gaps" appear to represent climatic periods that were uniformly hot and dry; the reason for their presence between the superbundles is unknown.

The superbundles are composed of seven eccentricity cycles that average 103,895 years each (discussed previously), and each superbundle consequently represents a period of a little more than 727,000 years. Fischer (1980) reported that Gilbert (1895), while investigating rhythmic features of the Upper Cretaceous Niobrara Formation in southeastern Colorado, found a sequence of rocks that consisted of 33 limestone-shale couplets ranging in thickness from about 1.5 to 2.6 ft. According to Fischer (1980, p. 96), Gilbert believed the 33 couplets represented 21,000 year precessional cycles, or a total of 693,000 years. The astronomical origin of Gilbert's 693,000 year cycle was not explained; however, it closely corresponds to the 727,000 year superbundles that are present in the Wilkins Peak Member.

Ramsbottom (1979) concluded from studies of the Carboniferous System in northwestern Europe that Westphalian rocks there transgressed and regressed as a result of eustatic changes at an average rate of 1.66 million years. Whether major sea-level changes of this sort could be related to the 1.6 million year period required for the deposition of the Wilkins Peak Member remains a matter for speculation.

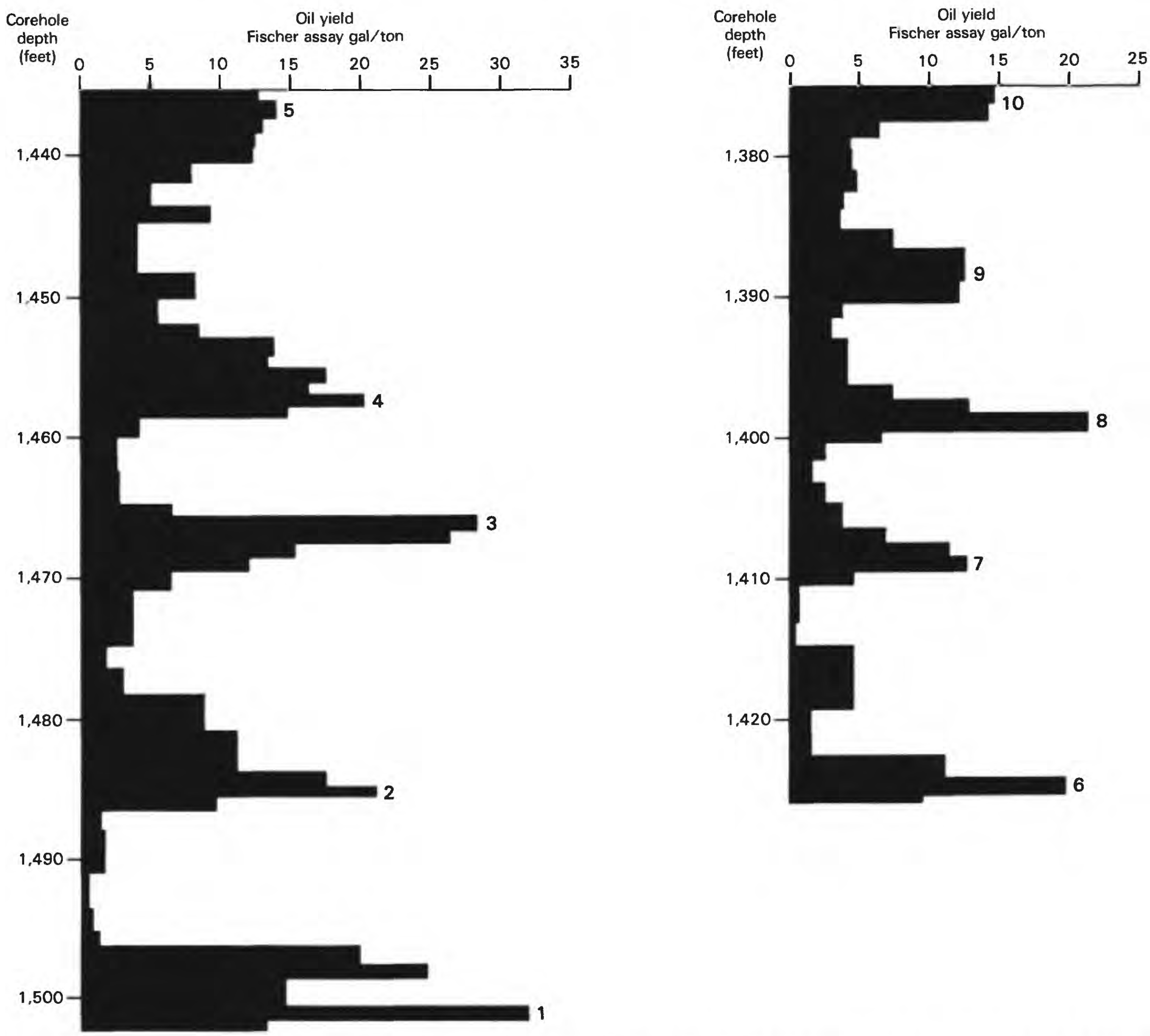



FIGURE 9.—Histograms of Fischer assays of oil-shale beds in the Blacks Fork Corehole No. 1 illustrating precessional cycles 1–5 of eccentricity cycle A and precessional cycles 6–10 of eccentricity cycle B. The stratigraphic positions of the histograms are indicated in figure 7.

## DEPOSITIONAL ENVIRONMENTS

Depositional environments are here defined as the paleogeographic locales where the physical, chemical, and biological conditions produced favorable habitats for specific plants and animals and where distinct types of sediments were deposited. Depositional environments are important to the study of Eocene rocks in the greater Green River basin because they comprise the principal lithologic associations (the mappable subdivisions) of the Wasatch, Green River, and Bridger (Washakie) Formations. The depositional environments in this report are classified as: (1) fluvial (includes mountain front alluvial fans and pediments and intrabasin flood plains), (2) paludal (includes swamps and marshes), (3) freshwater lacustrine (includes shorelines and deltas), (4) saltwater lacustrine, (5) pond (includes playa lakes), (6) salt pan (evaporites), (7) mudflat, and (8) volcanic (includes fluviovolcanics).

## FLUVIAL

### ALLUVIAL FANS AND PEDIMENTS

The fluvial environment along mountain fronts at the basin margins consists mostly of alluvial fans, or of coalescing alluvial fans that form pediments. The alluvial fans along the south and west margins of the basin are commonly several hundred feet thick and several miles wide, and they weather to high-standing ridges or plateaus. They are generally composed of conglomerates that grade basinward into sandstone, siltstone, and mudstone. At their distal edges most of the fans interfinger with normal flood-plain deposits, but, in places, they interfinger with lacustrine deposits to form deltas and beaches.

A classic example of an alluvial fan deposit is Richards Mountain, located near the southeast corner of the Green River basin in T. 12 N., Rs. 105–106 W. The rocks that form Richards Mountain are situated stratigraphically in the lower part of the main body of the Wasatch Formation. The mountain is a lenticular ridge about 7.5 mi long that rises 1,350 ft above the surrounding terrain. The crest of the mountain is located near the center of the alluvial fan (fig. 10). The beds near the center of the fan dip 5°–10° N. and are about 700 ft thick. Most of the beds at the center of the fan are lenticular conglomerates, less than 1 ft to more than 75 ft thick, composed of rounded, poorly sorted boulders, cobbles, and pebbles of sandstone, limestone, and chert in a coarse-grained sandstone matrix. The sandstone clasts are tan and gray and were eroded mostly from the Middle Pennsylvanian to Upper Permian Weber Sandstone and Lower Jurassic Glen Canyon Sandstone (fig. 11). The limestone is gray and the chert is varicolored; these clasts were derived mostly from the Mississippian Madison Formation. These formations crop out south of Richards Mountain along the north flank of the Uinta Mountains. Interbedded with the conglomerates are thinner beds of tan, coarse-grained sandstone, and gray and red, sandy mudstone that range in thickness from less than 1 ft to about 35 ft. The few cobbles of Uinta Mountain Group present in the conglomerate beds attest to the breaching of the Uinta Mountains to their Precambrian core during the early Eocene.

Another example of an alluvial-fan deposit is the Canyon Creek conglomerate facies of the Wilkins Peak Member of the Green River Formation located south of the Rock Springs uplift in Tps. 12–13 N., Rs. 101–103 W. This fan dips 1°–3° northward from the north flank of the Uinta Mountains (fig. 12). It is composed of the same conglomerates and other

FIGURE 10.—Outcrops of main body of the Wasatch Formation near center of Richards Mountain alluvial fan in SE1/4 sec. 13, T. 13 N., R. 106 W., southeastern Green River basin. View is northeast. Outcrops shown are about 700 ft thick.

clastic rocks as the Richards Mountain alluvial fan, but with more numerous and thicker interbeds of sandstone and mudstone. Along Canyon Creek drainage in T. 12 N., Rs. 101–102 W., the fan is relatively flat lying, about 300 ft thick, and it weathers to plateaus with sheer bounding cliffs. The distal edge of the fan crops out a few miles north of Canyon Creek along the drainage of Salt Wells Creek and its tributaries. There the conglomerates are missing and the coarse clastics that characterize the fan farther south change facies by intertonguing with finer textured saltwater lacustrine sandstone and oil-shale and mudflat mudstone. This intertonguing takes place over most of the north half of the fan, and where it occurs, some distal segments of the fan form lacustrine beaches and small deltas. These beaches and deltas locally contain abundant disarticulated fish, crocodile, and bird bones. The bird bones are concentrated in isolated layers that are believed to be the remains of rookeries. The largest bird-bone concentration is located near the top of the fan in C SE1/4 sec. 13, T. 12 N., R. 102 W. This fossil site is identified on the Scrivner Butte 7½′ geologic quadrangle, which was mapped by Roehler (1973a). The bird fossils from this site were collected and identified as primitive flamingos by P.O. McGrew of the University of Wyoming (oral commun., 1973).

The rocks of fluvial origin located along the front of the Granite and Wind River Mountains at the northeast and north margins of the greater Green River basin form coalescing alluvial fans, or pediments, composed mostly of arkose. The arkose comprises a distinct lithofacies that was named the

FIGURE 11.—Sandstone and limestone boulders in the Richards Mountain alluvial fan shown in figure 10. Scale is indicated by Brunton compass.

FIGURE 12.—Canyon Creek alluvial fan facies in Wilkins Peak Member of Green River Formation on west slopes of Pine Mountain in NE$^1/_4$ sec. 7, T. 12 N., R. 103 W., south of the Rock Springs uplift. Cliff face is about 150 ft high.

Battle Spring Formation by Pipiringos (1955). The Battle Spring Formation intertongues southwestward across the eastern Great Divide basin with less arkosic rocks of fluvial and lacustrine origins that comprise the typical lithologies of the Wasatch, Green River, and Bridger (Washakie) Formations (this volume, Chapter E, fig. 12).

## FLOOD PLAINS

The sedimentary rocks that compose the flood-plain depositional environment consist of mostly interbedded sandstone, siltstone, mudstone, and shale, and in places, of minor thin beds of conglomerate, limestone, and carbonaceous shale. The overall color of these rocks ranges from gray and green to red or variegated. The variegated sequences normally contain various shades of red, and may include other colors such as gray, green, orange, or black. A typical succession of rocks deposited on a flood plain is shown in a columnar section, figure 13.

The sandstone in the flood-plain environment was deposited mostly as stream channels and splays. The stream channel units or deposits are typically gray or tan, are lenticular in cross section, and exhibit scoured bases. They generally range in thickness from a few feet to a few tens of feet. The channels may contain layers of conglomerate, especially near their bases. The sandstone in the channels usually grades upward from very coarse grained near the base to fine grained at the top. It is usually trough crossbedded, but point bars with planar foresets are sometimes present within the crossbeds. Thin subparallel sandstone beds are commonly present at the top of the channels.

The splay deposits in the flood-plain environment are mostly thin, parallel- to subparallel-bedded sandstone and some interbedded siltstone and mudstone. They usually weather to thin, laterally persistent, parallel benches; this feature distinguishes them in outcrops from the stream-channel sandstones, which are thicker, massive, and lenticular in cross section.

An example of typical flood-plain deposition in Eocene rocks in the greater Green River basin is shown in a block diagram, figure 14. As indicated in figure 14, the distributary streams that crossed the flood plains would overflow their banks during periods of flood. The sediments expelled from the

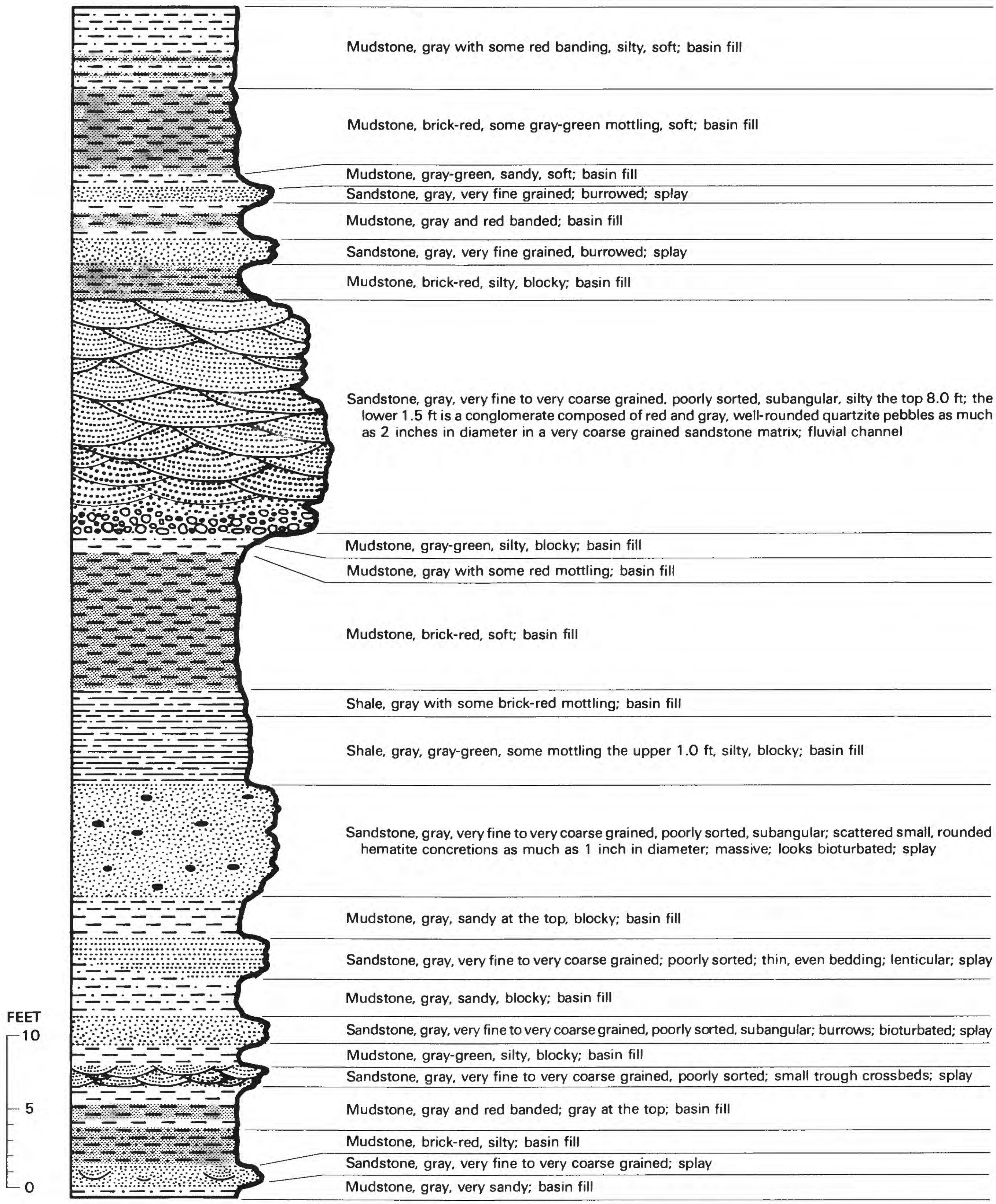



FIGURE 13.—Typical flood-plain deposits in upper part of main body of the Wasatch Formation in SE1/4 sec. 14, T. 13 N., R. 105 W., southeast of Little Mountain.

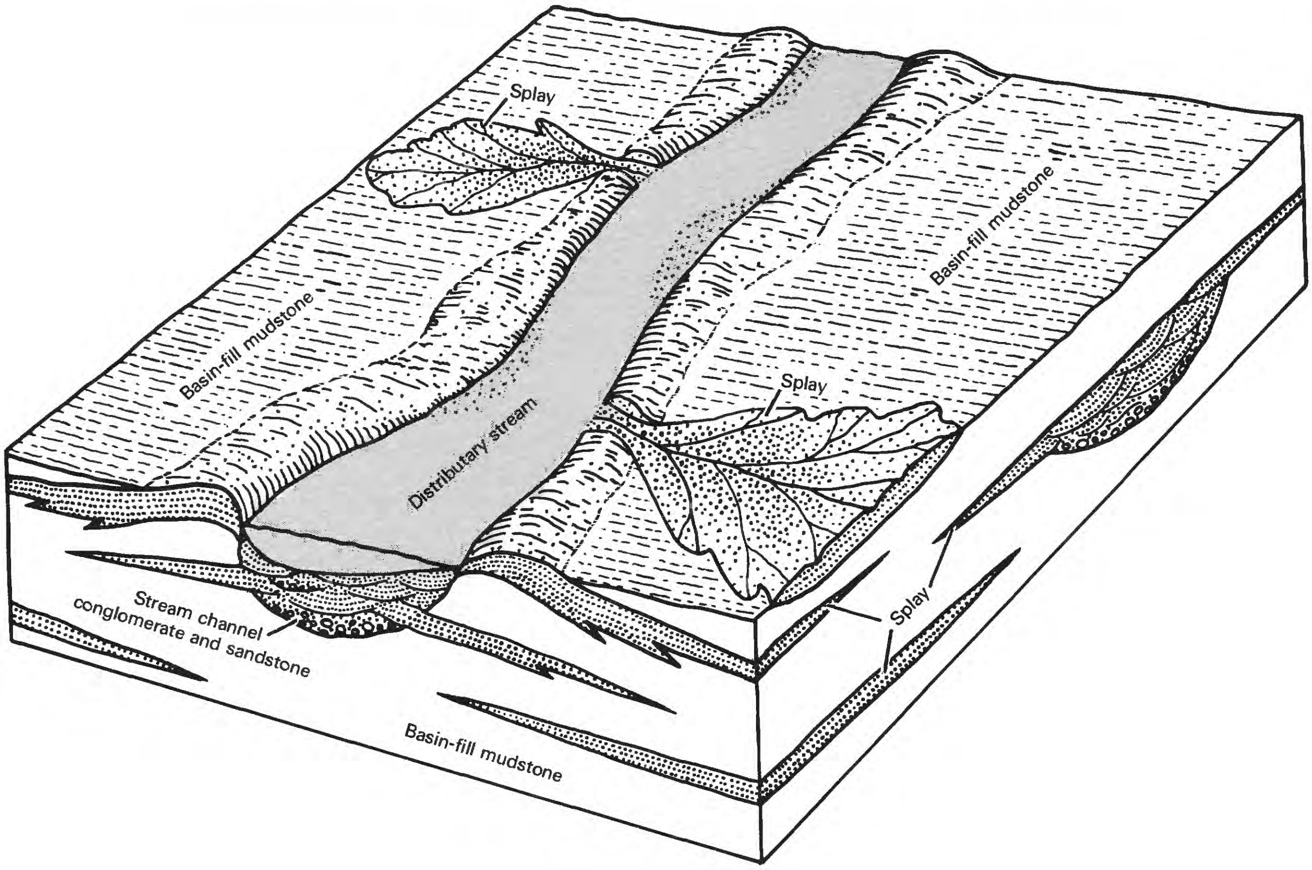



FIGURE 14.—Typical flood-plain deposits in Eocene rocks in greater Green River basin. Not to scale.

stream channels, through breaches or crevasses, fanned outward onto adjacent flood basins to form splays. The splay sediments that accreted from the breaches coarsen upwards from the base of the splay but become finer textured toward the distal edges of the splay.

Basin-fill mudstone was deposited in the flood basins between the splays and distributary streams. These mudstones are generally silty to sandy but seldom dolomitic. Thin beds of limestone or carbonaceous shale are occasionally present where the normal flood-basin mudstones were replaced by shallow ponds or marshes.

The configuration and composition of a typical flood-plain sequence in cross-sectional profile are shown in a schematic diagram, figure 15. Photographs of outcrops of flood-plain sequences are shown in figures 16 and 17.

The thickness and slope of splay deposits at the place where they exit the stream channels were dependent on the depth and width of the crevasse, the volume of sediments expelled by the stream during flood stage, and the gradient of the flood-basin margins adjacent to the stream. Examples of two kinds of channel-splay relationships are shown in figures 18 and 19. In figure 18, the splay is thick and slopes steeply to the right (basinward) from the channel margin. The flood-plain deposits in figure 18 are located in the Washakie basin near the east edge of the greater Green River basin, where there was moderate topographic relief and where the basin soils were well aerated and dominantly red. In figure 19, the splays are thinner than the one shown in figure 18, and they slope very gently, almost imperceptibly, to the right away from the edge of a sandstone-filled stream channel. The flood-plain deposits in figure 19 were located near the depositional center of the greater Green River basin where topographic relief was slight and where the basin soils were water saturated and dominantly gray and green.

Some red and gray banded flood-plain deposits are formed by successions of paleosoils. Good examples of this type of sedimentation are found in the upper part of the main body of the Wasatch Formation along the east margin of the Washakie basin in Tps.

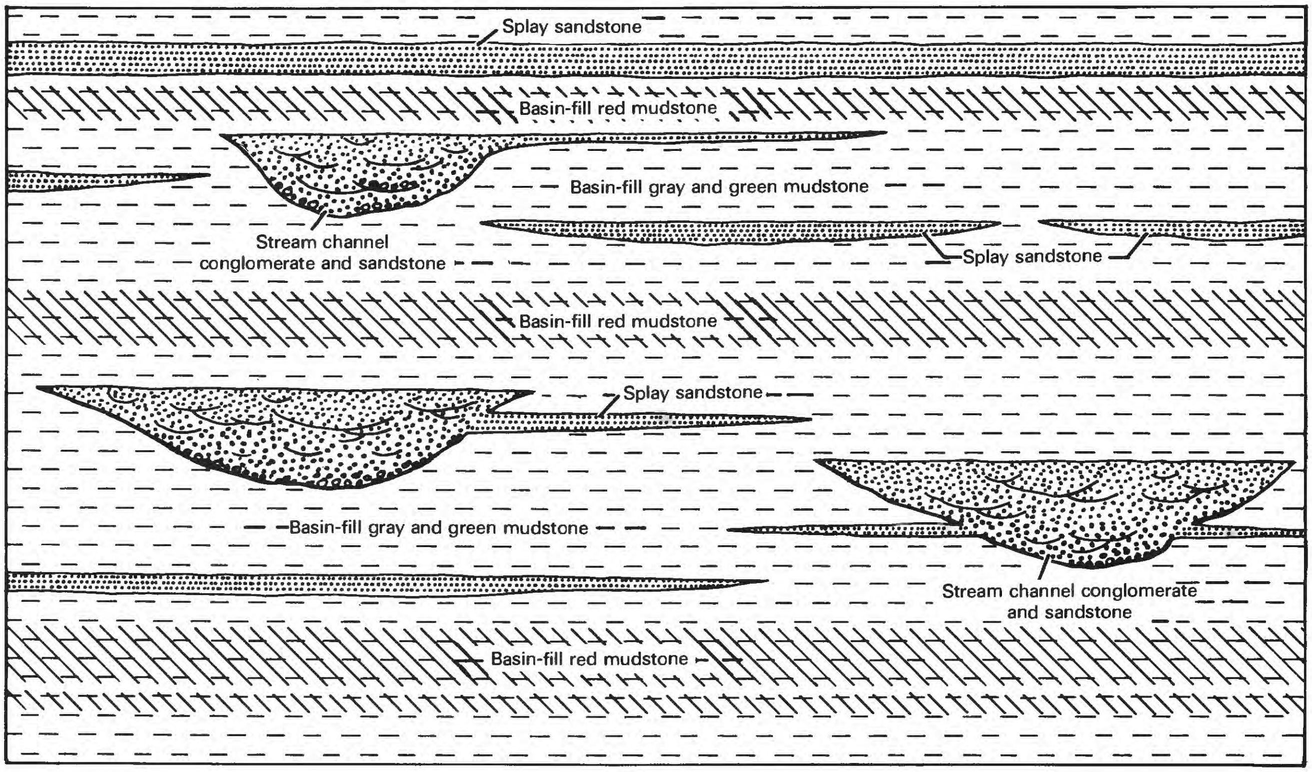



FIGURE 15.—Schematic cross section of typical flood-plain deposits in Eocene rocks in greater Green River basin.

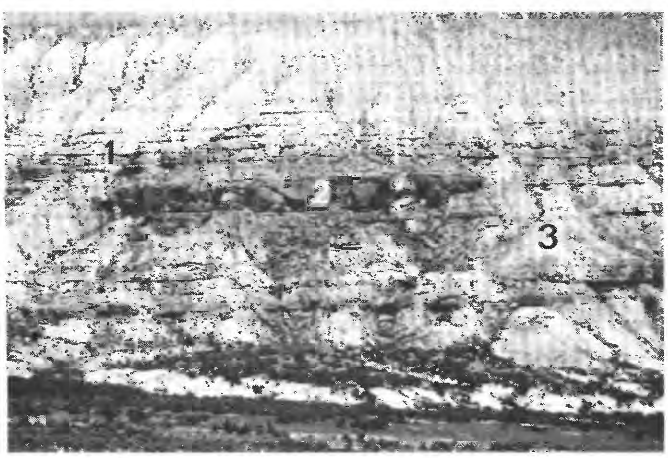



FIGURE 16.—Gray and green flood-plain deposits in Niland Tongue of Wasatch Formation on the north slopes of Middle Firehole Canyon in SW¼ sec. 34, T. 17 N., R. 106 W., southeastern Green River basin. 1, Brown-weathered, parallel-bedded splay sandstone; 2, brown-weathered, lenticular, trough-crossbedded, stream channel sandstone; 3, gray and green basin-fill mudstone. The stream channel sandstone is about 15 ft thick.

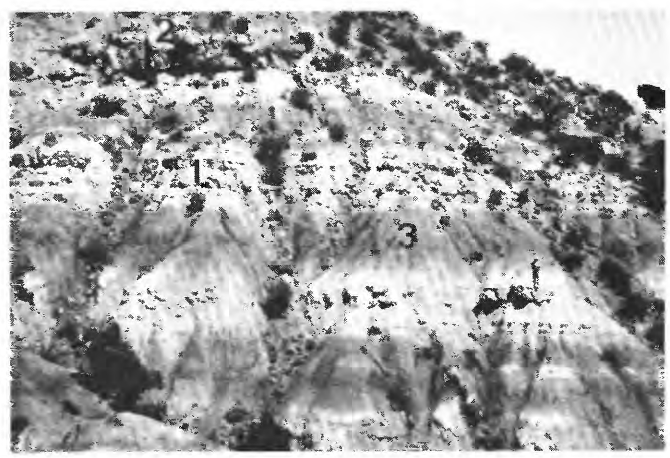



FIGURE 17.—Variegated flood-plain deposits in main body of Wasatch Formation on north slopes of Red Creek in NW¼SE¼ sec. 13, T. 13 N., R. 105 W., southeastern Green River basin. 1, White, parallel-bedded splay sandstone; 2, tan to brown, lenticular, trough-crossbedded, stream channel sandstone; 3, brick-red, basin-fill mudstone. Scale is indicated by person standing in lower right quarter of photograph.

14–16 N., R. 92 W. Figure 20 is a photograph of outcrops of one of these paleosoil intervals. The paleosoils are generally 1–3 ft thick and are composed of mudstone that was colored red by the oxidation of iron minerals in soils located on well-drained, well-aerated parts of flood plains. Underlying the red paleosoils are thicker green and gray mudstones that were probably deposited under water-saturated


FIGURE 18.—View to south, of red flood-plain deposits in main body of the Wasatch Formation in NE$^1/_4$SE$^1/_4$ sec. 13, T. 14 N., R. 92 W., southeastern Washakie basin. 1, Splay sandstone and mudstone beds dipping away from stream channel margins; 2, parallel-bedded, mudstone-filled stream channel. Scale is indicated by person standing at base of outcrops.

conditions, where the iron minerals in the soils were reduced.

## PALUDAL (SWAMP)

The paludal environment of deposition consists of forest swamps and reed swamps. Forest swamps are defined as the water-covered areas that were dominated by mosses, shrubs, and trees that formed bogs and produced peat (coal). Reed swamps were water-saturated marsh areas dominated by grasslike vegetation that produced carbonaceous mud (shale). With few exceptions, coal beds in the paludal environment are associated with carbonaceous shales. Thin beds of carbonaceous shale, however, may be present in flood-plain and shallow freshwater lacustrine environments where coal beds are absent.

Most coal beds in Eocene rocks in the greater Green River basin were deposited during the expansion and contraction stages of freshwater lakes. During the lake expansions, peat beds accumulated in drowned forest swamps. The resulting coal bed is usually underlain by reed swamp carbonaceous shale, and the carbonaceous shale is usually underlain by flood-plain sandstone and mudstone. The coal bed is usually overlain by freshwater lacustrine oil shale, which may contain mollusk shells at its base. This lithofacies succession is obviously reversed during lake contractions.

A block diagram illustrating the stratigraphic relationships of a drowned forest swamp is shown in figure 21. An example of a drowned forest swamp in outcrops is the Hay No. 2 coal bed in the upper part of the type section of the Niland Tongue of the Wasatch Formation in the Great Divide basin (fig. 22). Other examples of coal beds deposited in association with the expansions and contractions of freshwater lakes are the Vermillion Creek coal bed (fig. 23) and an unnamed coal bed (fig. 24), both of which crop out in the Niland Tongue of the Wasatch Formation in the Vermillion Creek basin.

## FRESHWATER LACUSTRINE

The Luman Tongue, Scheggs Bed of the Tipton Shale Member, and upper part of the Laney Member of the Green River Formation were deposited in


FIGURE 19.—Gray and green flood-plain deposits in main body of Wasatch Formation in roadcut on the west side of State Highway 373 in SW1/4 sec. 30, T. 17 N., R. 105 W., southeastern Green River basin. 1, Parallel-bedded splay sandstones and mudstones; 2, trough-crossbedded stream channel sandstone.

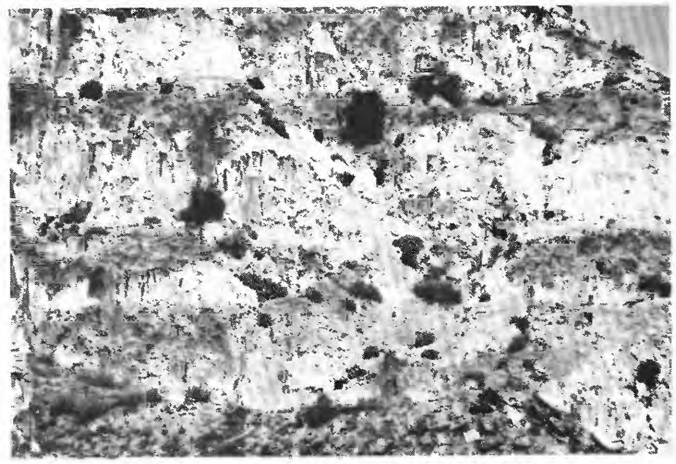


FIGURE 20.—Red paleosoils (dark bands) in main body of Wasatch Formation in SE1/4NE1/4 sec. 13, T. 15 N., R. 92 W., eastern Washakie basin. Outcrops shown are about 30 ft thick.

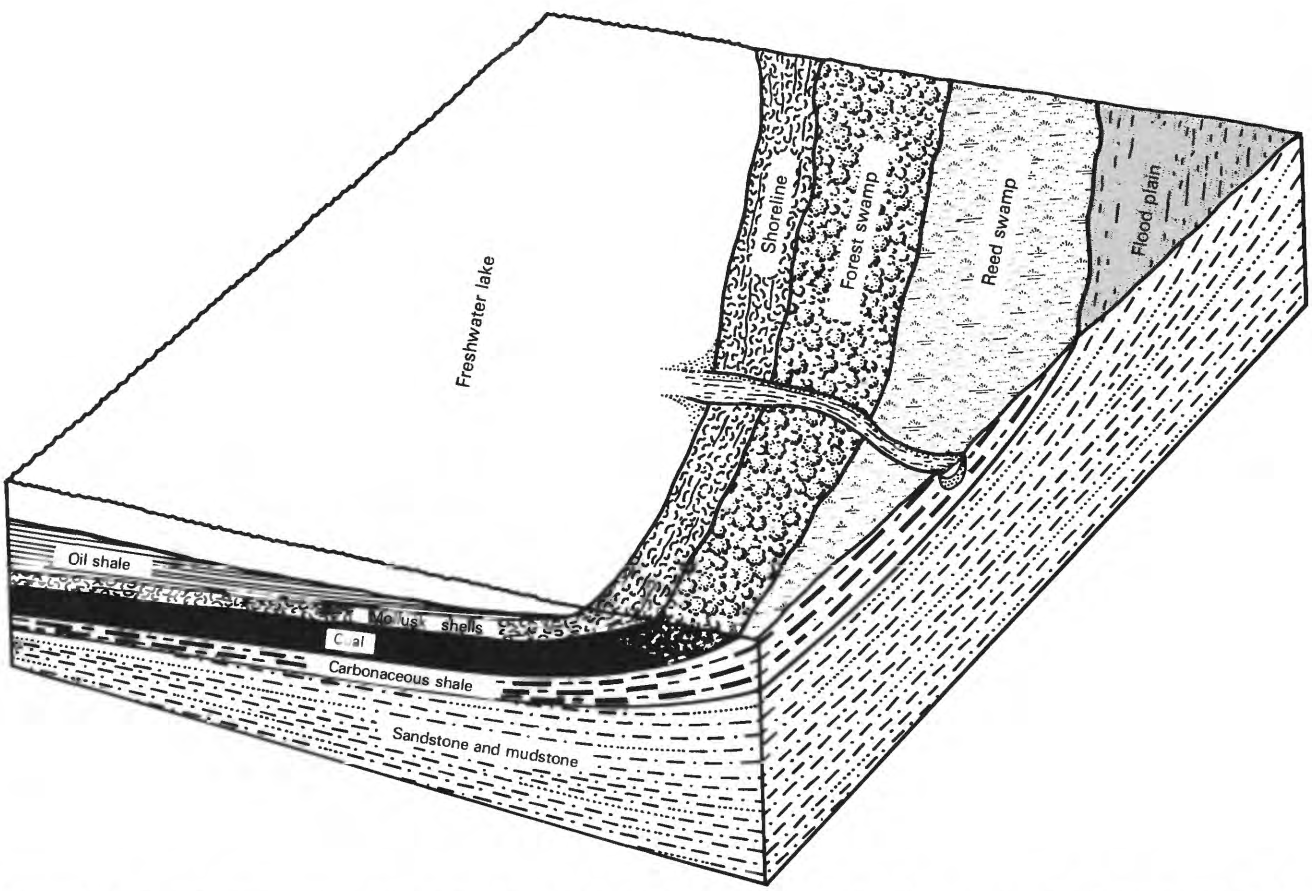



FIGURE 21.—Coal-forming stratigraphic relationships of a drowned forest swamp during the expansion of a freshwater lake. The lake expanded from left to right. Not to scale.

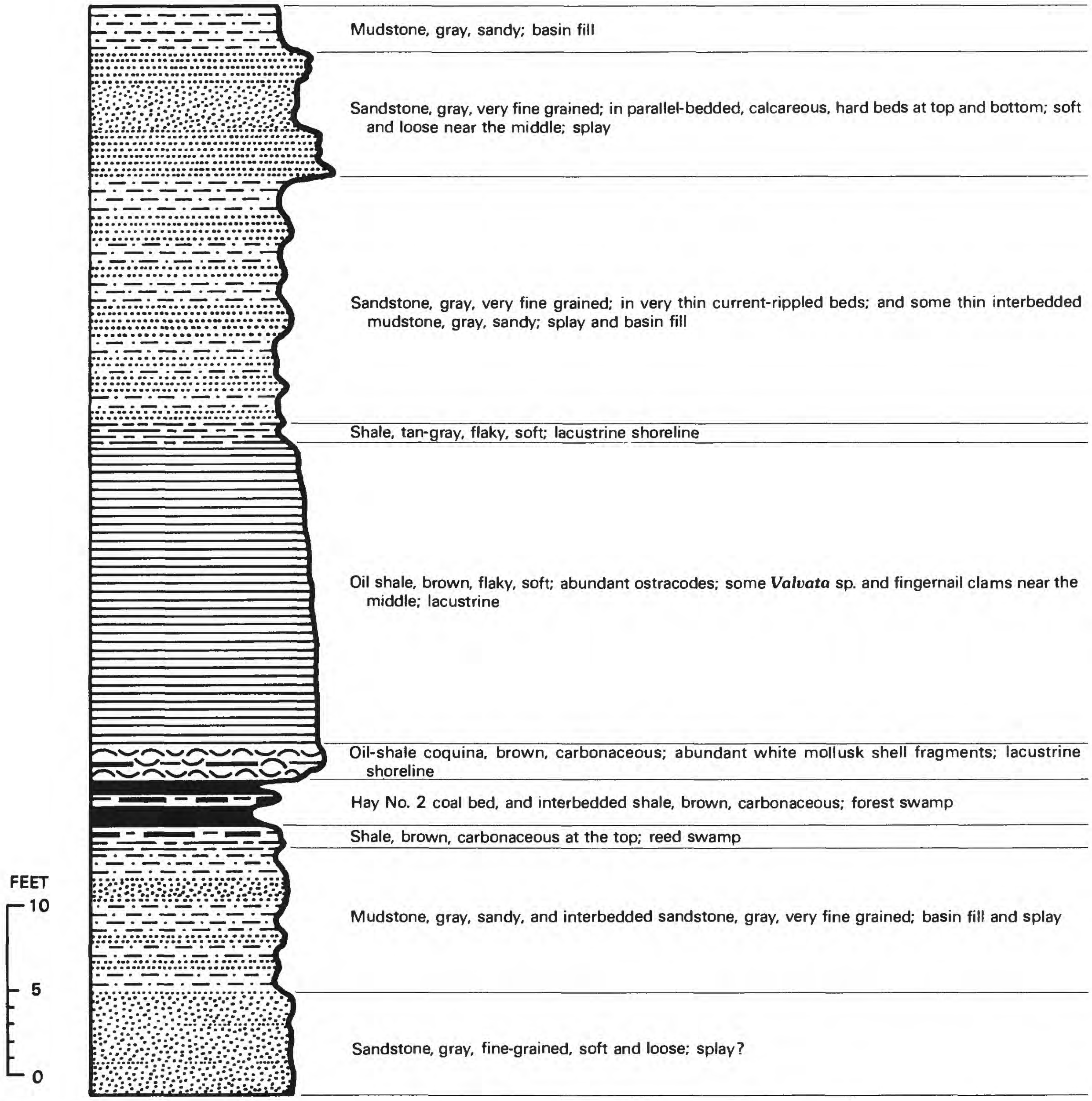



FIGURE 22.—Hay No. 2 coal bed and surrounding section. Coal bed derived from peat that accumulated in a drowned forest swamp. From type section of Niland Tongue of Wasatch Formation in NE1/4 sec. 23, T. 24 N., R. 96 W., central Great Divide basin (Roehler, 1989c).

freshwater lacustrine depositional environments. A few beds of freshwater lacustrine origin are also present in parts of the Wasatch, Bridger, and Washakie Formations.

The freshwater lacustrine environment primarily consists of two lithologies: (1) deep-water oil shale, and (2) offshore, nearshore, and onshore beach and delta sandstone. A generalized model for rocks deposited in the environment is shown in figure 25. Figure 25 is modeled for Eocene rocks deposited along the north flank of the Uinta Mountains, but it is typical of freshwater lacustrine and associated environments everywhere in the basin.

The oil-shale beds deposited in the freshwater lacustrine environment are generally tan to medium brown and varved. They usually weather to small flakes (fig. 26). The oil content seldom exceeds 15 gallons per ton of rock by Fischer assay. Disseminated specimens and thin coquinas of freshwater mollusk and ostracode fossils are present locally within the oil-shale beds.

FIGURE 23.—Vermillion Creek coal bed in Niland Tongue of Wasatch Formation in NW¼SE¼ sec. 3, T. 12 N., R. 100 W. The coal bed is underlain, overlain, and interbedded with carbonaceous shale. Arrow points to layer of freshwater mollusks.

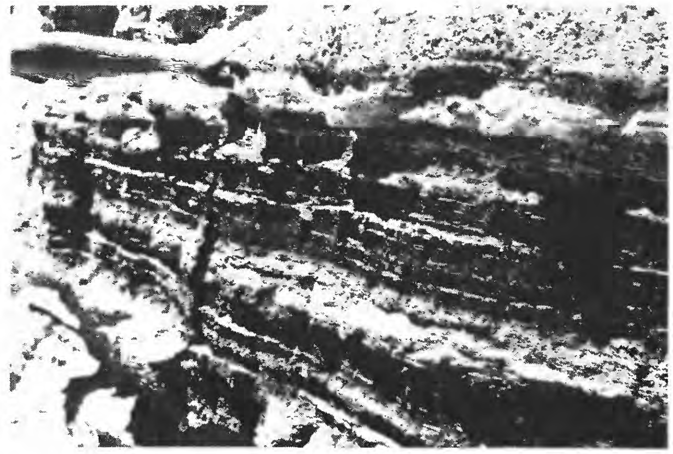


FIGURE 24.—Coal bed in Niland Tongue of Wasatch Formation in NE¼SW¼SE¼ sec. 23, T. 12 N., R. 101 W. The coal is interbedded with carbonaceous shale and molluscan coquina. Person's hand is resting on bed containing the freshwater lacustrine mollusks *Goniobasis tenera, Lampsilis* sp., and *Viviparus* sp.

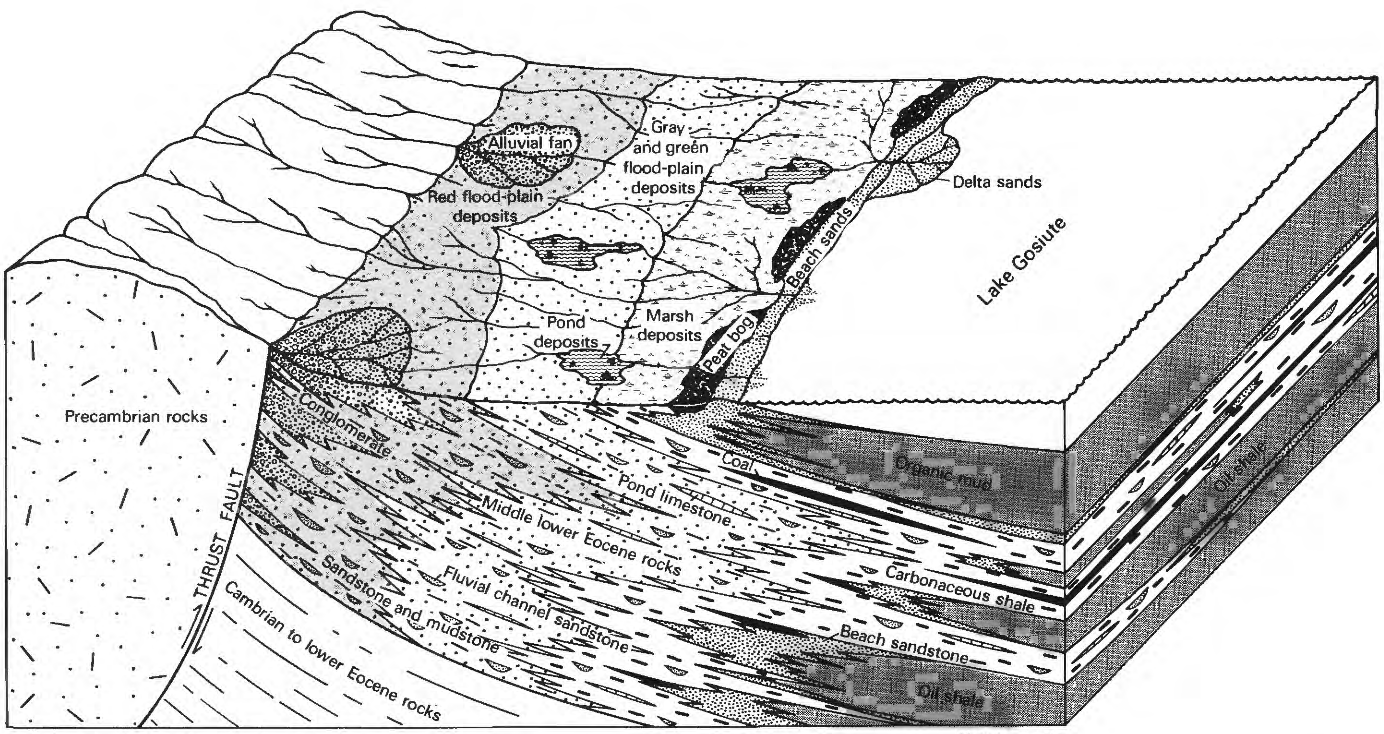



FIGURE 25.—Model for freshwater lacustrine and associated Eocene depositional environments in greater Green River basin.

FIGURE 26.—Light- to medium-brown, soft, flaky, freshwater lacustrine oil shale in Scheggs Bed of Tipton Shale Member of Green River Formation in Middle Firehole Canyon in SW1/4 sec. 34, T. 17 N., R. 106 W., southeastern Green River basin.

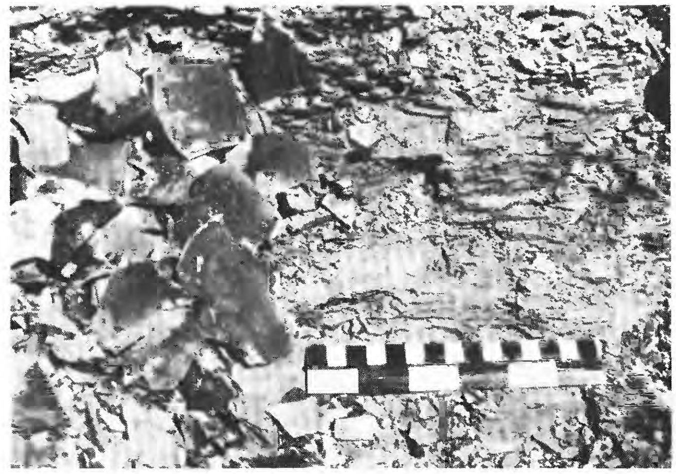


FIGURE 27.—Flaky to platy, black, saltwater lacustrine oil shale in Rife Bed of Tipton Shale Member of Green River Formation on White Mountain in sec. 31, T. 19 N., R. 105 W., eastern Green River basin. Scale is in centimeters and inches.

The fossils become more abundant near former shorelines of the lake.

The offshore, nearshore, and onshore sandstone beds in the freshwater lacustrine environment encircled the lakes and had combined total widths of as much as 10 mi (Roehler, 1990a). The sandstone is composed 80–90 percent of gray and milky quartz, 1–15 percent of feldspar and varicolored rock fragments, 2–5 percent of muscovite and biotite, and 1–2 percent of heavy minerals (Roehler, 1990a, p. 10). It consists of (1) thin, parallel-bedded, very fine grained sandstone and interbedded oil shale, which was deposited offshore in quiet, deep water, below wave base; (2) parallel, planar, and trough-crossbedded, fine- to medium-grained sandstone, which was deposited nearshore in wave-churned, shallow water; and (3) tabular-bedded, fine- to medium-grained sandstone, which was deposited onshore as beaches.

The stratigraphy and paleontology of the Cottonwood Creek delta, which was deposited in the Scheggs Bed of the Tipton Shale Member along the southeastern shores of Lake Gosiute in the Washakie basin, were investigated by Roehler and others (1988). The investigation indicated that the delta is a fan-shaped lens of quartzose sandstone, about 2 mi long, 1.5 mi wide, and 80 ft thick. Six distinct types of planar and trough crossbeds were described in various parts of the delta. Many of the beaches and feeder channels in the delta contain thick lenses of current-oriented mollusks, chiefly *Goniobasis tenera*, *Viviparus* sp., and *Lampsilis* sp. Rocks of flood-plain origin adjacent to the delta contain vertebrate fossils including *Lambdotherium popoagicum* and *Hyracotherium* sp. of late early Eocene age.

## SALTWATER LACUSTRINE

Three basic types of saltwater lakes (saline phases of Lake Gosiute) are represented in the Green River Formation. They are: (1) very deep, large, long-lived lakes, such as the lake in which the Rife Bed of the Tipton Shale Member was deposited; (2) recurrent, deep to very shallow, relatively short lived lakes, such as those in the Wilkins Peak Member; and (3) very deep, very large, long-lived, saltwater changing to brackish-water lakes, such as the one in which the lower part of the LaClede Bed of the Laney Member was deposited. The origin, size, salinity, and longevity

FIGURE 28.—Ledge-forming, subparallel- to parallel-bedded, saltwater lacustrine beach sandstone-siltstone in Wilkins Peak Member of Green River Formation on White Mountain in sec. 30, T. 19 N., R. 105 W., eastern Green River basin. Pick handle is 1.5 ft long.

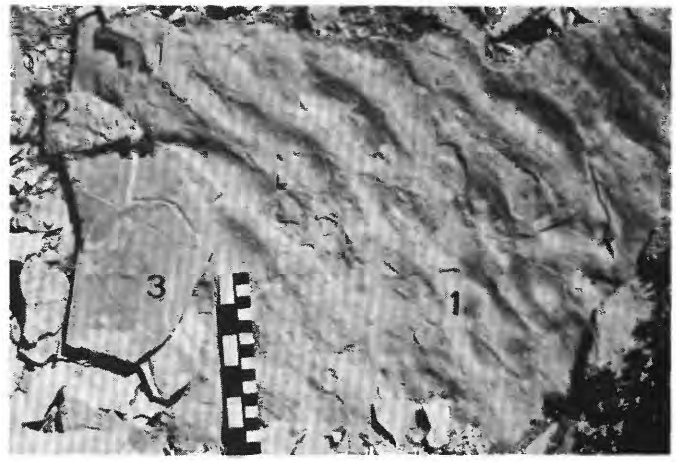



FIGURE 29.—Top view of saltwater lacustrine beach sandstone-siltstone shown in figure 28. 1, wave ripples; 2, synaeresis cracks; 3, mud cracks. Scale is in inches and centimeters.

of these lakes were mostly determined by the climatic changes and basin tectonics that have been discussed previously.

The oil-shale beds deposited in saltwater lacustrine depositional environments are generally dark brown to black and dolomitic. They are very thin bedded or laminated (varved), and on outcrops they weather to drab-gray or drab-silver-gray, brittle flakes and small plates (fig. 27). The oil yield of these beds generally ranges between 10 and 50 gallons per ton of rock by Fischer assay, a significantly higher yield than that of freshwater oil-shale beds.

The shorelines of the saltwater lakes consist of either thin beach sandstone-siltstone or mudflat mudstone. As discussed later, the beach sandstone-siltstone is usually associated with lacustrine transgressions, and the mudflat mudstone is usually associated with lacustrine regressions. The beach sandstone-siltstone ranges in thickness from less than 1 to about 5 feet and is composed of light-gray to white, often sugary, calcareous, siltstone or very fine grained sandstone. It consists of thin, parallel to subparallel beds that weather to jagged benches (fig. 28). Most of the beds in these benches are wave rippled. Synaeresis cracks and mud cracks are fairly common (fig. 29). The mudstones that formed the shorelines, where the sandstone-siltstone beach deposits are missing, are usually dark green and dolomitic. They are massive or parallel bedded and usually weather to small irregular blocks. Algal reefs (stromatolites) and oolites were abundant in the shallows near the muddy shorelines of the lake.

## POND AND PLAYA LAKE

Freshwater-pond limestones are present in widely spaced stratigraphic intervals throughout the Wasatch, Bridger, and Washakie Formations. The limestones are usually less than 2 ft thick and range from tan to black. They are characteristically hard and dense and weather to resistant ledges. Most appear to have been deposited as limy muds on the bottom of shallow bodies of waters having reedlike vegetation. The limestones are usually found interbedded with mudstone in flood-plain environments and interbedded with carbonaceous shale in paludal environments. They also have been found as partings in coal beds in the Niland Tongue of the Wasatch Formation. Tan and brown pond limestones are believed to have been deposited on the bottom of ponds where the water was well oxygenated, whereas gray and black pond limestones are believed to have been deposited on the bottom of ponds where the water was devoid of oxygen. Numerous mollusks, especially the pulmonate gastropod, *Physa pleromatis,* are present in most of the limestones.

Playa lake deposits are present in many core samples of the Wilkins Peak Member of the Green River Formation in the Green River basin. They commonly occur as thin beds, in multiple laminae, or in varves of dark-green, massive, dolomitic mudstone (fig. 8). The playas were mostly short lived saltwater ponds situated on mudflats that occupied the depositional centers of the greater Green River basin during interlacustrine periods (fig. 30). Moderately saline playa lakes were also present in a few places on

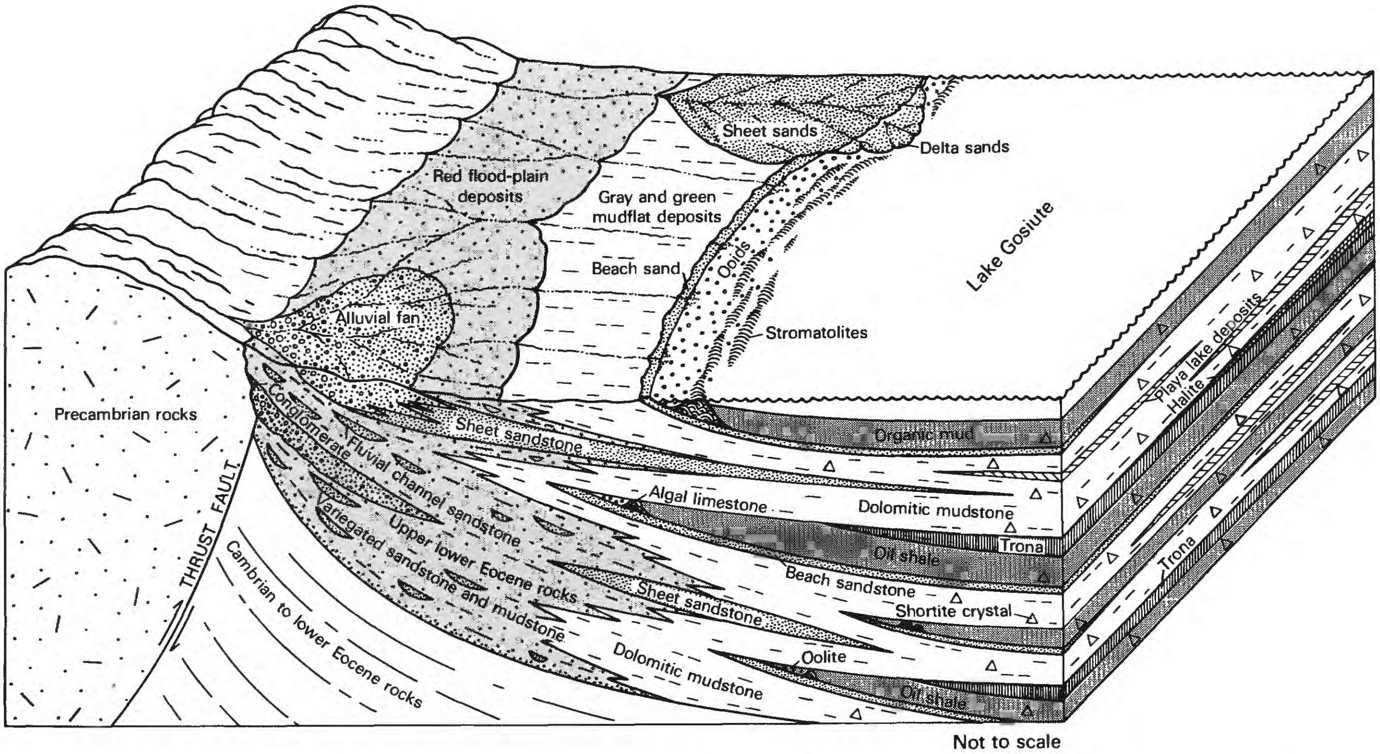



FIGURE 30.—Model for saltwater lacustrine, evaporite, mudflat, playa lake, and associated fluvial depositional environments in greater Green River basin.

FIGURE 31.—View to northeast of white playa-lake limestone (arrows) interbedded with dark-green mudflat mudstone in Wilkins Peak Member of Green River Formation on Muddy Creek in NW1/4 sec. 6, T. 18 N., R. 115 W., southwestern Green River basin. Limestone beds are each less than 1 ft thick.

mudflats around the margins of the lake basin. The less saline playa lake deposits are mostly composed of white, light-gray, or tan limestone, in thin beds usually less than 1 ft thick, that are interbedded with thick beds of dark-green mudstone of mudflat origin. The playa lake limestone beds shown in figure 31 constitute 2 of 16 playa lake deposits present in the Wilkins Peak Member along Muddy Creek, where the member is 208 ft thick. Some of the playa lake beds along Muddy Creek contain unidentified burrows, calcareous algae, oolites, ostracodes, and siliceous root fillings.

## EVAPORITE

Beds of the evaporite minerals trona ($Na_2CO_3{\cdot}NaHCO_3{\cdot}2H_2O$) and halite (NaCl), and a host of disseminated carbonate, sulfide, oxide, silicate, phosphate, and sulfate minerals were deposited in the Wilkins Peak Member in the southern part of the Green River basin as a result of the cyclic contractions and periodic drying up of saltwater lakes. As previously explained, the bedded evaporites mostly precipitated in salt pans that formed at depositional centers of the lake basin. The trona beds range in thickness from less than 1 ft to about 35 ft. They vary in lateral extent but mostly occur in a roughly oval shaped area of the basin about 55 mi long and 45 mi wide. The halite beds are thinner

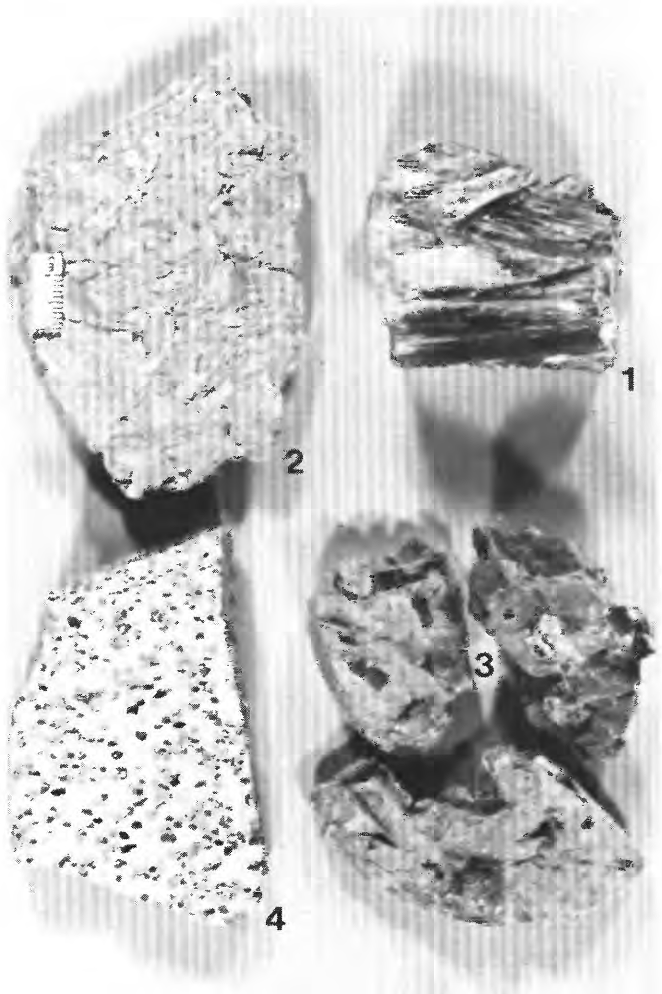



FIGURE 32.—Evaporite minerals from Wilkins Peak Member of Green River Formation. 1, mine sample of white and brown bladed trona crystals; 2, calcite pseudomorphs of trona crystals in outcrop sample; 3, core sample of mudstone containing shortite crystals; 4, calcite pseudomorphs and molds of shortite crystals in outcrop sample. Scale in centimeters.

and less extensive than the trona beds. They range in thickness from less than 1 to about 20 ft and were deposited in central parts of some of the salt pans. About 40 beds of trona, or trona and halite, have been identified in the Wilkins Peak Member.

Trona beds are usually composed of finely crystalline to coarsely crystalline, commonly bladed, white to brown crystals (fig. 32, No. 1). Trona is water soluble and never preserved on outcrops. On a few outcrops, however, such as one in Firehole Canyon (T. 16 N., R. 107 W.), calcite pseudomorphs of trona have been found (fig. 32, No. 2). Secondary acicular crystals are common in veins that formed when trona was extruded from layered beds during diagenesis (fig. 33).

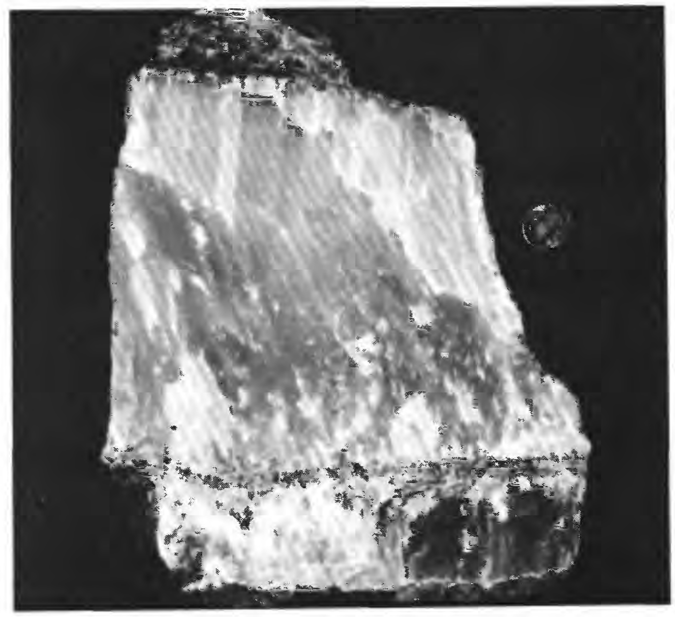


FIGURE 33.—Mine sample of acicular crystals of trona from the Wilkins Peak Member of Green River Formation.

Halite beds usually consist of compacted masses of large white or tan crystals. The beds are all located in the interior of the southern part of the Green River basin. No evidence of halite mineralization has been found on outcrops.

The most common evaporite mineral in the Wilkins Peak Member is shortite ($Na_2Ca_2(CO_3)_2$). It generally occurs as randomly oriented, triangular crystals, as much as 1 cm long (fig. 32, No. 3), which are usually disseminated through the mudstones and oil shales in the evaporite cycles (fig. 8). Calcite pseudomorphs and molds of shortite are fairly common in the Wilkins Peak Member in outcrops along the west flank of the Rock Springs uplift (fig. 32, No. 4). The shortite is believed to have crystallized from supersaline pore water during diagenesis.

## MUDFLAT

Mudflat deposits are abundant in the Wilkins Peak and Godiva Rim Members of the Green River Formation. Mudflats are composed mostly of dark-green to dark-gray mudstone, which may be dolomitic, silty, or sandy. The mudstone generally occurs in thin parallel or massive beds. On outcrops, it weathers to small blocky fragments (fig. 34).

Mudflats formed around the margins of large saltwater lakes, especially in areas where shoreline sands were absent. As the saltwater lakes shrank in size and disappeared during exceptionally dry periods, the mudflats occupied the former lake bottoms. Around

FIGURE 34.—Blocky, dark-green mudstone from mudflat deposits in the Wilkins Peak Member of Green River Formation on White Mountain in sec. 30, T. 19 N., R. 105 W. Scale is in centimeters and inches.


FIGURE 35.—Wilkins Peak Member of Green River Formation in roadcut in Big Firehole Canyon in sec. 20, T. 16 N., R. 106 W., southeastern Green River basin. 1, light-gray-weathered salt-water lacustrine oil shale; 2, drab-gray-green-weathered dolomitic mudflat mudstone. Person is pointing to exceptionally rich bed of oil shale.

the margins of these lakes, the mudflat mudstones are usually interbedded with oil shale (fig. 35). Mud cracks are abundant on mudflat surfaces that were exposed to subaerial drying.

## VOLCANIC AND FLUVIOVOLCANIC

Volcanic rocks deposited in the greater Green River basin are composed of airfall volcanic ash (tuff) derived from Eocene volcanic fields located in northwestern Wyoming, Idaho, and in States farther west (Axelrod, 1968). The only known exceptions to the deposition of airfall ash are rare occurrences of andesite pebbles and cobbles found mixed with other clastic rocks in stream-channel conglomerates in the Hartt Cabin Bed of the Laney Member of the Green River Formation and in the Washakie Formation in the Washakie basin. The andesite pebbles and cobbles are well rounded and may have been carried by streams from the Absaroka Mountains in northwestern Wyoming over Union Pass (at the northwest end of the Wind River Mountains) into the greater Green River basin.

Few beds of pure or nearly pure airfall volcanic ash (tuff) are preserved in the basin. Where they are encountered on outcrops or in cores, they generally occur as thin white or light-gray beds within darker overlying and underlying rocks. Most pure tuff beds were preserved because the volcanic ash fell onto deep-water parts of Lake Gosiute, where it settled to the bottom and was undisturbed by bottom-dwelling organisms, waves, or currents. Many of the beds

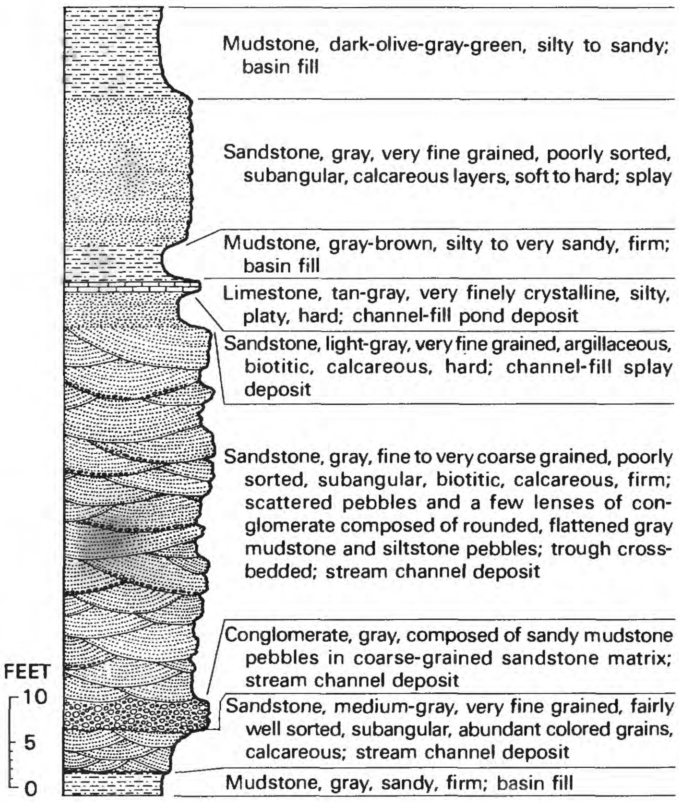



FIGURE 36.—Section showing limestone deposited in a pond that formed in an abandoned stream channel in upper part of Sand Butte Bed of Laney Member of Green River Formation in SW¼SW¼ sec. 16, T. 14 N., R. 99 W., on Kinney Rim in western Washakie basin.

have undergone alteration to zeolites (mainly mordenite, clinoptilolite, or analcime).

Most of the airfall ash that was deposited in the greater Green River basin fell onto land surfaces where it was reworked by wind and water, mixed with clastic sediments, and redeposited. The resulting "tuffaceous rocks" comprise the bulk of the upper part of the Green River Formation and the Bridger (Washakie) Formation.

## REPETITIOUS LITHOLOGIC SEQUENCES

Several types of repetitious, noncyclic, lithologic sequences have been identified in Eocene rocks in the greater Green River basin. Two of these sequences, repetitious soil zones (fig. 20) and drowned forest swamps (figs. 21 and 22), have been discussed previously. Three additional sequences that resulted from the disruption of drainages or from volcanism are discussed herein.

Thin limestone beds are commonly present in flood-plain environments at the top of splay and stream channel deposits as shown in the columnar section, figure 36. These limestones are believed to have been deposited on the bottom of ponds that formed along abandoned stream courses as shown in figure 37. They are usually gray, silty, and finely crystalline, and are commonly associated with very fine grained splay sandstone. The splay sandstone was deposited by small streams that persisted along the banks of the main stream channel after the main stream had been abandoned. The splay sandstone contributed to the infilling, burial, and obliteration of the main channel.

Tuff beds overlain by freshwater lacustrine limestone are commonly found interbedded with basin-fill mudstones (fig. 38). The lacustrine limestone beds are generally fossiliferous and usually weather to tan or light-gray ledges or benches. They form many of the "white layer" marker beds in the Bridger Formation (Chapter D, fig. 4). The association of the lacustrine limestones with the tuff beds is not coincidental. The tuff, which was deposited as airfall volcanic ash, is believed to have disrupted drainages by plugging channels and creating shallow, ephemeral lakes across low topographic areas of the basin. An example of how these lakes could have formed is shown in a block diagram, figure 39. Some of the limestone beds can be correlated in outcrops for more than 20 mi. The beds are rarely more than a few feet thick, which suggests that the lakes lasted only a few years before they drained, dried up, or filled in.

Examples of rich oil-shale beds (Fischer assay more than 25 gal/ton) directly overlying tuff beds are common on outcrops and in cores. The logical explanation for this relationship is that volcanic ash that fell into lakes and onto surrounding areas was a source of increased nutrients for indigenous plant and animal life. These nutrients, potash and (or) phosphate, undoubtedly caused algal blooms to occur. The algal blooms increased the kerogen content of lake bottom sediments, which is reflected by increased oil yields of oil shale overlying the tuff beds. An example of a rich oil-shale bed overlying a tuff bed is illustrated at 970 ft in the Energy Research and Development Administration Blacks Fork Corehole No. 1 (fig. 40).

## PALEOGEOGRAPHY

Thirteen paleogeographic maps have been constructed to illustrate the areal distribution of depositional environments in the Wasatch, Green River,

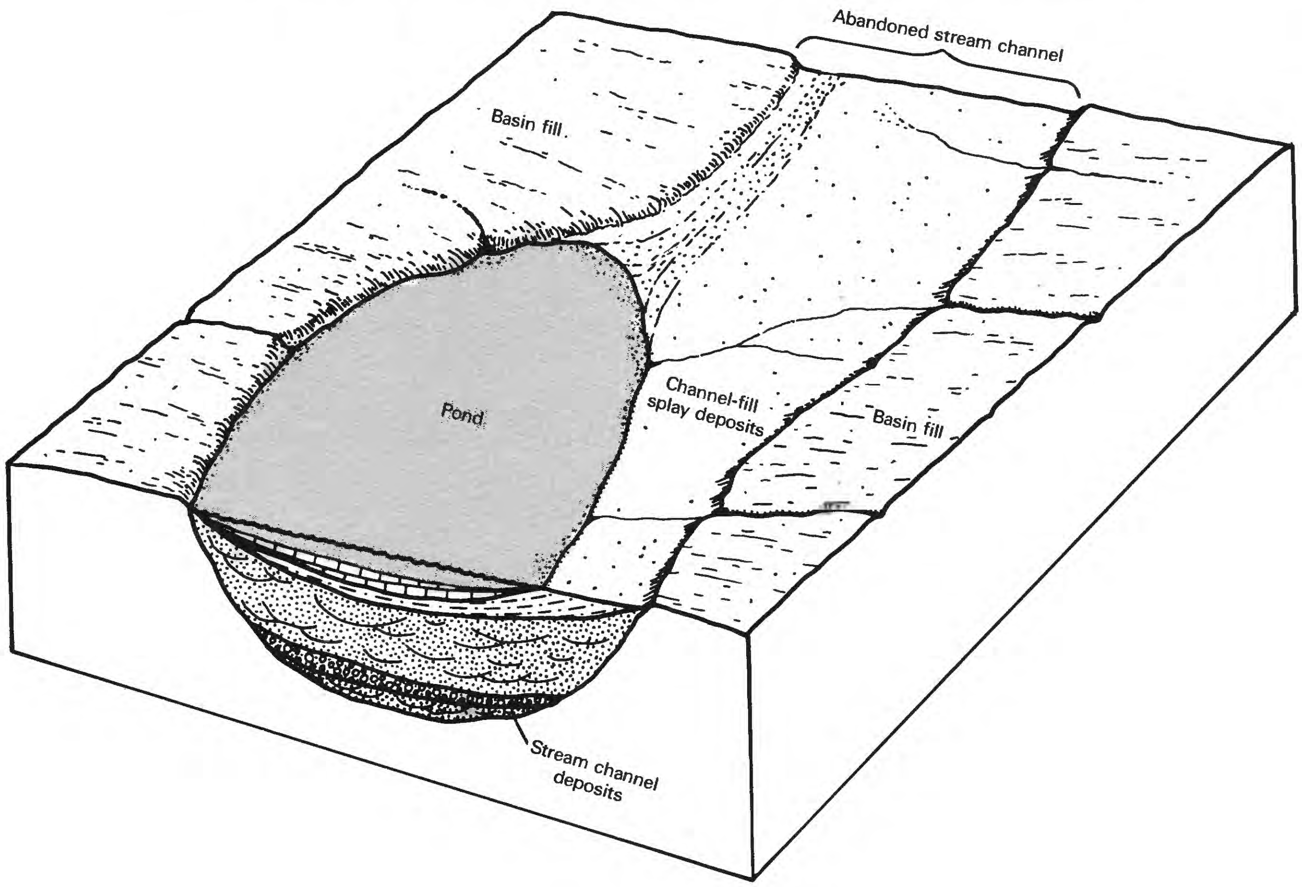



FIGURE 37.—Pond limestone deposited in an abandoned stream channel. These limestones are commonly present at the top of channel deposits, as shown in figure 36.

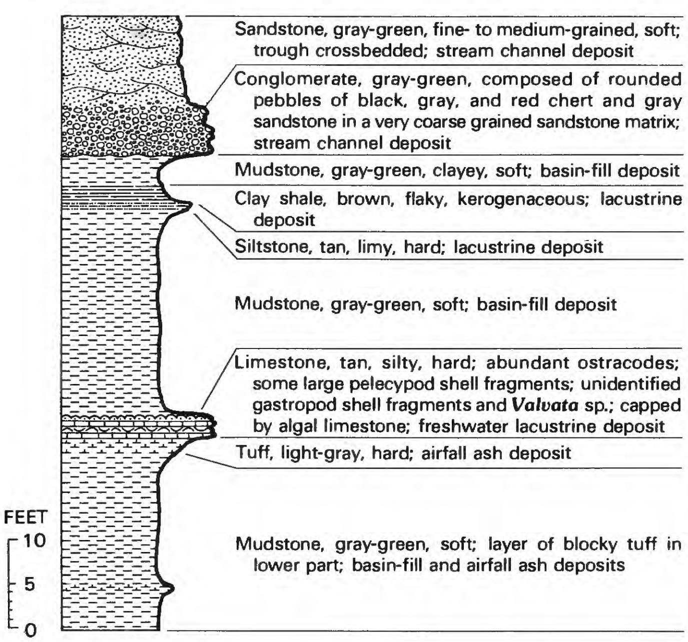



FIGURE 38.—Section showing freshwater lacustrine limestone overlying tuff in Bridger Formation in W½ sec. 15, T. 14 N., R. 109 W., on the north slopes of Black Mountain in southeastern Green River basin.

and lower parts of the Bridger and Washakie Formations. Paleogeographic maps were not prepared for the upper parts, or main bodies, of the Bridger and Washakie Formations, because they are incomplete as a result of middle and late Tertiary and Quaternary erosion. A generalized stratigraphic correlation diagram (fig. 41) is provided to locate the stratigraphic positions of the paleogeographic maps.

## MAIN BODY OF WASATCH FORMATION

The main body of the Wasatch Formation is composed of flood-plain deposits that have two distinct color patterns. Around the margins of the greater Green River basin, the flood-plain deposits are generally red or variegated with some shade of red predominating (fig. 42). The red colors, as previously indicated, are the result of the oxidation of iron compounds in well-drained, well-aerated soils that formed in areas having moderate topographic relief. In the central part of the basin, the red flood-plain deposits change to gray and green. In that area there was little or no topographic relief, the soils

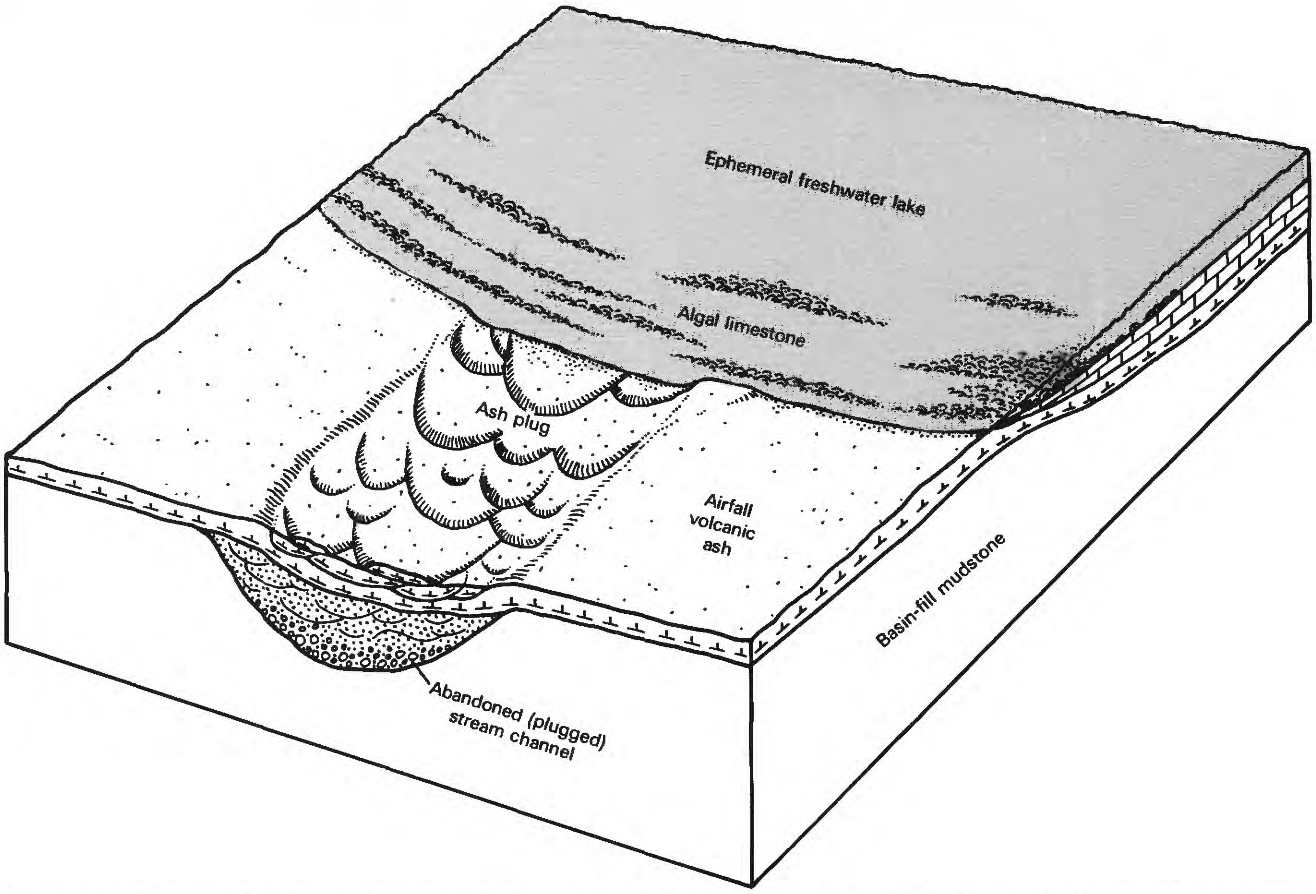



FIGURE 39.—Ephemeral freshwater lake formed when stream channel was plugged by airfall volcanic ash. An example of this type of deposition is shown in figure 38.

were permanently water saturated, and the iron compounds were reduced. The color change, where the two color patterns meet, occurs by a slow interfingering of the colors and not by noticeable changes in either the composition of the sediments or the depositional processes.

A few ponds and marshes were present on the flood plains east of the Rock Springs uplift (fig. 42). The pond deposits are composed of thin, tan to gray, silty, commonly fossiliferous limestones, and the marsh deposits are composed of thin, dark-gray to dark-brown carbonaceous shale (Chapter D, Washakie basin reference section, beds 52, 55, 57, and 79). Alluvial fans and pediments were present in some areas along the outer margins of the greater Green River basin (fig. 42).

The gray and green flood-plain deposits in the main body of the Wasatch Formation contain local concentrations of mammal teeth and bones. Many of these fossils concentrated in eddies or backwaters of streams, mostly in sandstones. These sandstones are commonly exposed as ridges or buttes, where they are subjected to wind erosion and ablation. The wind selectively concentrates coarser textured bone fragments and crowds of teeth by removing the finer textured sand grains. As a result of this natural sorting, the fossils are left exposed on flat surfaces that are present at the base of the ridges or buttes. If there are sufficient concentrations of bone and tooth fragments, the fossil material is used by red ants in constructing their cone-shaped hills. Ant hills as much as 18 inches high composed more than 50 percent of mammal bone and tooth fragments were discovered in NW¼SW¼SW¼ sec. 20, T. 16 N., R. 101 W., in bed 14 of the Washakie basin reference section (Chapter D). Several hundred complete crowns of mammal teeth were subsequently collected from across the length of the outcrop of bed 14, and large mammal bones were found concentrated in one small area. The site of the large mammal bones was later quarried by a field party from the University of California at Berkeley under the direction of D.E. Savage. Photographs of their quarry operation are shown in figures 43 and 44.

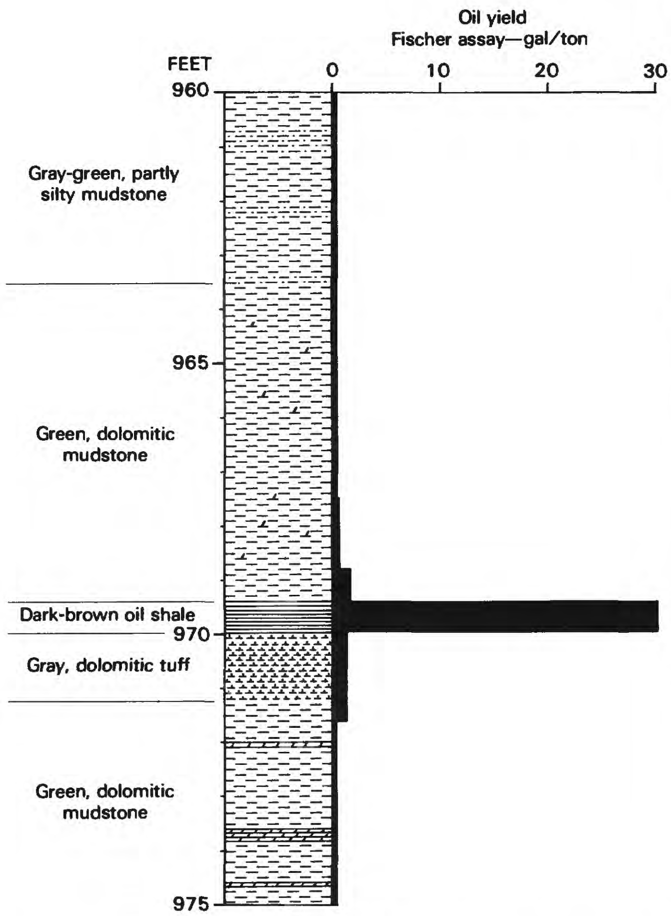



FIGURE 40.—Rich oil-shale bed overlying tuff bed in Wilkins Peak Member of Green River Formation in the Energy Research and Development Administration Blacks Fork Corehole No. 1, in SE1/4NE1/4 sec. 24, T. 16 N., R. 108 W., southeastern Green River basin. Stratigraphic position of the bed is shown in figure 7.

## RAMSEY RANCH MEMBER OF WASATCH FORMATION

The Ramsey Ranch Member, as discussed in Chapter E of this volume, was initially designated a member of the Green River Formation by Roehler (1965, p. 145). It has since been redesignated a member of the Wasatch Formation. The areal distribution and thickness of the member are indicated in figure 16 of Chapter E. Columnar sections and lithologic descriptions of five measured surface stratigraphic sections of the member were published by Roehler (1991a).

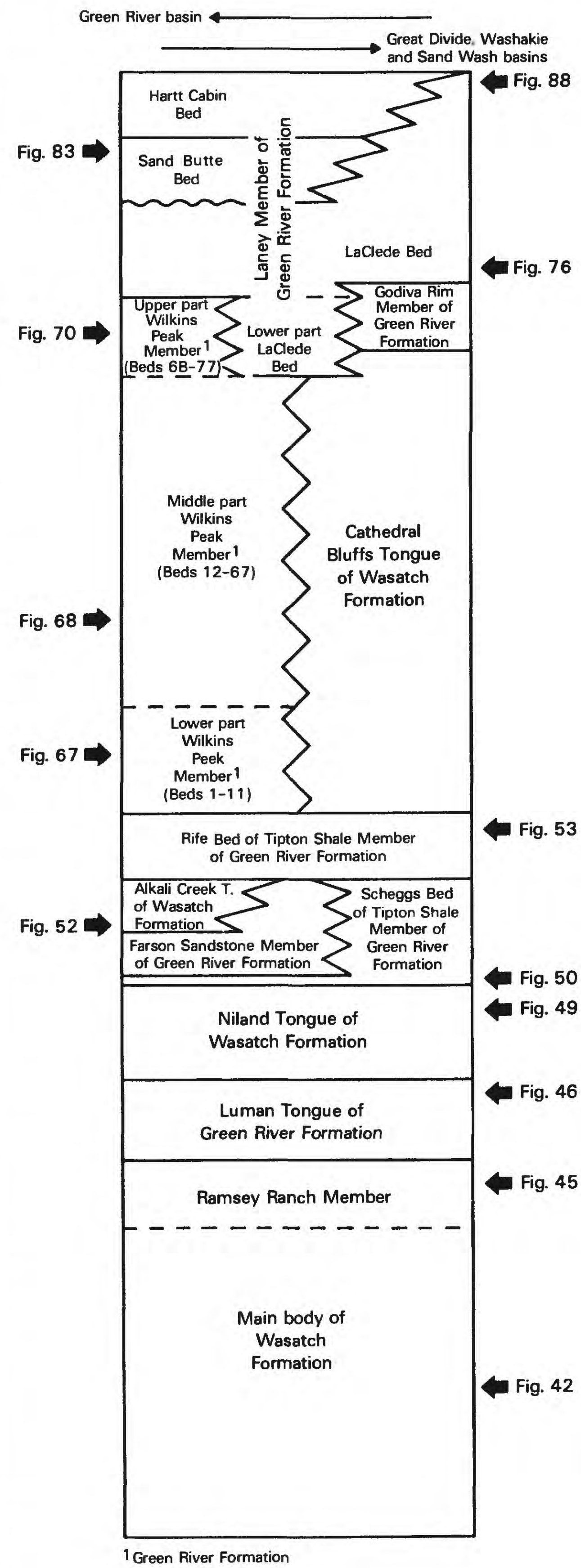



FIGURE 41 (facing column).—Nomenclature and intertonguing relationships of Wasatch and Green River Formations showing stratigraphic positions of paleogeographic maps (arrows and figure numbers).

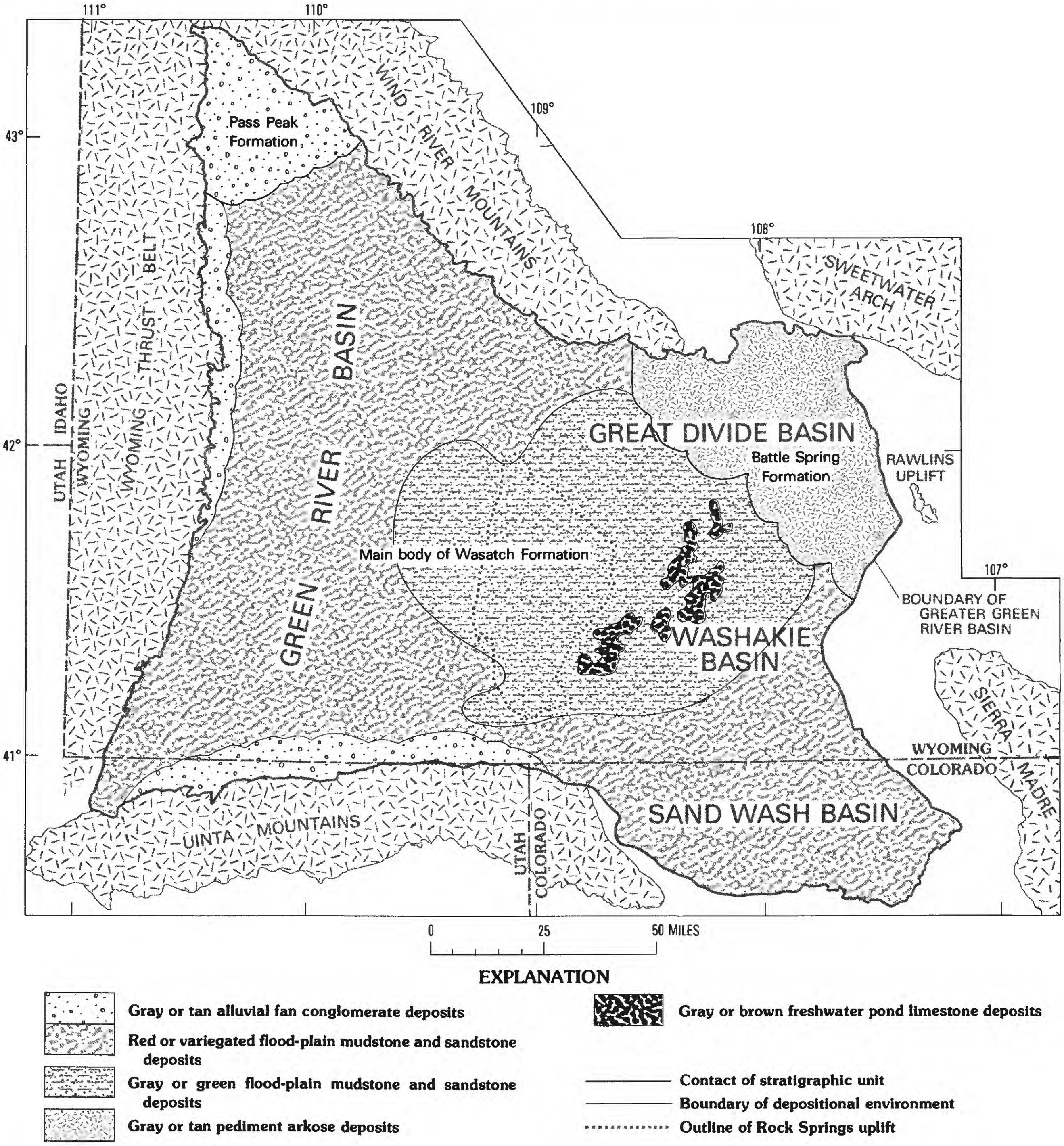



FIGURE 42.—Paleogeographic map of middle part of main body of Wasatch Formation and associated formations showing locations of depositional environments.

The Ramsey Ranch Member is depicted in figure 45 at a stratigraphic level about 350 ft below the base of the Luman Tongue of the Green River Formation (fig. 41). At that stratigraphic position, deep freshwater lake deposits occupy about 850 mi$^2$ of the Uinta Mountain trough in the eastern part of the greater Green River basin. Surrounding this lake and extending southward and westward along the length of the Uinta Mountain trough were swamps, small shallow lakes, and numerous ponds in which

FIGURE 43.—Fossil mammal quarry in main body of Wasatch Formation in bed 14 of the Washakie basin reference section (Chapter D, this volume). Shown in the photograph are D.E. Savage (center) and associates from the University of California at Berkeley.

FIGURE 44.—Fossil mammal bones exposed in quarry shown in figure 43. Large leg bone (femur) indicated by arrow is from *Coryphodon* sp. One-gallon can indicates scale.

carbonaceous shale, coal, oil shale, and limestone were deposited. The Ramsey Ranch Member intertongues to the north and south from the Uinta Mountain trough with either gray and green or red or variegated sandstone and mudstone flood-plain deposits that are typical of the main body of the Wasatch Formation (fig. 45). Near the northeast corner of the basin, the Ramsey Ranch Member intertongues with and is replaced by arkosic rocks that make up the Battle Spring Formation.

The outlet of the lake in which the Ramsey Ranch Member was deposited, shown in figure 45, is at a river that flowed eastward from the lake and exited the greater Green River basin south of the Rawlins uplift. The outlet is placed there because (1) the lake undoubtedly occupied the lowest topographic elevation in the basin, which was located along its eastern margin; and (2) barriers created by mountains surrounding the basin and the geographic distribution of depositional environments make this the logical place for an outlet.

## LUMAN TONGUE OF GREEN RIVER FORMATION

The lakes that intermittently occupied the Uinta Mountain trough during deposition of the Ramsey Ranch Member (fig. 45) were shallow and dispersed, but they coalesced to form a large, deep, open, freshwater lake that filled the trough during deposition of the Luman Tongue (fig. 46). The Luman lake was irregularly shaped, but at its maximum development it occupied about 6,650 mi$^2$. Shoreline sands were deposited about the margins of the lake, and brown, organic mud (low-grade oil shale) was deposited offshore (fig. 47). The deepest part of the lake, indicated by more than 400 ft of sediment accumulation, was located about 25 mi northeast of the common boundary of the States of Wyoming, Utah, and Colorado.

Surrounding the Luman lake (fig. 46) were narrow bands of gray and green flood-plain deposits, which interfingered laterally to the north and south with red or variegated flood-plain deposits. Deltas were present along the northeastern shores of the lake, where arkosic sediments composing the Battle Spring Formation entered the lake and mixed with lacustrine muds.

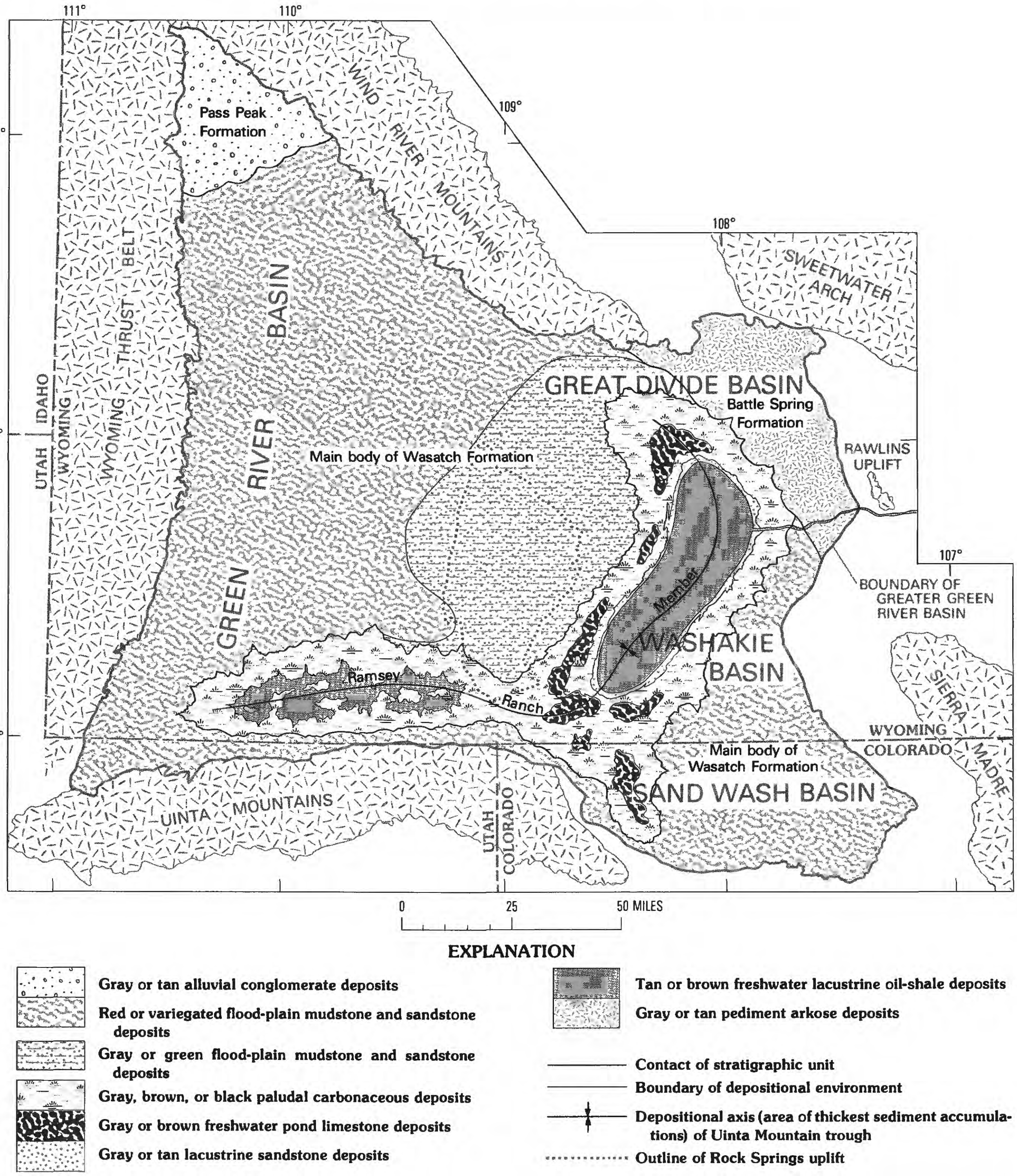



FIGURE 45.—Paleogeographic map of Ramsey Ranch Member of Wasatch Formation showing locations of depositional environments.

The outlet of the Luman lake is believed to have been located in the southeastern part of the Green River basin near the east end of the Uinta Mountains (fig. 46). Unfortunately, no reliable evidence exists for an outlet there, because the Luman in that area is presently buried under several hundred feet of younger Eocene rocks.

Near the end of deposition of the Luman Tongue, the Luman lake began to contract. The shallowing of the lake waters that accompanied

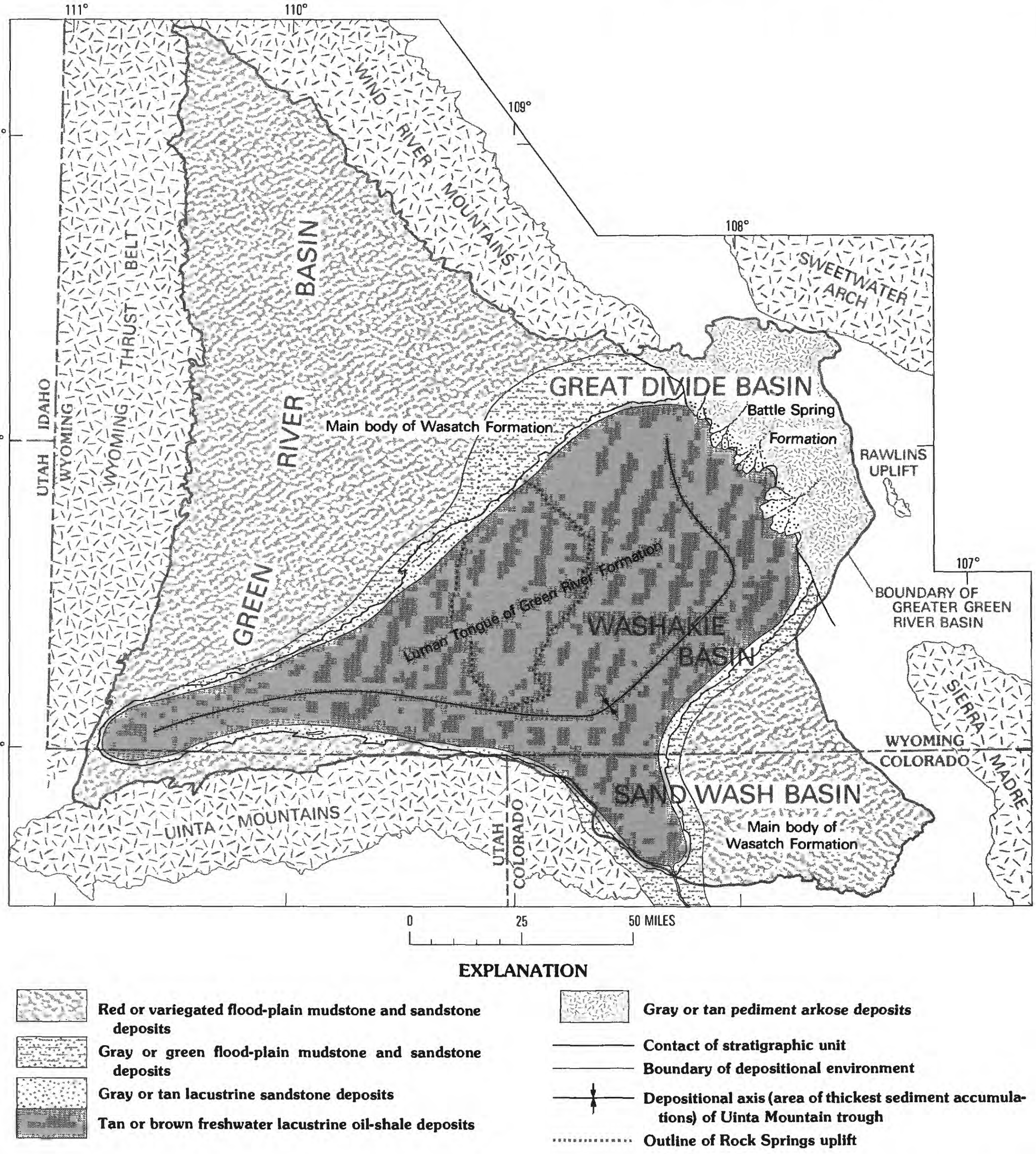



FIGURE 46.—Paleogeographic map of Luman Tongue of Green River Formation and associated formations showing locations of depositional environments.

this contraction is evident in rock outcrops at Canyon Creek Gas Field (fig. 48). The outcrops there expose deep-water oil shale at the base that intertongues upward with thin, parallel-bedded offshore sandstone. This intertonguing continues upward into what were former nearshore areas of the lake, where the sandstone beds thicken and replace the oil shale beds. The nearshore sequence is, in turn, replaced upward by thick, onshore beach sandstone. Overlying the beach sandstone, but not visible in figure 48, are beds of carbonaceous shale and coal.

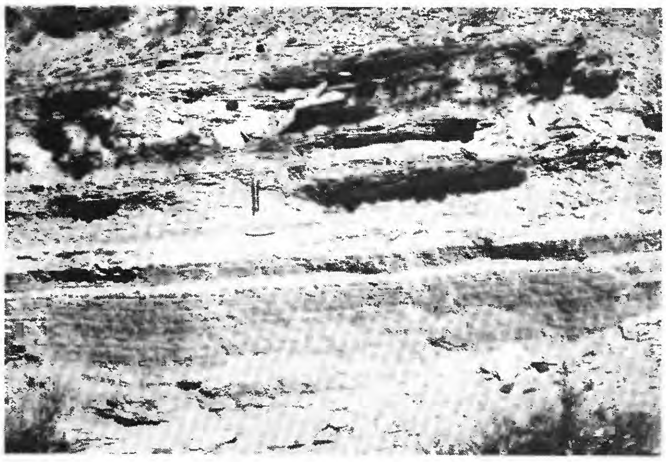


FIGURE 47.—Soft, brown, low-grade oil shale in Luman Tongue of Green River Formation in SW$\frac{1}{4}$SE$\frac{1}{4}$ sec. 7, T. 18 N., R. 105 W., near Rock Springs, Wyo. Outcrop contains abundant ostracodes and some weathered, white, mollusk shell fragments. Pick is 11 in. long.

## NILAND TONGUE OF WASATCH FORMATION

The Niland Tongue of the Wasatch Formation by definition occupies the same geographic area as the Luman Tongue of the Green River Formation, for where the Luman Tongue is missing, the Niland Tongue interval becomes part of the main body of the Wasatch Formation. The boundaries of the depositional environments of the Niland Tongue, however, do not conform to the boundaries of the Luman Tongue (compare figs. 46 and 49).

The Niland Tongue has nearly the same areal extent and depositional environments as the Ramsey Ranch Member (compare figs. 45 and 49). Both units were deposited in the Uinta Mountain trough, and both are composed of rocks of freshwater lacustrine, swamp, pond, and flood-plain origins. Figure 49 represents a stratigraphic level in the upper part of the Niland Tongue. At that level, a large freshwater lake with sand shorelines was present in the eastern part of the greater Green River basin. Surrounding the lake were swamps and surrounding the swamps and covering most of the remaining parts of the floor of the basin were extensive flood plains. Arkosic sediments composing the Battle Spring Formation were deposited in the northeast corner of the basin, and alluvial fan conglomerates were present along the north flank of the Uinta Mountains.

## SCHEGGS BED OF TIPTON SHALE MEMBER OF GREEN RIVER FORMATION

The Scheggs Bed, the lower freshwater part of the Tipton Shale Member, was deposited during the first

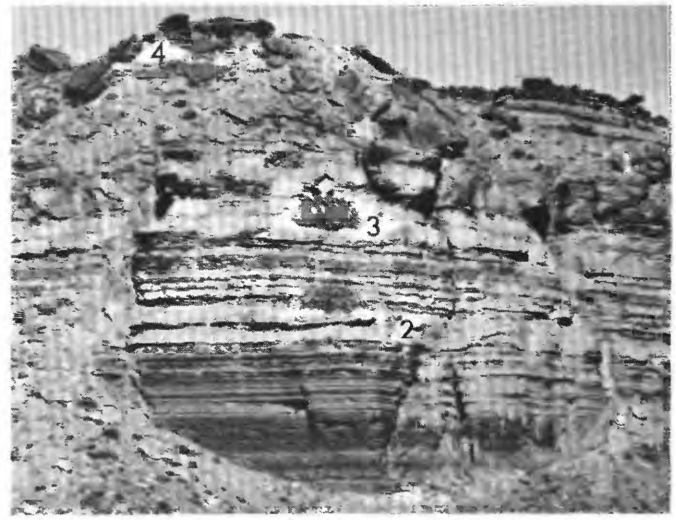



FIGURE 48.—Upper part of Luman Tongue of Green River Formation at Canyon Creek Gas Field in SE$\frac{1}{4}$SE$\frac{1}{4}$SW$\frac{1}{4}$ sec. 25, T. 13 N., R. 101 W. 1, Offshore freshwater oil shale; 2, offshore interbedded oil shale and sandstone; 3, nearshore interbedded sandstone and oil shale; 4, onshore beach sandstone. The outcrops are about 60 ft thick. Note nest of golden eagles to the left of the number 3.

major expansion of Lake Gosiute from the Uinta Mountain trough. The lake expanded from the trough in slow stages until it reached its maximum areal extent of about 15,000 mi$^2$ and covered about 75 percent of the basin (fig. 50). The lake expansion is attributed to previously discussed Eocene climate changes.

The sediments deposited in the open, fresh waters of the Scheggs lake were mostly organic muds (oil shale). Around the lake margins were sand shorelines on which the mollusks *Goniobasis tenera, Viviparus* sp., and *Lampsilis* sp. thrived. Calcareous algal reefs (stromatolites) were abundant in shallow waters of the lake, and several sand deltas were present along its eastern shores. The deepest part of the lake, where as much as 300 ft of sediments was deposited, was located in the southern part of the basin along the trend of the Uinta Mountain trough. Thick sediments also accumulated in a smaller, parallel-trending trough located in the southeastern part of the basin. Backshore areas of the lake were mostly occupied by flood plains, and arkosic sediments continued to be deposited in the Battle Spring Formation in the northeastern part of the basin (fig. 50).

The algae that form the algal limestone in the Scheggs Bed, and in other members of the Green River Formation, exhibit a variety of peculiar shapes and forms that are probably mostly related to

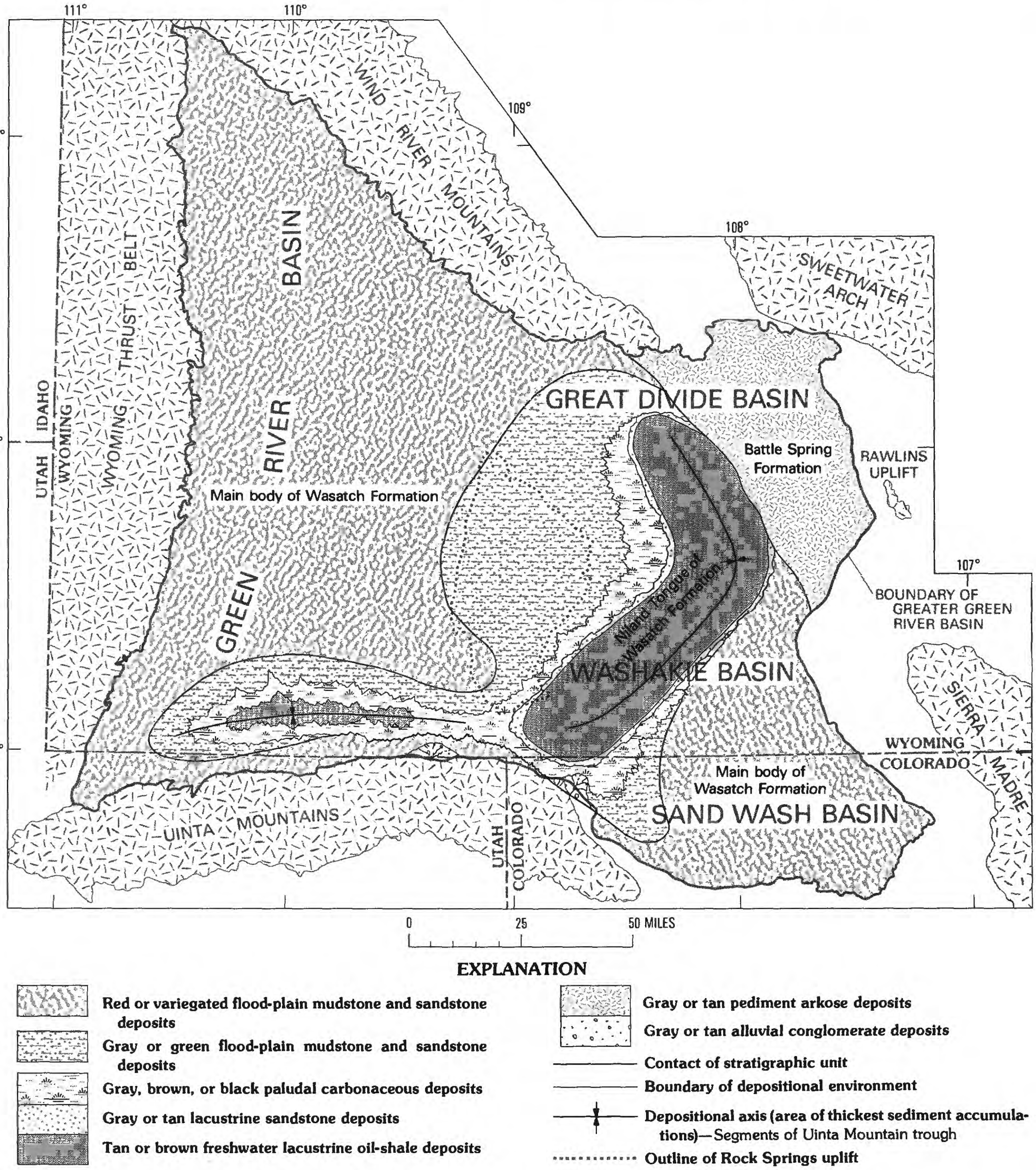



FIGURE 49.—Paleogeographic map of Niland Tongue of Wasatch Formation and associated formations showing locations of depositional environments.

ecological conditions, such as water depth, temperature and salinity, rate of sedimentation, type of substrate, and other factors. The algal limestones in this report are informally identified by their physical appearance. A few examples of algae from the Green River Formation are illustrated in figure 51.

The geology and paleoecology of the Cottonwood Creek delta, located on the eastern shore of the

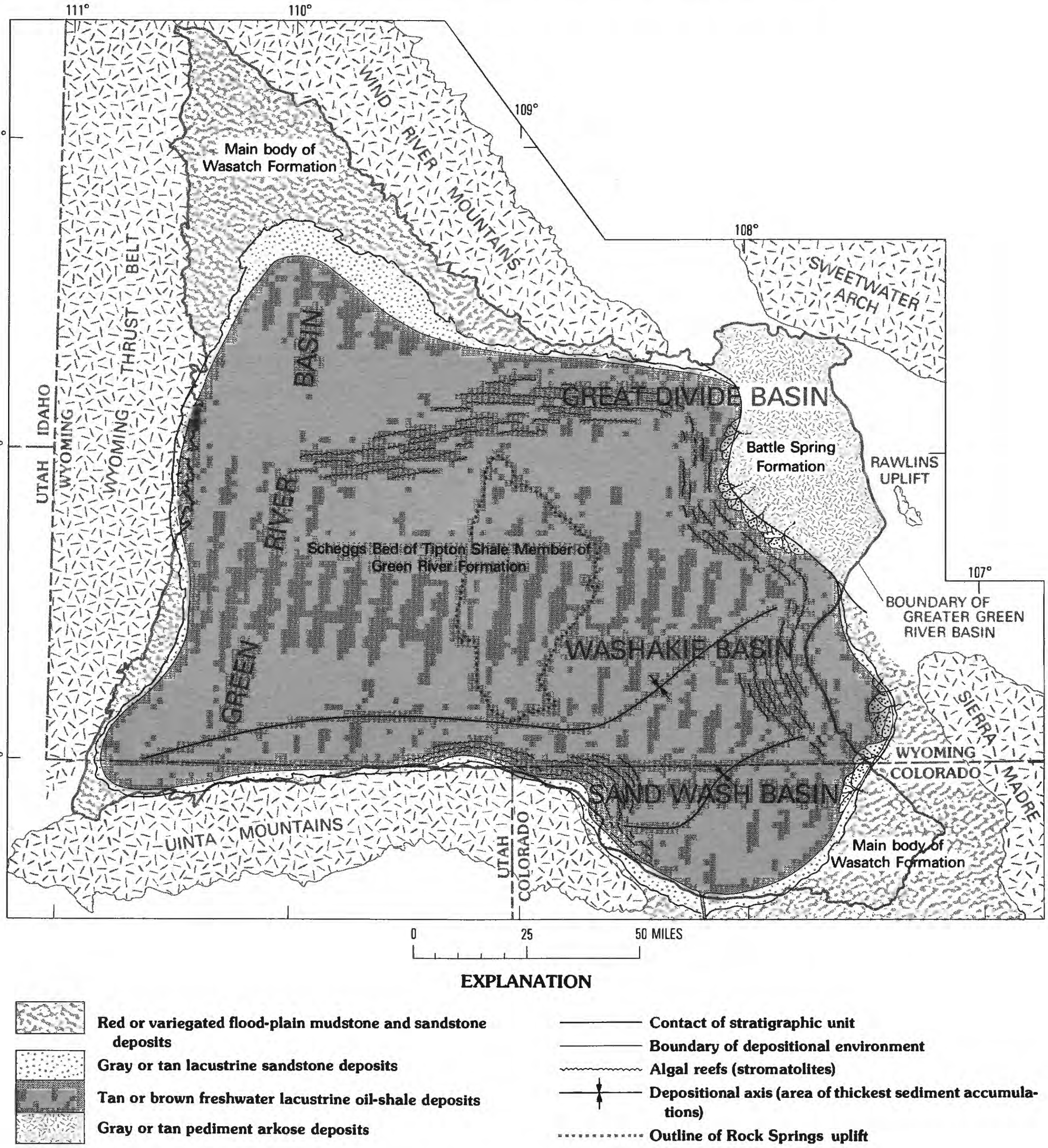



FIGURE 50.—Paleogeographic map of Scheggs Bed of Tipton Shale Member of Green River Formation and associated formations showing locations of depositional environments. Longer of the two depositional axes is Uinta Mountain trough.

Scheggs lake a few miles north of the Wyoming-Colorado State line, were reported on by Roehler and others (1988). The sedimentology of two well-developed shoreline sandstones of the lake located in the southeastern part of the greater Green River basin was described and illustrated by Roehler (1990a).

Near the end of deposition of the Scheggs Bed, the Wind River Mountains were uplifted. Erosion followed,

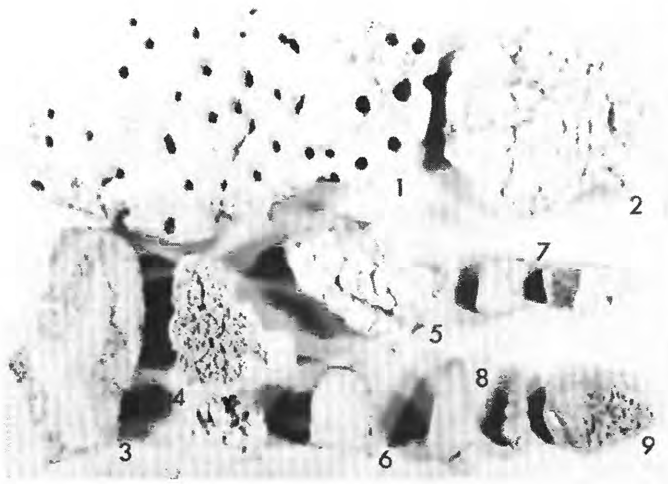



FIGURE 51.—Fossil algae from the Green River Formation. 1, Perforate type; 2, capsulate type; 3, algal coating on tree branch; 4, flowery type; 5, brain type; 6, toadstool type; 7, algal coating on turtle shell fragments; 8, oncolite formed by algal coating of shell of gastropod *Goniobasis tenera* and uncoated specimen of the same shell; 9, algal coating on upper surface of shell of pelecypod *Viviparus* sp. Centimeter scale is shown on No. 1.

and a thick wedge of coarse clastic sediments was deposited in the basin south of the mountains. This wedge of clastics was named the Farson Sandstone Member of the Green River Formation in Chapter B of this volume.

## FARSON SANDSTONE MEMBER AND UPPER PART OF SCHEGGS BED OF TIPTON SHALE MEMBER OF GREEN RIVER FORMATION AND ALKALI CREEK TONGUE OF WASATCH FORMATION

The Farson Sandstone Member of the Green River Formation consists of a lobate wedge of coarse clastic rocks, mainly sandstone, that spreads nearly 100 mi southward from the Wind River Mountains into the northwestern part of the greater Green River basin. The member is a freshwater deposit, which is contemporary with parts of the Scheggs Bed of the Tipton Shale Member of the Green River Formation and Alkali Creek Tongue of the Wasatch Formation (fig. 52).

The Farson Sandstone Member is composed of nearly 400 ft of sandstone and some thin interbedded conglomerate near the foothills of the Wind River Mountains. The conglomerate beds rapidly disappear south of the foothills and the sandstone beds thin and wedge out at the locations shown in figure 52. The member was deposited as prograding delta and shoreline deposits that filled the northwestern part of Lake Gosiute, thereby reducing the size of the lake by about 6,500 $mi^2$ (compare figs. 50 and 52). Along its south and east edges, the sandstone bodies intertongue with and are replaced by oil-shale beds that form the upper part of the Scheggs Bed (Roehler, 1989a and 1991b). Along its western boundary the Farson Sandstone Member intertongues with gray and green flood-plain sandstone and mudstone that compose the Alkali Creek Tongue of the Wasatch Formation. The Alkali Creek Tongue is as much as 250 ft thick along outcrops in the northwestern part of the basin, where it is underlain by the lower part of the Farson Sandstone Member (Roehler, 1989b and 1990b). In the subsurface, east of where it crops out, the Alkali Creek Tongue thins from its base upward by intertonguing with the upper part of the Farson Sandstone Member (Roehler, 1990b).

Sand deltas were present along the eastern shore of Lake Gosiute during this period of deposition (fig. 52). Isolated areas of flood plains were present along the margins of the basin, and arkosic sediments composing the Battle Spring Formation continued to be deposited in the northeastern part of the basin.

## RIFE BED OF TIPTON SHALE MEMBER OF GREEN RIVER FORMATION

The contact between the Scheggs and Rife Beds of the Tipton Shale Member (discussed previously) marks (1) the closing off of drainages leaving the greater Green River basin, (2) a major climate change, and (3) an abrupt change in the waters of Lake Gosiute from fresh to saline. The contact is visible in outcrops by an overall color change from drab brown in the Scheggs Bed to drab gray in the Rife Bed (this volume, Chapter B). Lake Gosiute was a deep saltwater body for nearly 500,000 years during deposition of the Rife Bed, but it was limited in size to a maximum area of about 7,000 $mi^2$ (fig. 53).

The Rife Bed is composed of mostly dark brown to black, high-grade oil shale that was deposited in offshore parts of Lake Gosiute (fig. 54). The oil shale generally contains thin beds that will yield more than 25 gal/ton of oil by Fischer assay. The thickest intervals of oil shale in the bed, in several places more than 200 ft, are located along the trend of the Uinta Mountain trough (fig. 53). Algal reefs were abundant in the shallow nearshore waters of the lake, thin sand beaches were present along the lake shores, and most

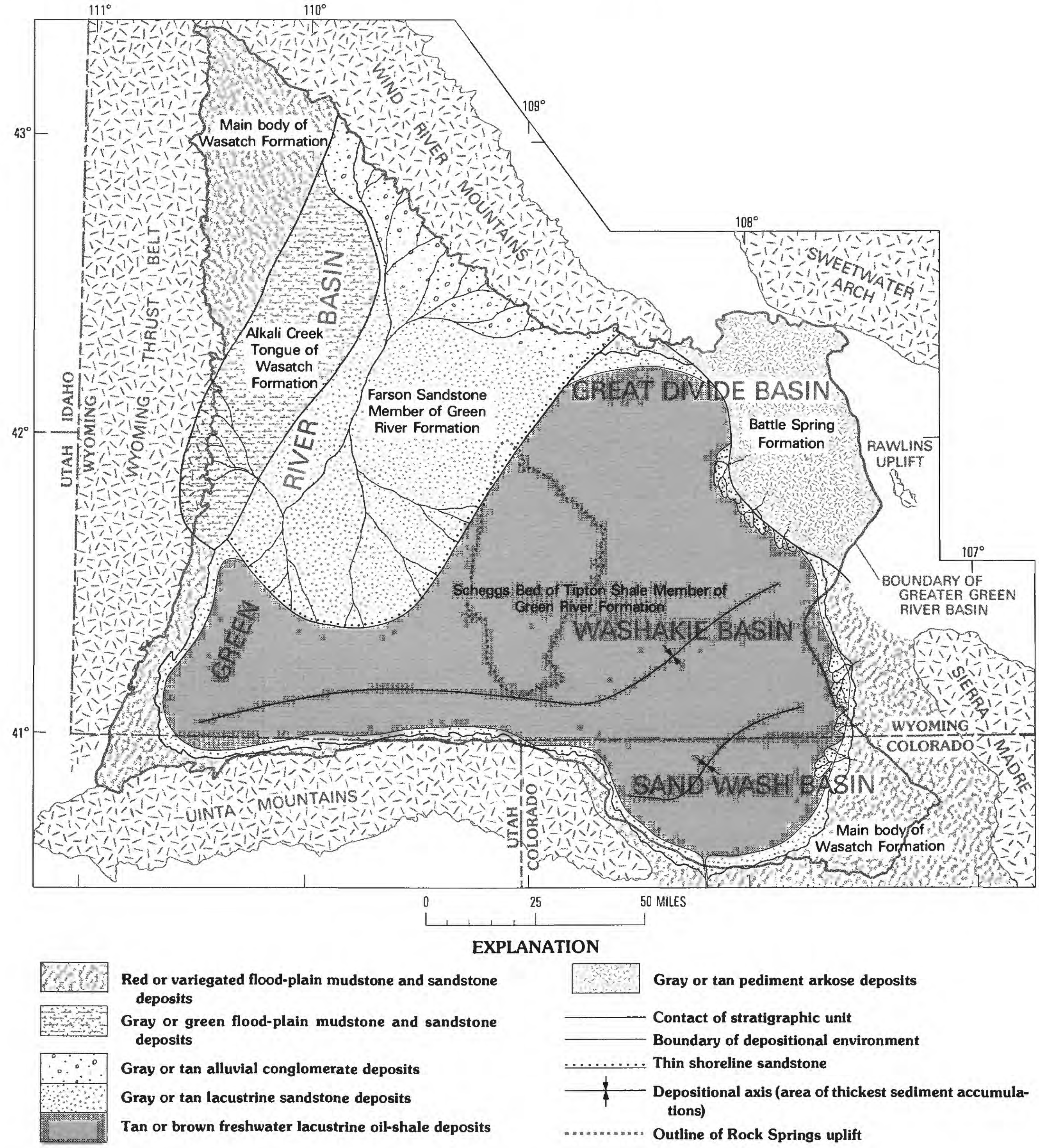



FIGURE 52.—Paleogeographic map of Farson Sandstone Member and upper part of Scheggs Bed of Tipton Shale Member of Green River Formation and Alkali Creek Tongue of Wasatch Formation showing locations of depositional environments. Longer of the two depositional axes is Uinta Mountain trough.

backshore areas consisted of mudflats. Flood-plain and arkosic sediments continued to be deposited at the outer margins of the basin.

Salinity of the waters of Lake Gosiute increased from bottom to top of the Rife Bed. A few small planorbid gastropod fossils are present in the lower

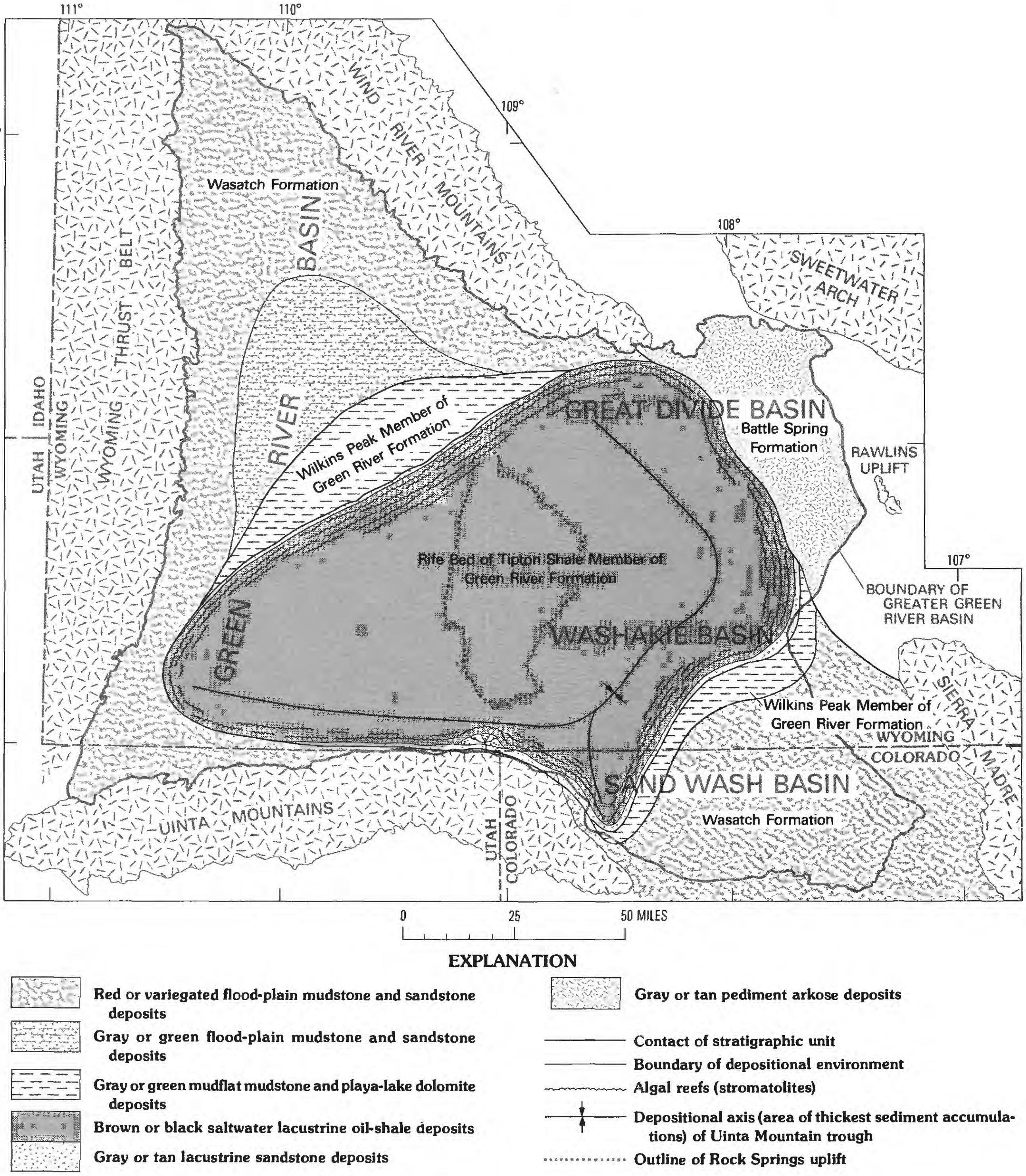



FIGURE 53.—Paleogeographic map of Rife Bed of Tipton Shale Member of Green River Formation and associated formations showing locations of depositional environments.

few feet of the bed, but they quickly disappear upward. Saline minerals are rare in the bed, but thin layers of nahcolite ($NaHCO_3$) and disseminated crystals of shortite ($Na_2Ca_2(CO_3)_3$) are present in its upper 20 ft in the Union Pacific Railroad Company El Paso Corehole No. 44–3, located in sec. 3, T. 15 N., R. 109 W. in the southern part of the Green River basin (Roehler, 1991d). Small, flat pods of tan- to

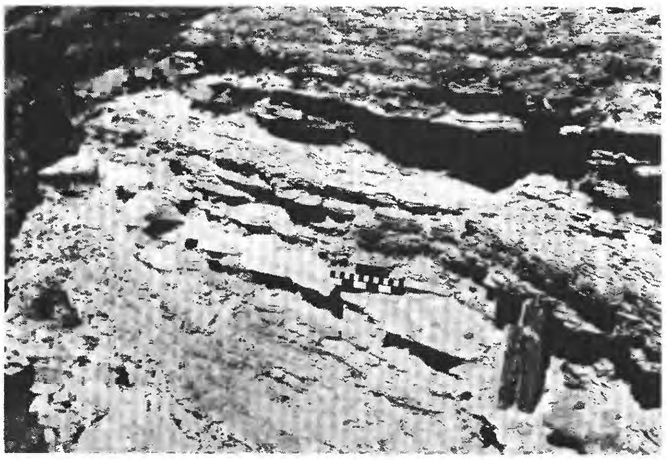


FIGURE 54.—High-grade, saltwater lacustrine oil shale in Rife Bed of Tipton Shale Member of Green River Formation near base of White Mountain in sec. 31, T. 19 N., R. 105 W., eastern Green River basin. The oil shale is dark brown to black but weathers drab gray. Scale is in centimeters and inches.

orange-weathered, gray dolomite interbedded in oil shale are fairly common along outcrops.

## WILKINS PEAK MEMBER OF GREEN RIVER FORMATION

The Wilkins Peak Member has long attracted the attention of geologists because of its intriguing sedimentology, mineralogy, and paleontology. The publications resulting from studies of the member have advanced numerous theories concerning its origin, composition, and mode of deposition. Examples of these theories can be seen in the descriptions and classification of the depositional cycles in the member. The Wilkins Peak Member, as discussed earlier, consists of 77 depositional cycles composed of ascending sequences of oil shale, trona and halite, and mudstone at the former lake basin center. The lithologic units that make up these cycles, however, change laterally (horizontally) from the former lake basin center toward the former margins of the lake. Most of these lateral lithologic changes have not been adequately recognized and explained.

Bradley (1964, p. A40) described the Wilkins Peak Member as "a great lens of sediment laid down in a closed lake***which repeatedly shrank to relatively small size***and then expanded repeatedly to considerably greater size." He went on to say that inside the great lens of sediment was a smaller lens of saline sediment composed of trona and other evaporite minerals that make up the saline facies of the Wilkins Peak Member. The marginal facies of the Wilkins Peak Member were thought by Bradley (1964, p. A40–A41) to have been deposited rhythmically as alternating "greenish-drab marlstone" (mudstone) and "light-grayish-brown marlstone" (low-grade oil shale). The rhythmic deposition of limy and sandy beds with sage-green shale beds was thought to represent alternating low-lake-level and high-lake-level stages (Bradley and Eugster, 1969, p. B25). Although Bradley and Eugster (1969, p. B24) correctly concluded that Lake Gosiute expanded and contracted repeatedly during deposition of the Wilkins Peak Member, they did not believe that the lake ever dried up, and they were probably never fully aware of the sedimentologic and chronologic significances of the rhythmic depositional sequences.

Eugster and Hardie (1975, p. 326) treated the depositional cycles in the Wilkins Peak Member as 40–50 repetitive transgressive-regressive episodes. They distinguished four types of lithologic successions: (1) a basal flat-pebble conglomerate overlain by oil shale overlain by mudstone containing thin stringers of lime sandstone toward the top, (2) thin-bedded lime sandstone with thin mudstone partings overlain by oil shale overlain by mudstone, (3) thin-bedded lime sandstone overlain by mudstone, and (4) oil shale overlain by trona overlain by mudstone, a succession which is restricted to the central part of the basin. The flat-pebble conglomerate, oil shale, and lime sandstone were considered to be transgressive deposits and the mudstone was considered to be a regressive deposit. Eugster and Hardie (1975, p. 326–327) believed that the mudstones "always represent the top of a cycle," the oil shale "forms the middle of the cycles," and the lime sandstone units "formed in the waters of a slowly expanding lake." The trona was thought to have precipitated from salt lakes located at the center of the basin. The salt lakes were described as "playas" that were seasonally dry.

My investigations have found some discrepancies in the depositional cycles described by Eugster and Hardie (1975), although I agree with most of their conclusions. Eugster and Hardie apparently only studied the upper 200 ft of the Wilkins Peak Member in nine sections that they measured on outcrops on White Mountain along part of the west flank of the Rock Springs uplift. Even though their study was limited in areal extent, I agree that their type 2 and type 4 cycles are correctly interpreted and are well represented in the Wilkins Peak Member. The type 1 and type 3 cycles, on the other hand, are believed to be incorrect because they are composed of either randomly occurring lithologic units or lithologic units that are geographically restricted.



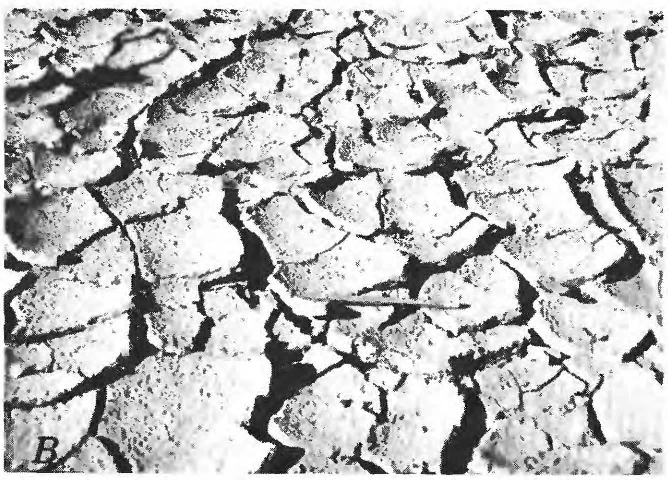
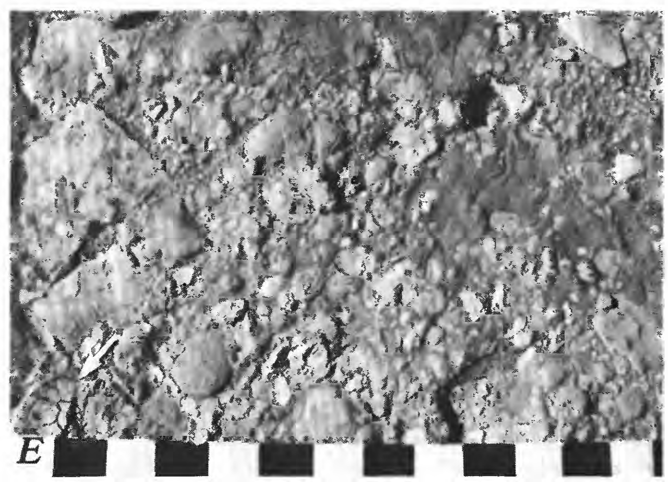




FIGURE 55.—Formation of recent lake-bed mud cracks and disintegration of mud clasts, greater Green River basin, and flat-pebble conglomerate of probably similar origin. Scale is indicated by a pencil, coin, or centimeter scale. *A*, Normal polygonal mud cracks develop on bottom of a dry lake bed. *B*, With continued drying, mud cracks begin to curl upwards at their margins. *C*, Curls fragment as a result of weathering. *D*, Rounded mud-crack clasts exhibit random sorting as a result of fluvial transport. *E*, Flat-pebble conglomerate from the Wilkins Peak Member contains a mud-cracked pebble (arrow).

Eugster and Hardie (1975) placed the flat-pebble conglomerate at the base of their type 1 cycle. I have measured the Wilkins Peak at dozens of locations around the greater Green River basin and have found that the pebble conglomerates are not consistently present in the type 1 cycle, and where present, are randomly located within the mudstone beds that form the upper part of the cycle. The origin and distribution of the flat-pebble conglomerates in the cyclically deposited mudstones in the Wilkins Peak Member can be explained by using modern analogs. These analogs are shown by photographs of mud cracks, figure 55*A–E*. The sequence illustrates the way in which mud cracks could have disintegrated to form the flat-pebble conglomerates present in the Wilkins Peak Member. Flat-pebble conglomerates obviously can

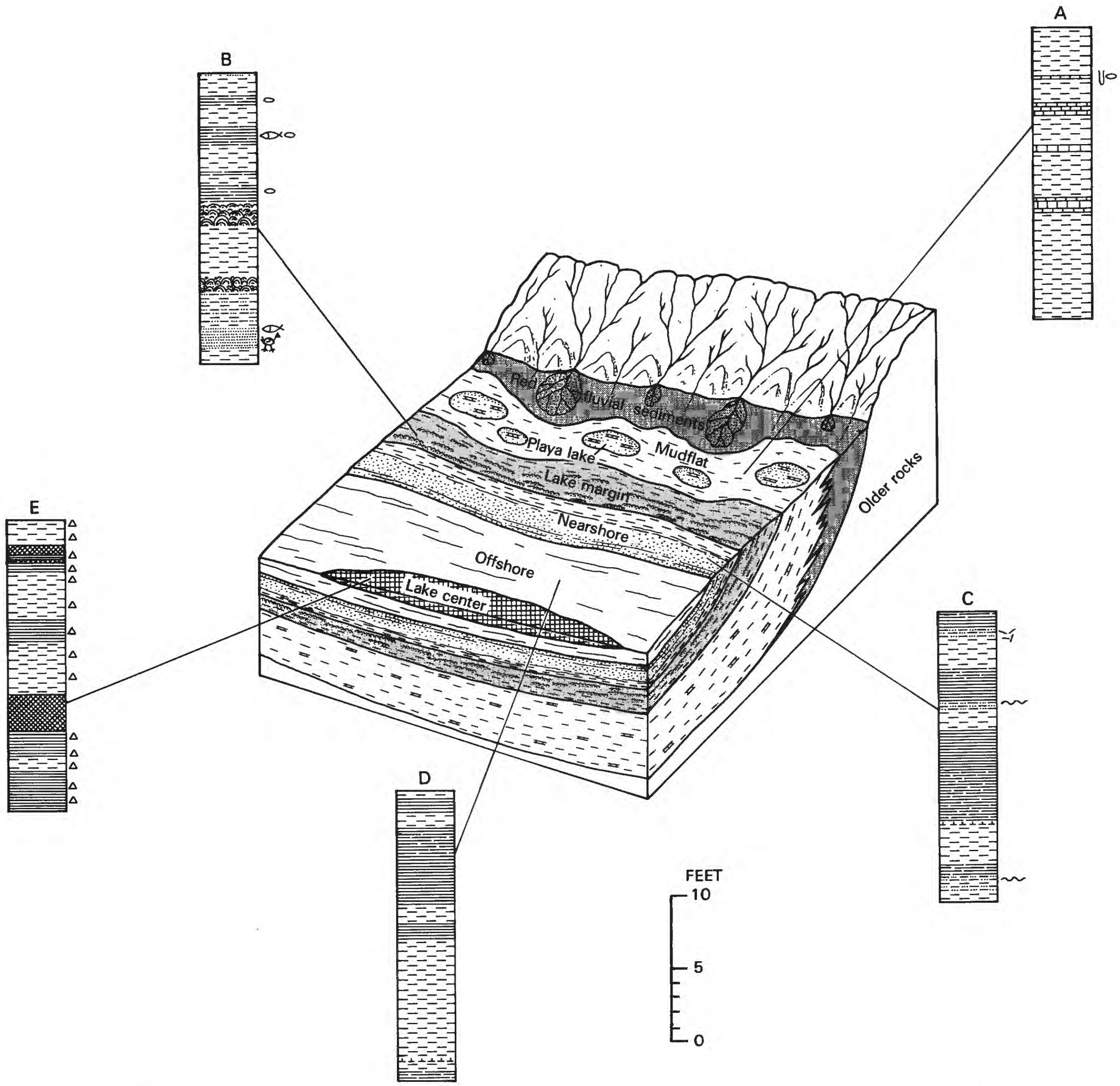



FIGURE 56 (above and facing page).—Measured sections *A* to *E* illustrating lithologies in various parts of the basin of Lake Gosiute during deposition of Wilkins Peak Member of Green River Formation.

form from mud crack fragments derived from any desiccated mud surface. As the mudstones in the Wilkins Peak Member are commonly composed of several superposed mudflat sequences, it follows that flat-pebble conglomerates are not necessarily restricted to one horizon within or at the top of the mudstones. It also follows that both the mudstones and flat-pebble conglomerates were probably deposited more frequently during regressive stages of the lake than they were during transgressive stages of the lake.

The lime sandstones at the base of the type 3 cycles of Eugster and Hardie (1975, p. 327) were correctly determined to be transgressive units. My work further indicates that they are transgressive beach deposits that are rare in outcrops of the Wilkins Peak Member, except along part of the west flank of the Rock Springs uplift. Thus the type 3

**EXPLANATION**

Gray or green dolomitic mudstone

Tan or light-brown kerogenaceous claystone

Medium-brown to black oil shale

Gray siltstone

Gray sandstone

Light-gray limestone

Tan or gray algal limestone (stromatolite)

Tan or gray tuff

White or light-brown trona

Burrows

Ostracodes

Fish

Bird bones

Shortite crystals

Synaeresis cracks

Wave ripples

**LOCATION OF SECTIONS**

A. Cumberland Gap measured section 2486, beds 27–35 NE¼NW¼SE¼ sec. 1, T. 18 N., R. 116 W.

B. Washakie basin measured section 168, beds 277–281 N½NW¼ sec. 29, T. 16 N., R. 100 W.

C. White Mountain–Rock Springs measured section X679, beds 114–130 SW¼SW¼SE¼ sec. 30, T. 19 N., R. 105 E.

D. White Mountain–Boars Tusk measured section 1786, beds 46–56 SE¼SE¼SW¼ sec. 13, T. 23 N., R. 105 W.

E. Energy Research and Development Administration Blacks Fork Corehole No. 1 (1,129–1,159 ft) NW¼SE¼NE¼ sec. 24, T. 16 N., R. 108 W.

cycle appears to be geographically restricted and probably should not be called typical of the member. In addition, the lime sandstone of the type 3 cycle is usually overlain by transgressive oil shale and is seldom interbedded with only regressive mudstone as indicated by Eugster and Hardie (1975, fig. 17).

The Wilkins Peak Member is composed of so many different lithologies and lithologic successions, cyclic and noncyclic, that no attempt is made herein to classify them as to types. My discussion of the member begins at the outer margins of the former lake basin, where the beds are diverse in thickness and composition and generally noncyclic, and it proceeds toward the center of the former lake basin, where the beds are more uniform in thickness and composition and form easily recognized depositional cycles. A few of the lithologies that make up the member are illustrated by a block diagram and columnar sections in figure 56, and others are illustrated by photographs.

FIGURE 57.—North-dipping delta sandstone (arrow) in Wilkins Peak Member of Green River Formation on south slopes of Little Mountain in SE1/4 sec. 20, T. 13 N., R. 105 W., southeastern Green River basin. The delta sandstone is about 50 ft thick.

The Wilkins Peak Member generally intertongues along its outer margins with red or variegated floodplain deposits that compose either the Cathedral Bluffs Tongue or the main body of the Wasatch Formation. Across the northeastern part of the Great Divide basin, the member also intertongues with arkoses that make up the Battle Spring Formation. Deltas formed in the Wilkins Peak Member at the mouths of major rivers and along the distal edges of alluvial fans during expanded stages of Lake Gosiute. A delta that formed at the distal edge of an alluvial fan on the north flank of the Uinta Mountains is shown in figure 57. During contracted lake stages, mudflats formed on the evacuated margins of the lake basin. The streams that entered the elevated outer margins of the basin during these times occupied sand-filled, confined drainages (fig. 58). Farther basinward, across flat-lying mudflats, the streams were unconfined and in those places they deposited broad sheets of sand (fig. 59). The resulting sheet sandstones weather to resistant dark bands in otherwise light-gray weathered outcrops along the west flank of the Rock Springs uplift (fig. 60).

Playa lakes were present on some of the mudflats located around the margins of the lake basin, as indicated in figure 56, section A, and as illustrated in figure 31. The limestones in these beds are often interbedded with mudflat mudstones in repetitious lithologic sequences, but the limestones are probably not cyclic. Along the lake margins, the mudstone deposited on the mudflats (fig. 34) is interbedded with shoreline sandstone (fig. 28), algal limestone (fig. 51), and shallow-water oil shale (fig. 27). These

FIGURE 58.—Lenticular, trough-crossbedded, stream channel sandstone (arrow) in Wilkins Peak Member of Green River Formation in roadcut on State Highway 373 south of Little Mountain in NE1/4 sec. 35, T. 13 N., R. 106 W. Dark bands in outcrops are mostly dark green mudstone; light bands are mostly sandstone and siltstone.

FIGURE 59.—View to northeast of dark-brown-weathered fluvial sheet sandstone (arrow) in Wilkins Peak Member of Green River Formation in Big Firehole Canyon in sec. 24, T. 16 N., R. 107 W., southeastern Green River basin. The sandstone is about 20 ft thick. Note the thin parallel bedding and lack of scouring at base of sandstone.

FIGURE 60.—View to northeast of Wilkins Peak Member of Green River Formation in Big Firehole Canyon near Flaming Gorge Reservoir in secs. 23, 24, and 26, T. 16 N., R. 207 W. Dark bands are mostly dark-brown-weathered fluvial sheet sandstone. Light bands are interbedded lacustrine oil shale and siltstone and mudflat mudstone. Distant buttes are capped by Sand Butte Bed of Laney Member of Green River Formation. Scale is indicated by paved road at lower left.

FIGURE 61.—Ledge formed by toadstool-type algal limestone in Wilkins Peak Member of Green River Formation at Alkali Draw in west-center sec. 4, T. 24 N., R. 100 W., western Great Divide basin.

relationships are shown in figure 56, section B. The lacustrine oil-shale beds generally alternate with mudflat mudstone; this alternation reflects the cyclic expansions and contractions of the lake. The algal limestones deposited in the shallow waters along the lake margins commonly formed extensive matlike reefs. An outcrop of one of these algal limestones is shown in figure 61.

Ascending sequences of limy sandstone-siltstone, oil shale, and mudstone were deposited along nearshore areas of the lake basin (fig. 56, section C) in clearly defined depositional cycles (fig. 62). As already stated, the sandstone-siltstone beds in these sections were deposited mostly as beaches and the overlying oil-shale beds were deposited in saltwater lakes during lake transgressions; the intervening


FIGURE 62.—Basal Wilkins Peak Member of Green River Formation exposed on north side of Interstate Highway 80, 3 mi west of Rock Springs, Wyo. Three transgressive-regressive cyclic sequences of Lake Gosiute in the exposures consist of (1) light-gray, parallel-bedded, limy sandstone-siltstone (beach deposits); (2) tan-gray, varved oil shale (saltwater lacustrine deposits); and (3) dark-gray-green, parallel-bedded, dolomitic mudstone (mudflat deposits). The lake expanded to the right (east) during deposition of beds No. 1 and 2 and contracted to the left (west) during bed No. 3.

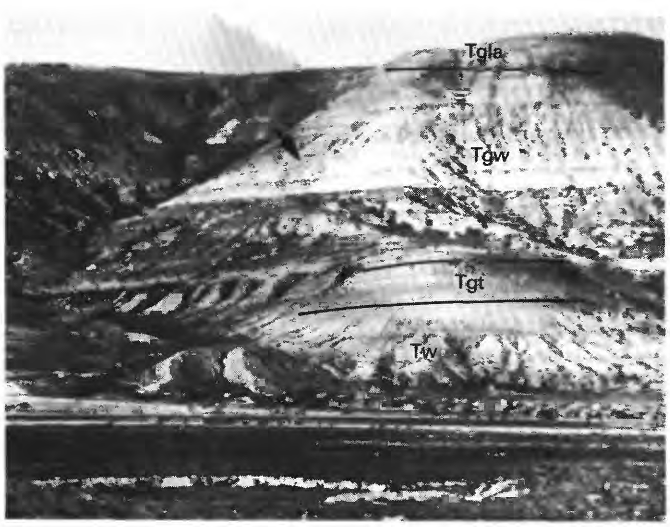



FIGURE 63.—View to northwest of white beds (arrow) in Tgw, Wilkins Peak Member of Green River Formation, on White Mountain west of Rock Springs, Wyo., near the intersection of Tps. 18–19 N., Rs. 105–106 W. Twn, Niland Tongue of Wasatch Formation; Tgt, Tipton Shale Member of Green River Formation; and Tgla, Laney Member of Green River Formation. Outcrops shown total about 1,200 ft thick.

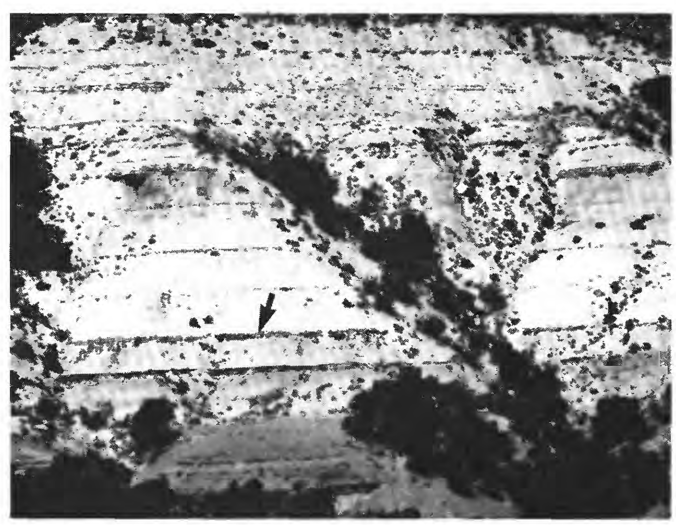


FIGURE 64.—View to west of ledges (arrow) formed by beach sandstone-siltstone in white beds of Wilkins Peak Member of Green River Formation on White Mountain shown in figure 63. Detailed views of the beach deposits are in figures 28 and 29. Outcrops shown are about 70 ft thick.

FIGURE 65.—Fossil bird (flamingo) quarry in mudflat mudstone of Wilkins Peak Member of Green River Formation in sec. 24, T. 25 N., R. 102 W. on the north slopes of Parnell Creek. Shown are P.O. McGrew (standing) and associates from the University of Wyoming.

mudstones were deposited on mudflats that developed during lake regressions. The sandstone-siltstone beach deposits weather to distinctive ledges in an interval of white outcrops along the east face of White Mountain near Rock Springs, Wyo. (figs. 63, 64). The offshore parts of the lake basin were the site of mostly interbedded saltwater lacustrine oil shale and mudflat mudstone (fig. 56, section D). At the lake basin center (fig. 56, section E), ascending sequences of oil shale, trona and halite, and mudstone were deposited. The oil shale and mudstone beds in this area commonly contain numerous disseminated crystals of shortite (fig. 8).

The mudflats at the outer margins of the basin of Lake Gosiute during deposition of the Wilkins Peak

Figure 66.—Closeup view of bird quarry shown in figure 65. Large, elongated objects on right side of photograph are algae-covered tree limbs.

Member were locally the nesting sites of shallow-aquatic birds, mostly primitive flamingos. One of the flamingo sites, located on Parnell Creek north of the Rock Springs uplift, was quarried by a field party from the University of Wyoming under the direction of P.O. McGrew (figs. 65, 66).

### LOWER PART OF WILKINS PEAK MEMBER (BEDS 1–11) OF GREEN RIVER FORMATION

The saline waters of Lake Gosiute expanded and contracted 11 times across the central and southern parts of the greater Green River basin during deposition of the lower part of the Wilkins Peak Member (fig. 67). The size and configuration of the lake basin of the lower part of the Wilkins Peak Member were similar to those of the lake basin that was present earlier during deposition of the Rife Bed of the Tipton Shale Member (compare figs. 52 and 67). The primary depositional axis was centered along the Uinta Mountain trough and the deepest parts of the lake were located north of the Uinta Mountains in the southern part of the Green River basin. Oil shale was deposited during the lake expansions and mudstones were deposited during the lake contractions. At least 10 beds of trona, or trona and halite, were deposited during the contractions of the lake to salt pans. The lower part of the Wilkins Peak Member is 150–200 ft thick near the center of the basin, but it thins toward the lake basin margins. The expanded lake stages occupied as much as 8,700 $m^2$ and lasted for as long as 20,000 yr. Lakes of this size and duration can hardly be classified as playa lakes.

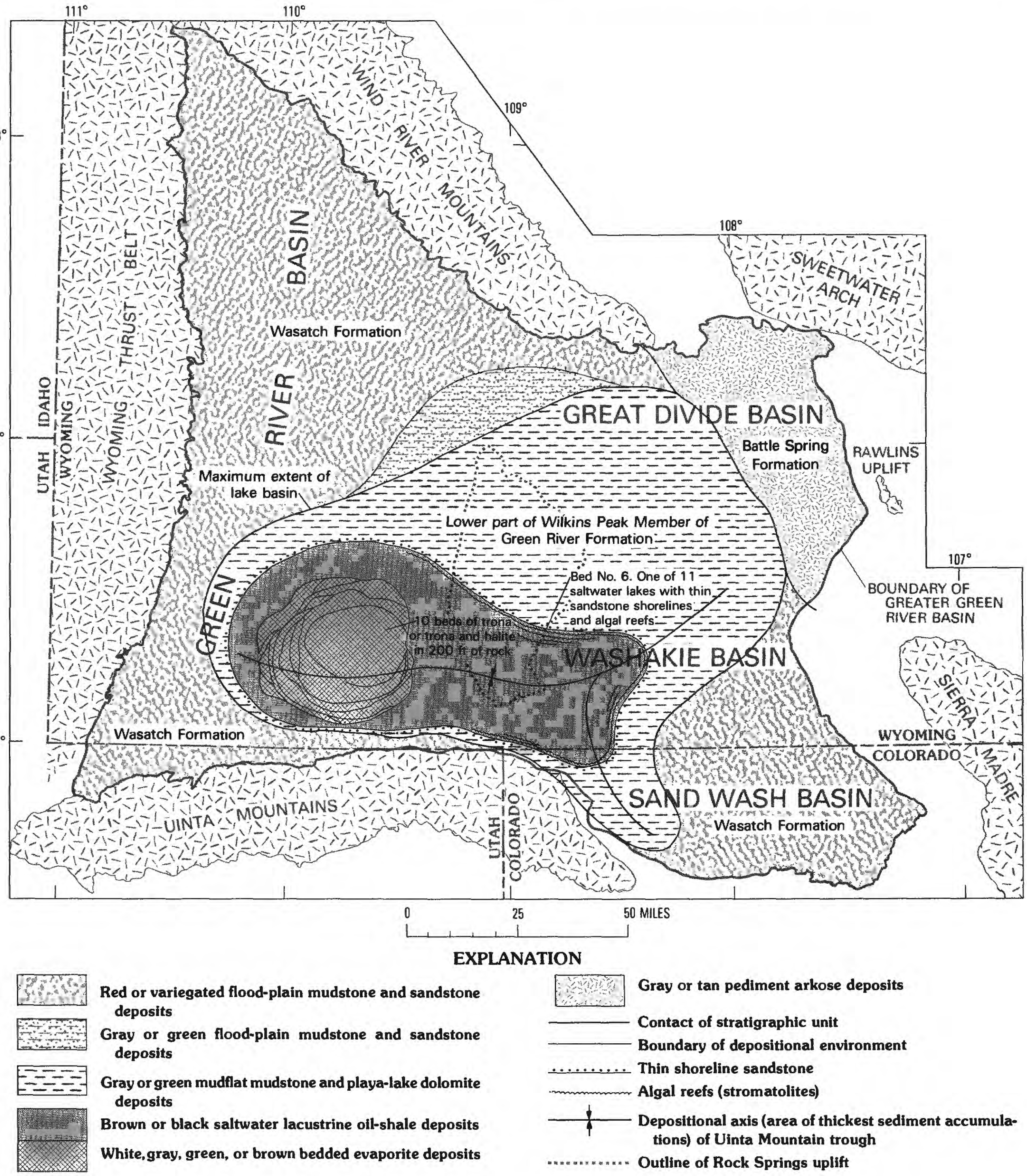



FIGURE 67.—Paleogeographic map of lower part of Wilkins Peak Member (beds 1–11) of Green River Formation and associated formations showing locations of depositional environments.

Figure 67 shows the maximum areal extent of Lake Gosiute during deposition of bed 6 (fig. 7) in the lower part of the Wilkins Peak Member. The lake during deposition of bed 6 was elongated in an east-west direction and occupied about 3,200 mi$^2$ of the Uinta Mountain trough north of the Uinta Mountains. When the lake contracted to a salt pan located at the west end of the trough, more than 12 ft of trona and halite were deposited in an irregularly shaped area that covered about 600 $mi^2$ of Tps. 13–16 N., Rs. 107–112 W. (fig. 1).

The shorelines of the saltwater lakes during this period of deposition were partly sandy and partly muddy. Algal limestones were present in the shallow, nearshore waters. Surrounding the lake were gray and green or red or variegated flood-plain deposits of the Wasatch Formation, and arkosic sediments composing the Battle Spring Formation in the northeastern part of the basin.

#### MIDDLE PART OF WILKINS PEAK MEMBER (BEDS 12–67) OF GREEN RIVER FORMATION

Tectonic events in the greater Green River basin at the beginning of deposition of the middle part of the Wilkins Peak Member caused the entire floor of the basin to tilt from east to west. These tectonic events involved the last movements of the Wind River and Sparks Ranch thrust faults (fig. 68). The basin tilting caused a reconfiguration of the basin of Lake Gosiute and the evacuation of the lake from the Great Divide, Washakie, and Sand Wash basins. The reconfigured lake basin was irregularly circular in shape and occupied about 12,000 $mi^2$ (fig. 68). The depositional center of the lake basin during deposition of the lower middle part of the Wilkins Peak Member was located along a remnant of the Uinta Mountain trough in the southern part of the Green River basin. The depositional center later slowly shifted as much as 25 mi north of the Uinta Mountain trough, toward the center of the Green River basin, during deposition of the upper middle part of the Wilkins Peak Member.

The rocks deposited in the middle part of the Wilkins Peak Member have a maximum thickness of about 900 ft. At least 26 beds of trona, or trona and halite, were deposited in these rocks. The trona and halite beds are concentrated in an irregularly oval-shaped area about 50 mi long (north-south) and 75 mi wide (east-west) that occupied about 1,375 $mi^2$ and covered parts of Tps. 13–21 N., Rs. 107–113 W. (fig. 1). The trona and halite each generally range in thickness from 1 to 15 ft. They are locally as much as 30 ft thick in Tps. 14–15 N., Rs. 110–112 W., where the deepest parts of several salt pans were located.

The areal extent of bed 24 (fig. 7) in the middle part of the Wilkins Peak Member is shown in figure 68. The lake during deposition of bed 24 occupied about 4,350 $mi^2$ of the basin during the period of maximum lake expansion. Although mudflat mudstone overlies oil shale in the bed, indicating that the lake probably retreated to form a salt pan and subsequently dried up, no bedded evaporites have been identified with bed 24.

Lake Gosiute underwent 56 cyclic expansions and contractions during deposition of the middle part of the Wilkins Peak Member. These cycles have been discussed at length previously. Surrounding the lake basin during and following these cycles were mostly gray and green or red or variegated flood-plain deposits of the Wasatch Formation; arkoses of the Battle Spring Formation continued to be deposited in the northeastern part of the basin; and along the Uinta Mountains, several alluvial fans spread coarse clastics northward onto the floor of the greater Green River basin. The Canyon Creek alluvial fan was deposited at this time (fig. 12).

The middle part of the Wilkins Peak Member, of largely lacustrine origin, intertongued extensively with the Cathedral Bluffs Tongue of the Wasatch Formation, of flood-plain origin, across the eroded area presently occupied by the Rock Springs uplift. Thin eastern remnants of some of the lacustrine tongues of the Wilkins Peak Member are present in outcrops mapped as Cathedral Bluffs Tongue along the western margins of the Washakie and Sand Wash basins. These lacustrine tongues consist of beach sandstone containing fish bones, ostracodes, and oolites, and of algal limestone. They are usually less than 3 ft thick and are most abundant in the upper and lower parts of the Cathedral Bluffs Tongue (Chapter D, pl. 1). One outcrop of brain-type algal limestone is remarkably well preserved in one of these lacustrine tongues located 155 ft above the base of the Cathedral Bluffs Tongue on the west slopes of Lookout Mountain in the western part of the Sand Wash basin (Chapter E, pl. 1 and fig. 6; measured section 4373). The algal limestone is 1–2 ft thick and crops out in small, isolated heads, or mounds (fig. 69). The algal limestone is overlain and underlain by thick red or variegated mudstones that are locally typical of the Cathedral Bluffs Tongue.

#### UPPER PART OF WILKINS PEAK MEMBER (BEDS 68–77) AND EQUIVALENT PARTS OF LANEY MEMBER OF GREEN RIVER FORMATION

The upper part of the Wilkins Peak Member, beds 68–77 (fig. 7), is generally 40–125 ft thick. It is laterally equivalent to the lower part of the Laney Member in the northern Green River, southwestern Washakie, and western Sand Wash basins (fig. 70). A vertical shift in the stratigraphic position of the Wilkins Peak–Laney contact in the northern Green River basin is discernible by the position of a stratigraphic marker known as the layered tuff bed. This tuff is only a few centimeters thick (fig. 71), but it consists of seven remarkably uniform layers of sequentially

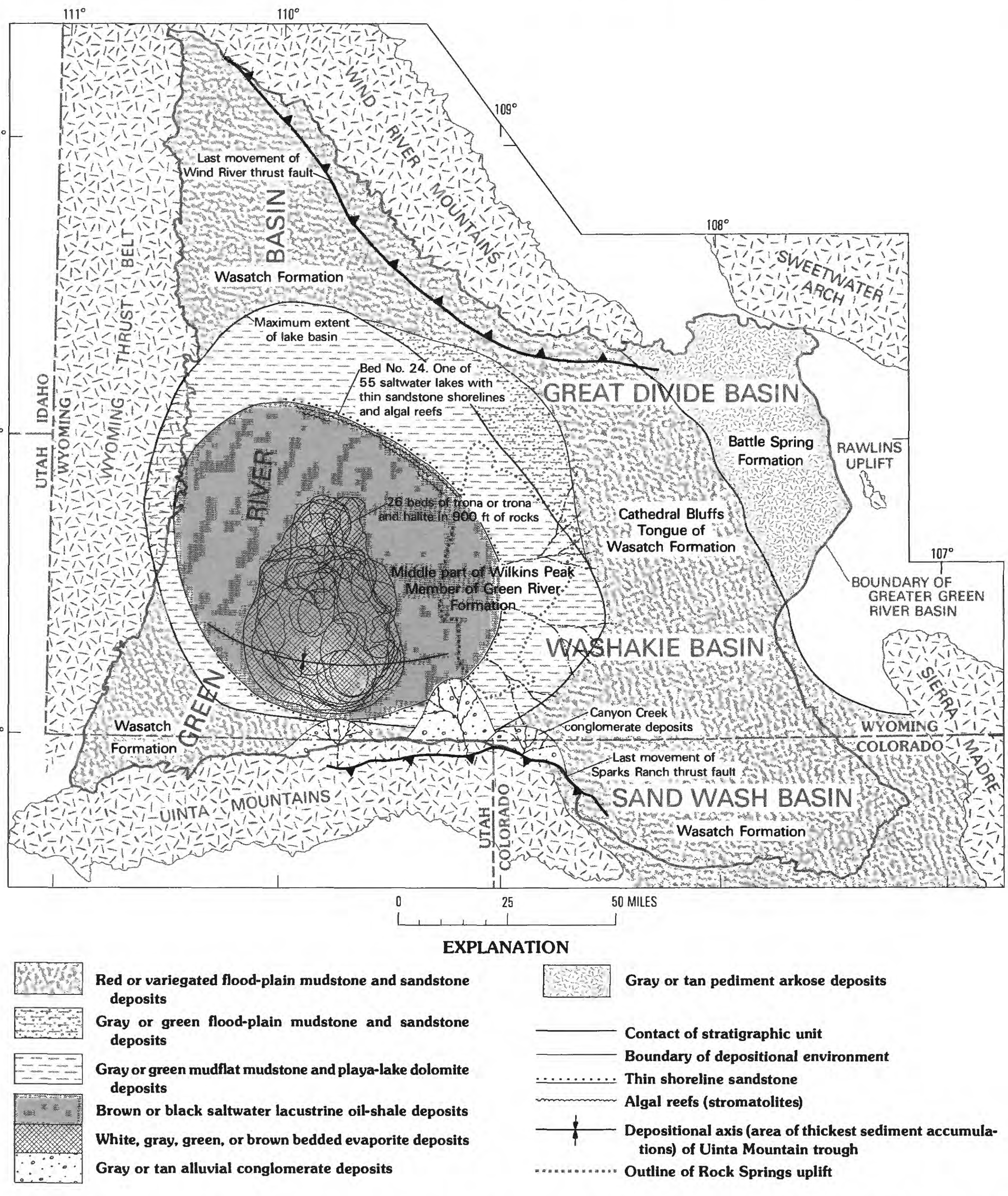



FIGURE 68.—Paleogeographic map of middle part of Wilkins Peak Member (beds 12–67) of Green River Formation and associated formations showing locations of depositional environments, and the western remnant of the Uinta Mountain trough. Sawteeth on overthrust block of fault.

deposited volcanic ash that can be correlated over thousands of square miles in the Green River basin. In coreholes in the central part of the Green River basin, the layered tuff is situated about 100 ft below the top of the Wilkins Peak Member; along outcrops in the northern part of the basin, it has been mapped in

FIGURE 69.—Brain-type algal limestone from lacustrine bed in Cathedral Bluffs Tongue of Wasatch Formation in SE¼ sec. 28, T. 11 N., R. 99 W., on west slopes of Lookout Mountain. Pocket knife indicates scale.

the lower 25 ft of the Laney Member (Roehler, 1990b). The same shift in the stratigraphic position of the contact between the Wilkins Peak and Laney Members can be found by correlating oil-shale beds between the southern Green River basin and the Washakie basin (Roehler, 1991b) and between the Washakie basin and the Sand Wash basin (Roehler, 1991e).

The upper part of the Wilkins Peak Member and its Laney Member equivalents occupied about 8,800 $mi^2$ of the greater Green River basin (fig. 70). The rocks deposited in these units consist mostly of interbedded oil shale and gray to green mudstone with minor thin beds of limestone, siltstone, and tuff. The oil shale and mudstone were deposited during lake expansions and contractions, in cycles similar to those described in the lower and middle parts of the Wilkins Peak Member. The oil shale and mudstone contain a few layers of disseminated shortite crystals and locally, nahcolite vugs, but the upper part of the Wilkins Peak Member is not known to contain bedded evaporites, such as trona or halite. The absence of bedded evaporites can be explained by the connection of Lake Gosiute to Lake Uinta that occurred at the east end of the Uinta Mountains during this time (Chapter C, fig. 10; Chapter E, fig. 32). This connection caused the waters of Lake Gosiute to freshen to the extent that salt pans no longer developed during the contraction stages of the lake.

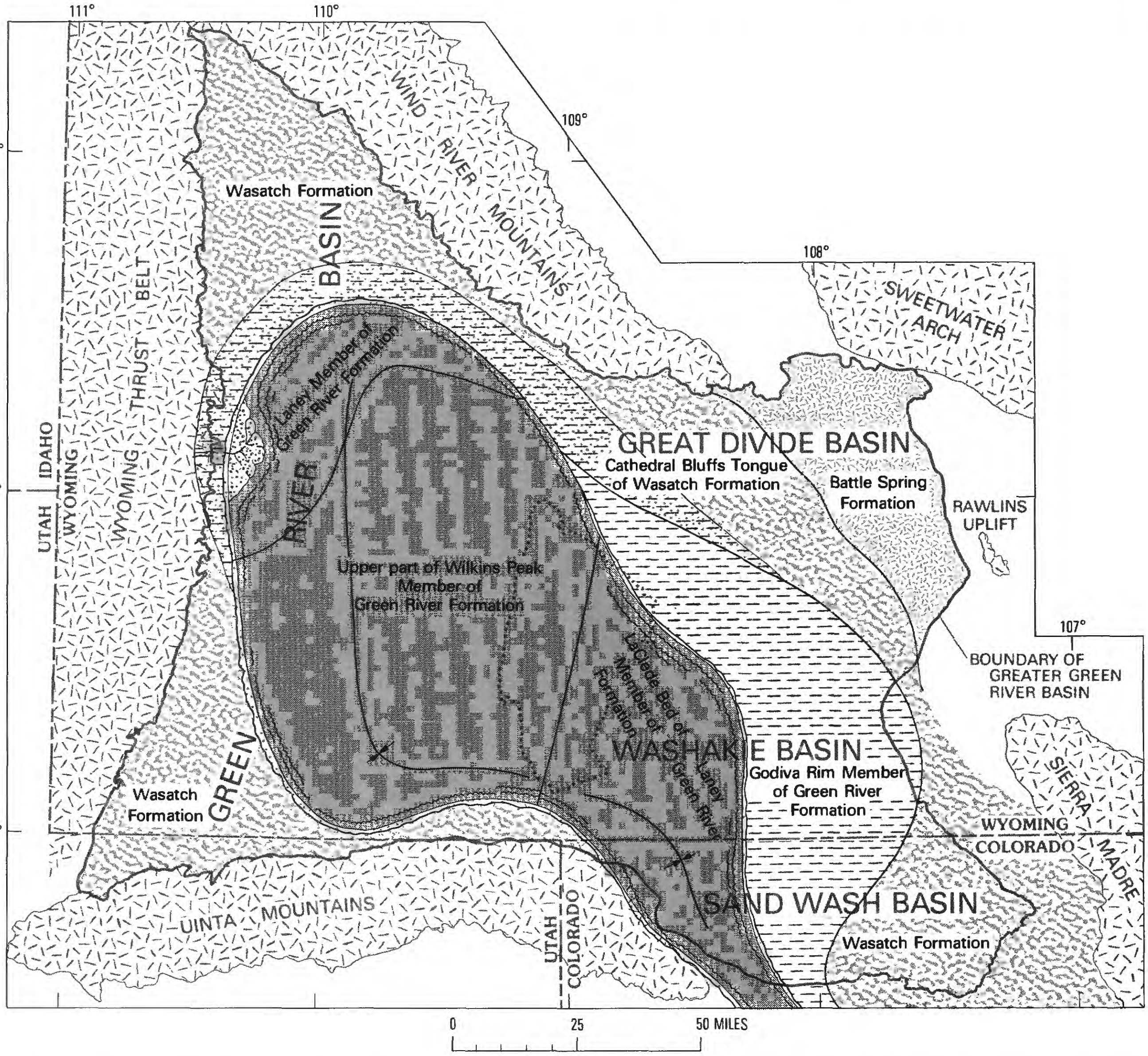
The depositional axis of Lake Gosiute during deposition of the upper part of the Wilkins Peak Member was oriented north-south across the northern and central parts of the Green River basin (fig. 70). In the southern part of the greater Green River basin, the axis turned eastward and paralleled the north flank of the Uinta Mountains. Those parts of the axis that paralleled the north flank of the Uinta Mountains conform in location to segments of the Uinta Mountain trough, which was present during earlier Eocene times.

The upper part of the Wilkins Peak Member contains a variety of well-preserved fossils. Complete fossil fish, similar to one collected by the author from the Green River Formation in the Fossil basin (fig. 72), are fairly common in finely laminated oil-shale beds. Tuffaceous mudstones along the margins of the lake basin have yielded numerous fossil leaves (fig. 73). Perhaps the most unusual fossils are insects and insect larvae (figs. 74, 75) that abound in oil-shale outcrops at several stratigraphic horizons in the upper 250 ft of the Wilkins Peak Member along White Mountain on the west flank of the Rock Springs uplift (Roehler, 1981).

## LACLEDE BED OF LANEY MEMBER OF GREEN RIVER FORMATION

The lower part of the LaClede Bed, as much as 350 ft thick (Chapter E, fig. 29), was deposited under saltwater and brackish-water conditions; the upper part of the LaClede Bed, as much as 450 ft thick, was deposited under freshwater conditions (Roehler, 1991c, p. B9). The change from saltwater to freshwater resulted from a significant early middle Eocene climate change from hot and arid to warm and humid conditions (Leopold and MacGinitie, 1972, p. 171) and from the continued presence of an outlet of Lake Gosiute at the east end of the Uinta Mountains. At its maximum areal extent, the upper freshwater part of the LaClede Bed occupied about 15,400 $mi^2$ and covered more than 75 percent of the floor of the greater Green River basin (fig. 76). The depositional axis of the lake paralleled the north flank of the Uinta Mountains.

The sediments that accumulated in the deep, central part of Lake Gosiute during deposition of the LaClede Bed formed oil shale and thin interbedded sandstone, siltstone, mudstone, shale, limestone, and tuff. Mostly silt and sand were deposited in the nearshore and shoreline areas of the lake. Numerous algal reefs (stromatolites) were present in some of the shallow, nearshore waters. These algal reefs generally consist of 1–2-ft-thick beds of toadstool-type algae (fig. 77). A few reefs, however, were much larger. One reef that crops out along the southern




EXPLANATION

- Red or variegated flood-plain mudstone and sandstone deposits
- Gray or green flood-plain mudstone and sandstone deposits
- Gray or tan lacustrine sandstone deposits
- Brown or black saltwater lacustrine oil-shale deposits
- Gray or tan pediment arkose deposits
- Gray or green mudflat mudstone and playa-lake dolomite deposits
- Contact of stratigraphic unit
- Boundary of depositional environment
- Algal reefs (stromatolites)
- Depositional axis (area of thickest sediment accumulations) of lake basin
- Outline of Rock Springs uplift

FIGURE 70.—Paleogeographic map of upper part of Wilkins Peak Member (beds 68–77) of Green River Formation and associated formations showing locations of depositional environments.

margins of the basin has weathered to linear clusters of huge, partly siliceous algal heads as much as 10 ft in diameter and 25 ft high (figs. 78–80). The stratigraphic position of this reef is shown in measured section 8 in figure 2. In places, former shorelines of the lake are formed by oolitic or pisolitic limestone beds that were deposited between linear algal reefs or on beaches (fig. 81). Surrounding the lake were

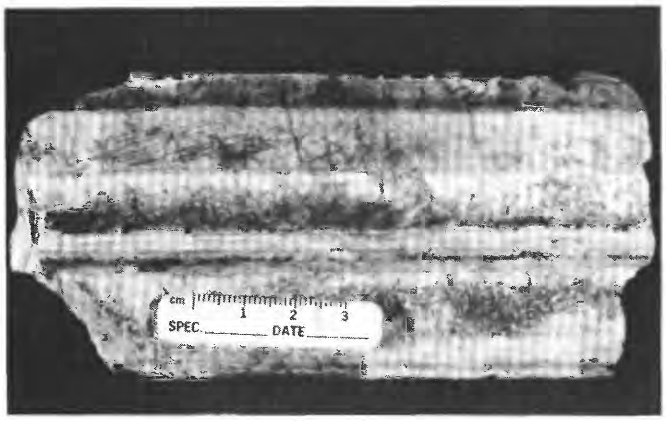



FIGURE 71.—Sample from layered tuff marker bed in upper part of Wilkins Peak Member of Green River Formation in sec. 7, T. 15 N., R. 106 W., on Sage Creek, southeastern Green River basin. See Chapter E, fig. 5, measured section X8–1079, X1979.

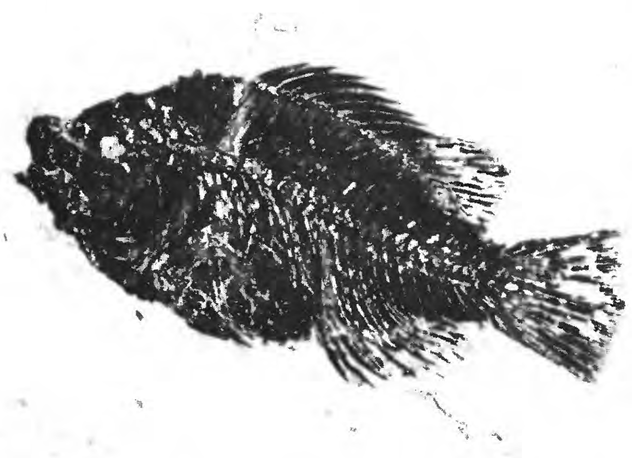


FIGURE 72.—Fossil sunfish(?), *Priscacara* sp., from Green River Formation in Fossil basin, southwestern Wyoming. Specimen is 6 inches long.

mostly gray and green flood-plain deposits that make up parts of the Bridger Formation. Deposition of the Battle Spring Formation continued along the northeastern part of the basin.

The LaClede Bed is 50–450 ft thick where it was partly eroded across the crest of the Rock Springs uplift, but where the section is complete in the western part of the Sand Wash basin, it is more than 800 ft thick (Chapter E, fig. 29). The uneroded parts of the bed comprise the thickest section of oil shale deposited in the Green River Formation in the greater Green River basin. The oil shale generally yields from 5 to 15 gal of oil per ton by Fischer assay (Roehler, 1991e). Some beds that are less than 5 ft

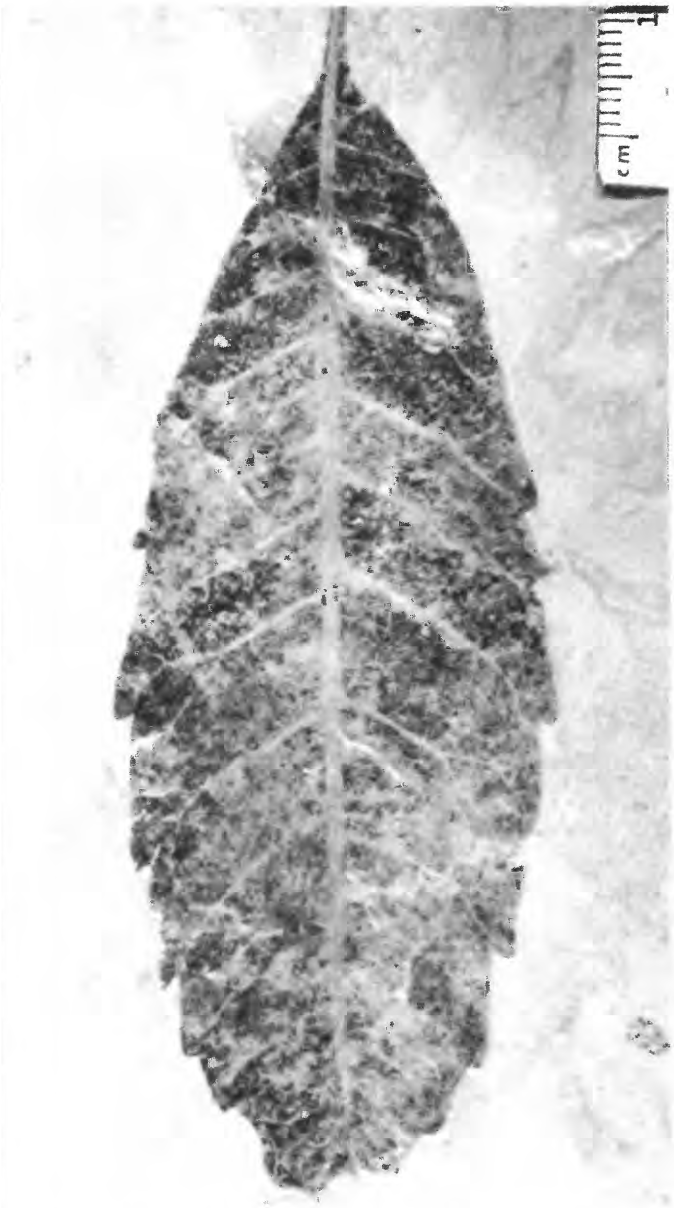



FIGURE 73.—Fossil leaf from Green River Formation, southwestern Wyoming. The collection site is unknown, but is believed to be the upper part of Wilkins Peak Member at MacGinitie's (1969) Little Mountain locality.

thick will yield in excess of 25 gal/ton, and a few very thin, very rich beds will yield more than 45 gal/ton. A sample of a 0.6-ft-thick very rich bed of oil shale collected from outcrops of the LaClede Bed along Middle Marsh Creek in the southeastern Green River basin is shown in figure 82.

The lower 160–375 ft of the oil-shale beds that compose the LaClede Bed in the central part of the greater Green River basin thin eastward by

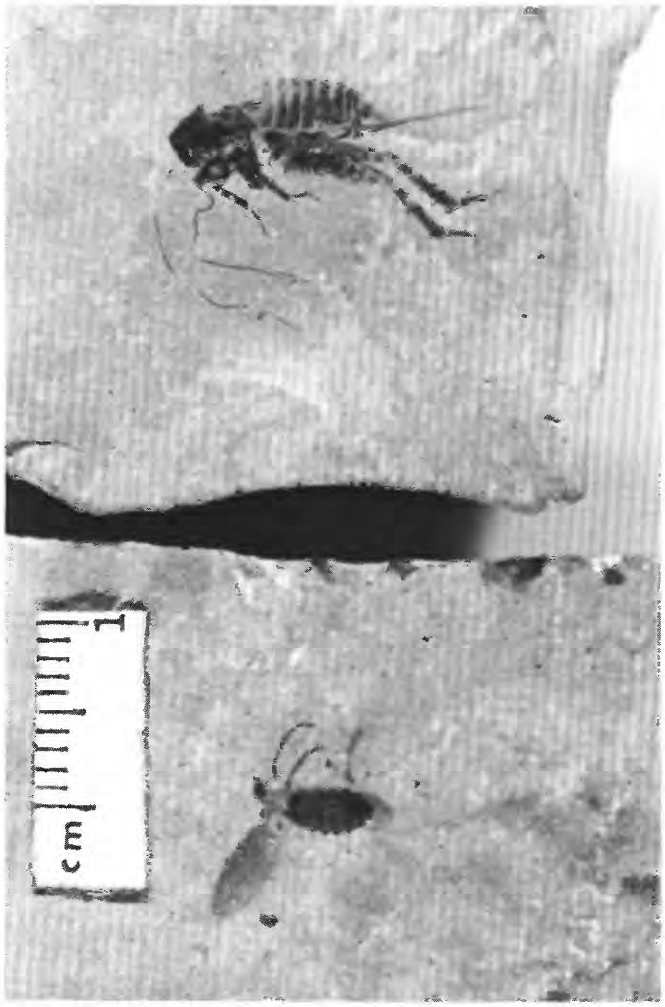


FIGURE 74.—Fossil insects from upper part of Wilkins Peak Member of Green River Formation in sec. 30, T. 19 N., R. 105 W., on White Mountain on west flank of Rock Springs uplift. Bottom, a marsh fly, *Plecia* sp. Top, a cricket, *Pronemobius* sp.

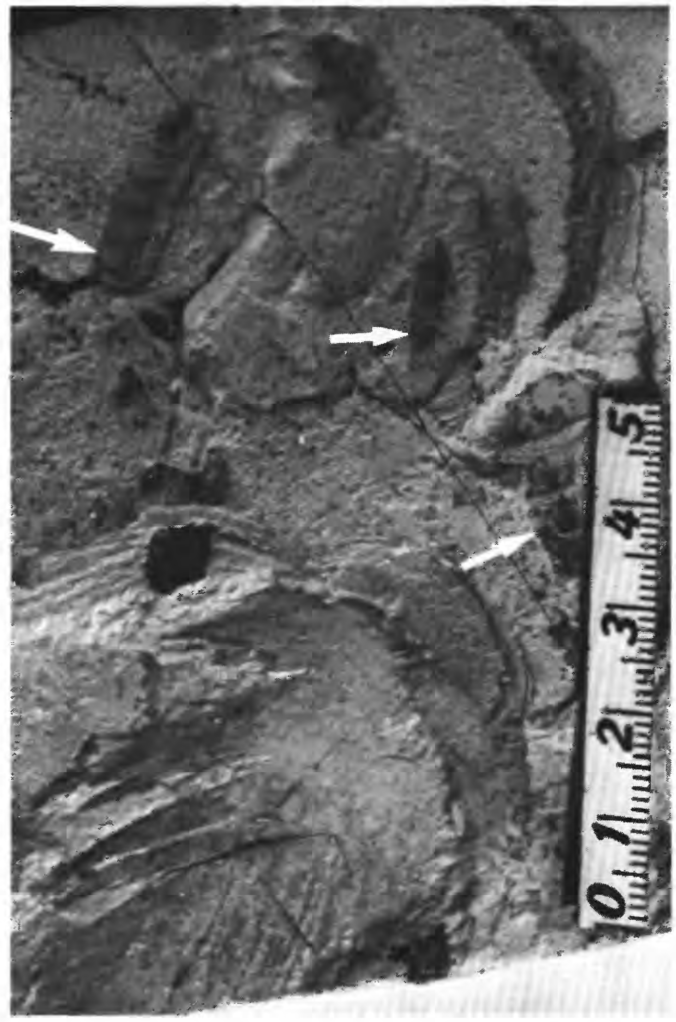


FIGURE 75.—Bot fly larvae, *Lithophypoderma* sp. (arrows), from upper part of Wilkins Peak Member of Green River Formation in sec. 30, T. 19 N., R. 105 W., on White Mountain on west flank of Rock Springs uplift. Note bird feather in lower part of photograph. Scale in centimeters.

intertonguing and gradual replacement by mostly gray mudflat mudstone and flood-plain sandstone and mudstone. Along the eastern margins of the basin, these rocks make up the Godiva Rim Member of the Green River Formation (Chapter C). The Godiva Rim Member, in turn, intertongues with and is replaced from its base upwards by red or variegated flood-plain deposits composing the Cathedral Bluffs Tongue of the Wasatch Formation. Stratigraphic correlations suggest that as much as 100 ft of the basal part of the type section of the Godiva Rim Member in the southern part of the Sand Wash basin may be chronologically equivalent to the upper part of the Wilkins Peak Member in the Green River basin. The paleogeographic relationships of the Godiva Rim Member are illustrated in figure 70.

## SAND BUTTE BED OF LANEY MEMBER OF GREEN RIVER FORMATION

The Sand Butte Bed was deposited in a 3,500 $mi^2$ area of the central part of the greater Green River basin following an anticlinal uplift of the Rock Springs anticline. The uplift was accompanied by an increase in volcanic activity west of the basin that introduced large quantities of airborne ash into the basin. As a result of these tectonic and volcanic events, the climate in the basin began to cool and Lake Gosiute began to contract and retreat southward. As a result of the uplift, the Rock Springs anticline initially formed an island in the middle of Lake Gosiute. This island soon became a peninsula connected to the northern shoreline of the lake. Then

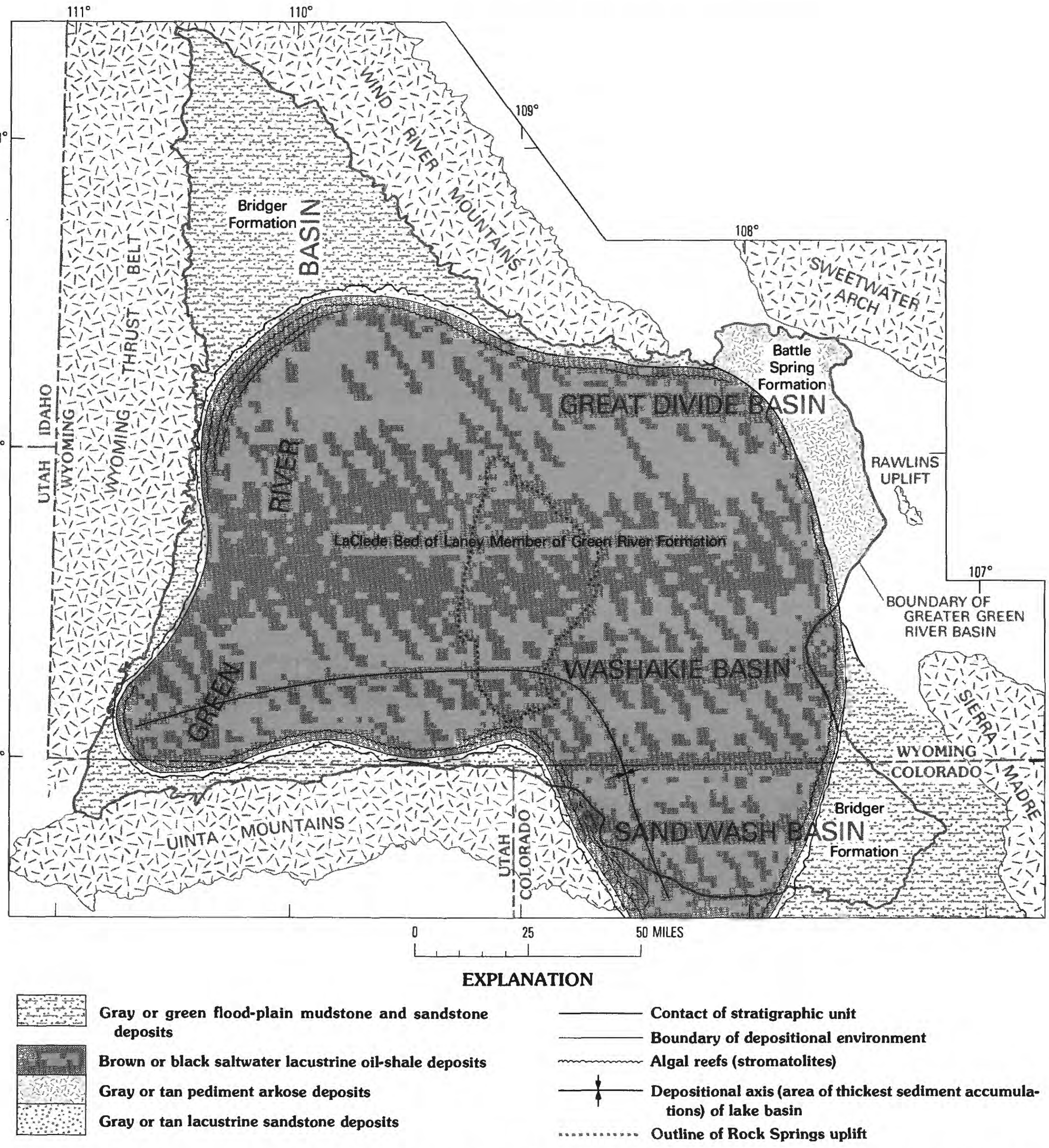



FIGURE 76.—Paleogeographic map of the LaClede Bed of Laney Member of Green River Formation and associated formations showing locations of depositional environments.

the lake retreated southward around this peninsula to its deepest parts that were located along its depositional axis north of the Uinta Mountains (fig. 83). The crest of the Rock Springs anticline was rapidly eroded following the uplift, and as much as 700 ft of soft oil shale in the exposed LaClede Bed was removed. The resulting erosion surface, which had moderate topographic relief (figs. 84 and 85), has been named the Tower unconformity (Roehler and Trudell, 1981).

The Sand Butte Bed is composed of mostly very tuffaceous siltstone and sandstone and interbedded

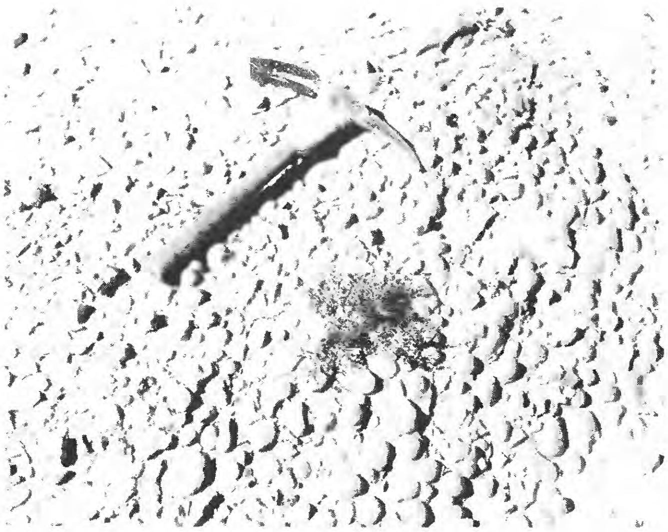


FIGURE 77.—Top of reef formed by toadstool-type algae in LaClede Bed of Laney Member of Green River Formation in NE¼NE¼ sec. 19, T. 14 N., R. 99 W. on Kinney Rim, southwestern Washakie basin. Pick handle is 1.5 ft long.

FIGURE 78.—View to north of linear clusters of algal heads in LaClede Bed of Laney Member of Green River Formation in SW¼SE¼ sec. 32, T. 10 N., R. 100 W., western Sand Wash basin.

FIGURE 79.—Top view of one of the algal heads shown in figure 78.

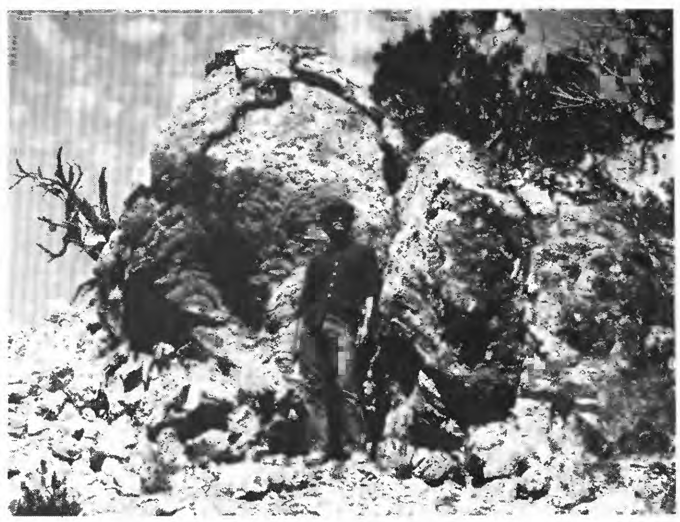


FIGURE 80.—Side view of algal heads shown in figure 78.

tuff. It is irregularly lenticular in cross section and ranges in thickness from less than 1 ft to as much as 900 ft (Roehler, 1973b, p. E7). The bed is fluvial in origin in the northern two-thirds of the Rock Springs uplift and adjoining areas, where it displays fluvial channel and interchannel sedimentation. The volcanic ash deposited in these fluvial beds was water saturated and had considerable plasticity during diagenesis, which locally caused many of the beds to become convoluted. The Sand Butte Bed is lacustrine in origin in the southern one-third of the Rock Springs uplift and in the area south of the uplift along the depositional axis of the lake (fig. 83). Organic mud (oil shale) was deposited in the LaClede Bed in deep-water remnants of the lake, contemporaneously with the sands, silts, and tuffs of the Sand Butte Bed.

Lake Gosiute periodically expanded northward and eastward from its depositional axis north of the Uinta Mountains, so that the maximum extent of the lake basin, about 7,100 mi$^2$, was much larger than the 3,900 mi$^2$ area occupied by the lake shown in figure 83. The lake margin deposits in figure 83 are mostly fluvial sandstone and mudstone with thinly interbedded lacustrine limestone and sandstone. These rocks compose the lower part of the Hartt Cabin Bed of the Laney Member.


FIGURE 81.—Oolitic and pisolitic limestone in LaClede Bed of Laney Member of Green River Formation in sec. 33, T. 14 N., R. 99 W., on Kinney Rim, southwest Washakie basin. 1, oolites; 2, pisolites; 3, algae. Scale in centimeters.

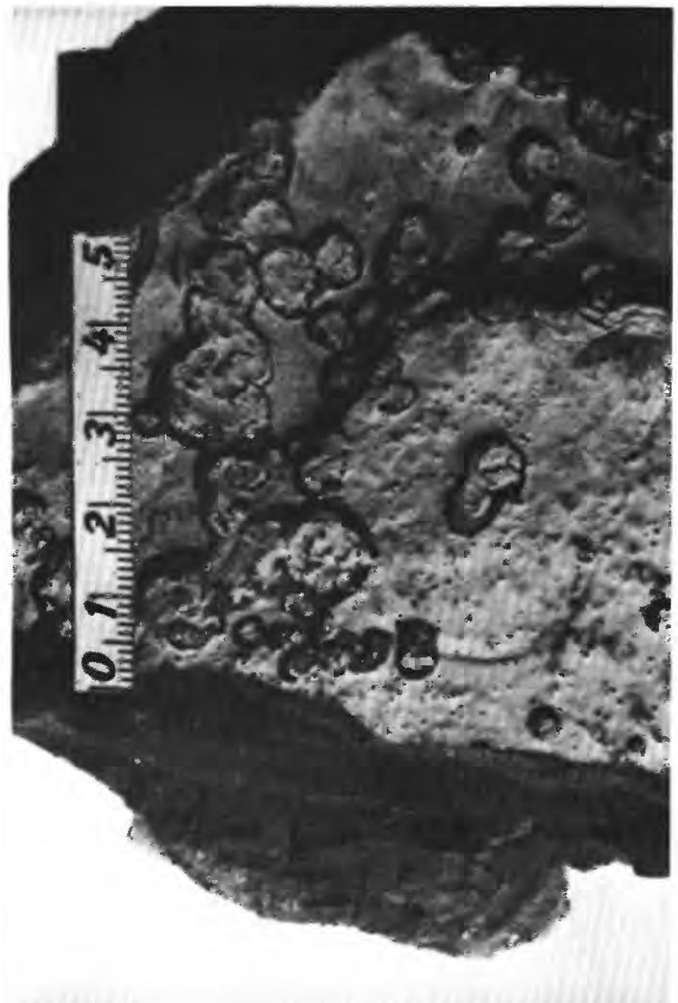



FIGURE 82.—Very rich oil shale in LaClede Bed of Laney Member of Green River Formation in NE¼NE¼ sec. 19, T. 13 N., R. 107 W., Middle Marsh Creek, southeastern Green River basin. The oil shale is black, but weathers silver gray. The sun has baked the bed to form tar bubbles on its upper surface. Scale in centimeters.

Several sand fan-deltas formed along the northern shores of Lake Gosiute during deposition of the Sand Butte Bed (fig. 83). One of the largest of these deltas, which crops out for about 2 mi along Delaney Rim in the northern Washakie basin, was discovered in 1969 during measurement of stratigraphic section No. 2369 (Chapter E, fig. 6, pl. 1). This delta has well-defined bottomset, foreset, and topset beds. It is composed mostly of sandstone, siltstone, and very silty mudstone of deep-water origin that crop out in parallel to subparallel beds and laminae (fig. 86). In composition and configuration it bears only slight resemblance to the fossil lacustrine deltas described by Gilbert (1885). A similar delta was discovered west of Flaming Gorge Reservoir, southwest of the Rock Springs uplift. This delta is also composed of mostly parallel bedded, partly wave rippled sandstone, siltstone, and very silty mudstone (fig. 87).

## HARTT CABIN BED OF LANEY MEMBER OF GREEN RIVER FORMATION

Lake Gosiute retreated to the southeastern part of the greater Green River basin during its terminal, drying-up stages (fig. 88). Fossil-mammal occurrences indicate that the lake disappeared completely during the late middle Eocene (Roehler, 1973b, p. E10). The maximum extent of the lake basin during

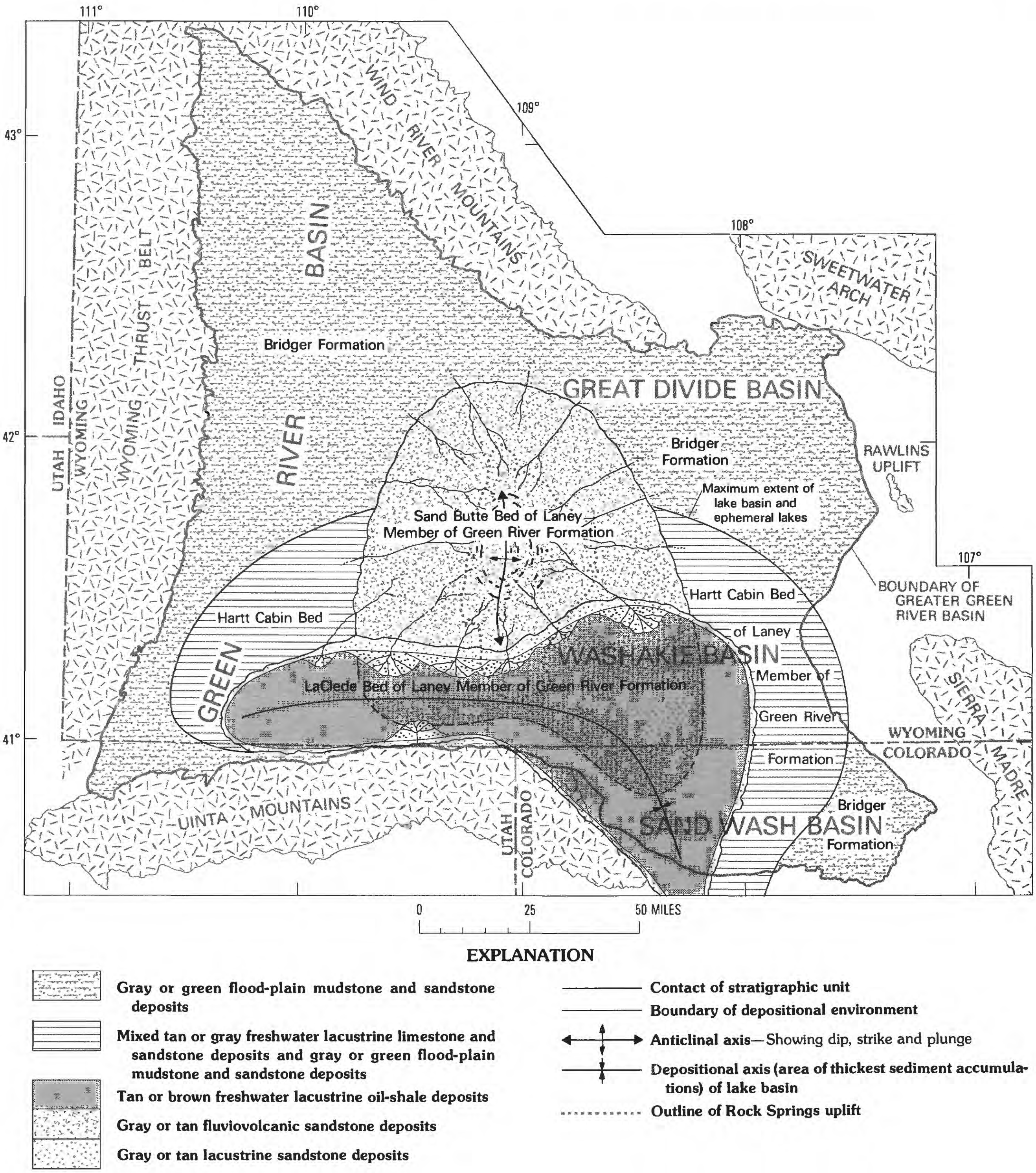



FIGURE 83.—Paleogeographic map of Sand Butte Bed of Laney Member of Green River Formation and associated formations showing locations of depositional environments. Interrelation of Sand Butte Bed and LaClede Bed is discussed on page F61.

this period was about 7,800 $mi^2$. More permanent, deep-water parts of the lake, however, were generally restricted to an area of about 1,700 $mi^2$ located at the east end of the Uinta Mountains. From this deep-water area, where organic mud (oil shale) continued to be deposited to form the LaClede Bed of


FIGURE 84.—Tower unconformity (arrow) between 1, Sand Butte Bed and 2, LaClede Bed of Laney Member of Green River Formation north of Interstate Highway 80 west of Green River, Wyo., in sec. 9, T. 18 N., R. 107 W. Upper part of 3, Wilkins Peak Member, is also visible in the outcrops.

FIGURE 85.—Tower unconformity (arrow) between Sand Butte Bed and underlying LaClede Bed of Laney Member of Green River Formation in sec. 30, T. 16 N., R. 106 W., southeastern Green River basin.

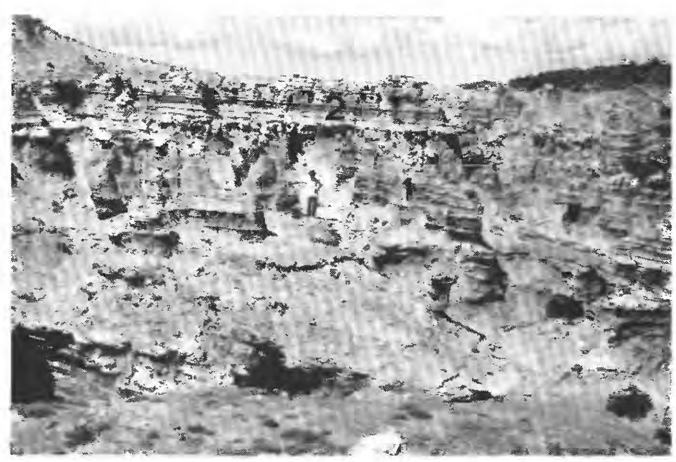


FIGURE 86.—Outcrops of fan-delta sandstone, siltstone, and silty mudstone in Sand Butte Bed of Laney Member of Green River Formation in NE$^1/_4$ sec. 23, T. 17 N., R. 98 W. on north slopes of Delaney Rim, northern Washakie basin. 1, foreset beds; 2, topset beds. Bottomset beds are also present but are not visible. Foreset beds dip to right (southward) into the Washakie basin.

the Laney Member, the lake periodically expanded and contracted toward the outer margins of the lake basin, across the area where sediments of the Hartt Cabin Bed were deposited (fig. 88). Because of these expansions and contractions, the Hartt Cabin Bed intertongues with the LaClede and Sand Butte Beds

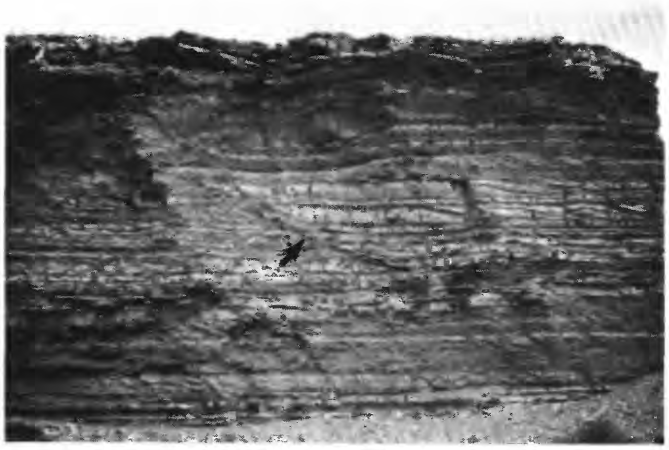


Figure 87.—Outcrop of fan-delta sandstone, siltstone, and silty mudstone in Sand Butte Bed of Laney Member of Green River Formation in NW1/4NE1/4 sec. 18, T. 14 N., R. 108 W., southwest of Rock Springs uplift. View is eastward. Note small syngenetic fault (arrow). Outcrop is about 15 ft thick.

of the Laney Member of the Green River Formation, with the Bridger Formation, and with the Kinney Rim Member of the Washakie Formation.

The Hartt Cabin Bed is composed of fluvial sandstone, siltstone, mudstone, and shale, and interbedded lacustrine oil shale, sandstone, siltstone, and limestone. The thicknesses of the bed are variable because of its intertonguing relationships with other formations and because it is unconformably overlain by the Adobe Town Member of the Washakie Formation in the eastern part of the Washakie basin (Roehler, 1973b, fig. 3). The bed is 625 ft thick in its type section in Tps. 14–15 N., R. 93 W. in the southeastern part of the Washakie basin. It thins southward to about 300 ft in T. 11 N., R. 96 W. in the central part of the Sand Wash basin, where it is unconformably overlain by the Oligocene Bishop Conglomerate. It has a maximum known thickness of about 800 ft in subsurface rocks near the center of the Washakie basin.

#### BRIDGER AND WASHAKIE FORMATIONS

The Bridger and Washakie Formations are the youngest Eocene stratigraphic units exposed in the greater Green River basin. They generally consist of gray and green sandstone and mudstone of flood-plain origin that contain large amounts of reworked and disseminated volcanic ash. Interbedded with the sandstone and mudstone are thin beds of conglomerate, limestone, shale, siltstone, tuff, and rare thin beds of carbonaceous shale, carbonaceous siltstone, and oil shale. The maximum recorded thicknesses for these formations are 2,106 ft for the Bridger Formation and 3,177 ft for the Washakie Formation (Chapter D, tables 1 and 2).

The Bridger and Washakie Formations, however, differ in age, color, specific composition, and thickness (Roehler, 1973c, p. 8–13), even though they both overlie and intertongue at their bases with the Green River Formation. The base of the Bridger Formation along the western margins of the Green River basin is very early middle Eocene in age (McGrew and Sullivan, 1970). The base of the Washakie Formation in the Washakie basin is younger middle Eocene in age and is located more than 500 ft stratigraphically higher in section than the base of the Bridger Formation in the Green River basin (Chapter D, fig. 2). The Washakie Formation contains several intervals of red beds (Chapter D, pl. 2), whereas red beds are rare in the Bridger Formation (Chapter D, pl. 1). The Washakie Formation contains large amounts of arkose, which is generally missing in the Bridger Formation. The Washakie Formation has a major unconformity within it; none has been recognized in the Bridger Formation. Stratigraphic equivalents of the upper 875 ft of the Washakie Formation in the Washakie basin are missing by either erosion or nondeposition in the Bridger Formation in the Green River basin.

## SUMMARY AND CONCLUSIONS

### CLIMATE

The Eocene climates in the greater Green River basin have been interpreted mostly from fossil flora and lithostratigraphy. The data suggest that the early Eocene climate was warm temperate to subtropical; the late early and early middle Eocene climate was cyclically hot arid and warm temperate, changing later in the early middle Eocene to subtropical to tropical and during the late middle Eocene to warm temperate; and the late Eocene climate was cool temperate. The average annual precipitation and temperature ranges and the types of Eocene climates in the Washakie basin, where the fossil data are most abundant, are shown in figure 89.

The factors that affected the Eocene climates in the greater Green River basin were both terrestrial and astronomical in origin. The principal terrestrial factors were latitude, altitude, regional geography, tectonism, and volcanism. The principal astronomical factors were the precession of the equinoxes and orbit eccentricity.

The latitude of the greater Green River basin during the Eocene was about 35° N., about 5°–8° south of its present location. Both the Eocene latitude and

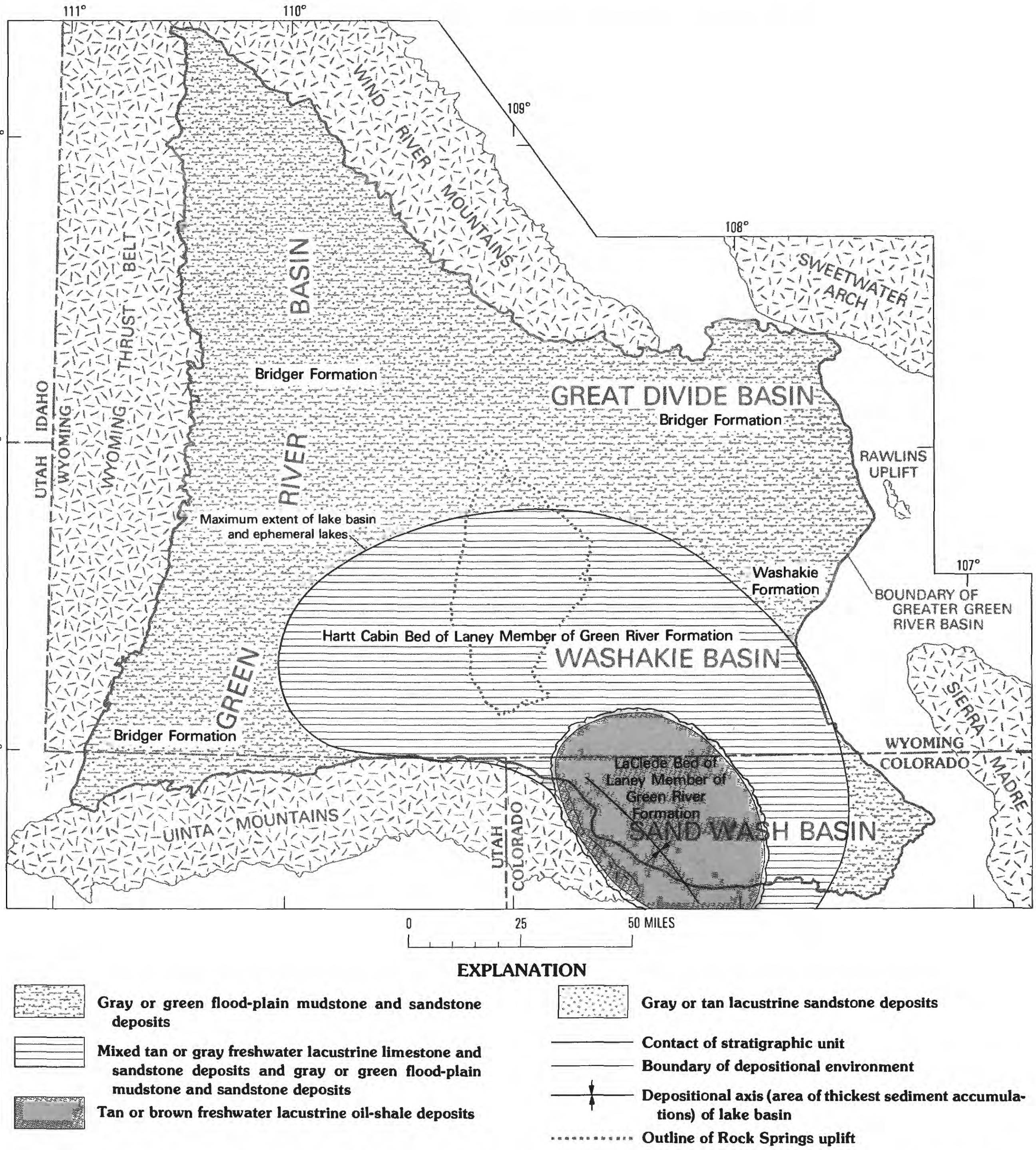



FIGURE 88.—Paleogeographic map of Hartt Cabin Bed of Laney Member of Green River Formation and associated formations showing locations of depositional environments.

the present-day latitude lie near the juncture of the Hadley and Ferrel circulation cells, where high pressures dominate and the prevailing winds are westerly. The altitude of the basin during the Eocene is believed to have been about 1,000 ft above sea level, with surrounding mountains rising 3,000 to 4,000 ft higher.

The Eocene greater Green River basin was an intermontane area located hundreds of miles inland from the closest ocean, whose circulating currents might have influenced climate. The prevailing westerly winds that crossed the basin undoubtedly cooled and lost moisture as they rose over the mountains that bordered the basin to the west. Such drying winds may have contributed to the arid conditions that prevailed in the basin during deposition of the Wilkins Peak Member of the Green River Formation.

The waning stages of the Laramide orogeny occurred during deposition of the Wasatch, Green River, and Bridger (Washakie) Formations in the Eocene Epoch. The Laramide orogeny involved uplift and flank thrusting of the mountains surrounding the greater Green River basin, which was accompanied by rapid subsidence at depositional centers located within the basin. As a result of these tectonic events, the depositional centers of the basin during early Eocene shifted from east to west during middle Eocene and then from west to east during late Eocene.

A volcanic field extended from the Yellowstone Park area across the northwestern United States during the Eocene. Airborne volcanic ash from intermittent eruptions in this field spread eastward across the basin during the early Eocene, when tuff beds up to a few feet thick were deposited. The intensity and frequency of these eruptions increased during the middle Eocene, and from then until the close of the Eocene, the rocks deposited in the basin were mostly tuffaceous. Volcanism is believed to be responsible for a cooling of the late Eocene climate, and it probably contributed to the infilling and extinction of Lake Gosiute.

A record of seasonal lacustrine deposition in Lake Gosiute is recorded by varves in oil-shale beds. An interval of these varves was counted and was found to average about 4,200 years per foot. Eleven- to twelve-year sunspot cycles have been reported in the varved oil-shale beds, but I did not identify such cycles during this investigation.

The precession of the equinoxes is recorded in the Wilkins Peak Member of the Green River Formation by 77 depositional cycles. These cycles average about 20,779 years in duration, and at the lake basin center each consists of three repetitive lithologies: (1) oil shale that was deposited at the base of each cycle during expansions of Lake Gosiute, when the climate was warm and temperate, (2) bedded evaporites that were deposited in the middle of each cycle in salt pans, as the lake retreated to its depositional centers when the climate was hot and arid, and (3) mudflat mudstone that was deposited at the top of each cycle, after the lakes had dried up, and also when the climate was hot and arid. Some playa lake limestones and dolomites are interbedded with the mudflat mudstone. Stages of cyclic deposition in the Wilkins Peak Member are illustrated by schematic cross sections in figure 90.

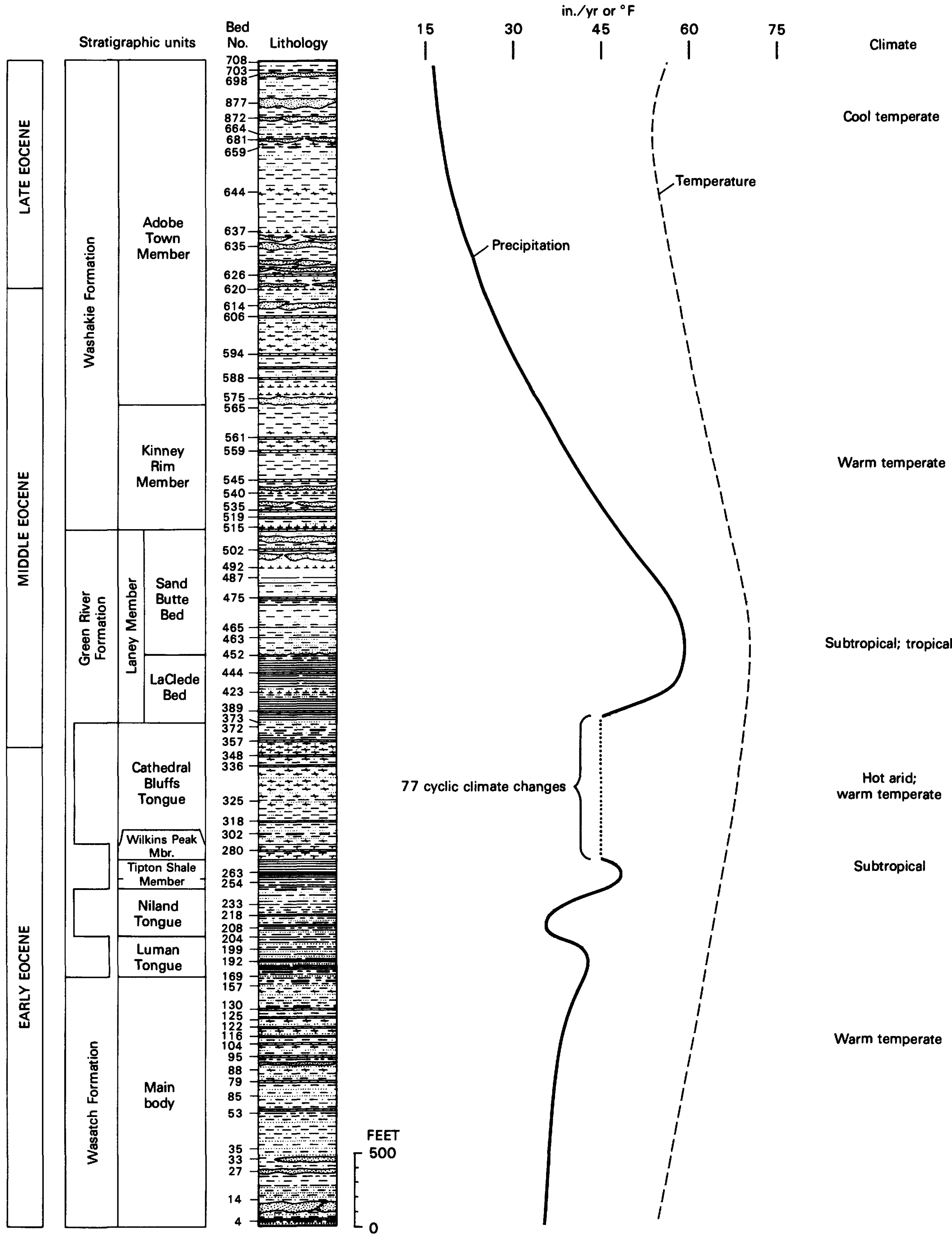
The 77 depositional cycles that record the 20,779 year cycles of the precession of the equinoxes are grouped into bundles of 4 to 6, but averaging 5. Each bundle of five then comprises about 103,895 years, which conforms to the 100,000-year eccentricity cycle. The eccentricity cycles are further grouped into superbundles of seven each, representing approximately 727,000 years. The origin of the superbundles has not been determined.

## DEPOSITIONAL ENVIRONMENTS

Eight depositional environments are identified in Eocene rocks in the greater Green River basin: (1) fluvial, (2) paludal, (3) freshwater lacustrine, (4) saltwater lacustrine, (5) pond and playa lake, (6) salt pan, (7) mudflat, and (8) volcanic and fluviovolcanic. The fluvial environments consisted of mostly alluvial fans and large pediments that were located along mountain flanks and the basin margins, and fluvial flood plains that were located in the interior of the basin. Freshwater ponds were fairly common on the flood plains. Paludal environments, consisting of forest swamps and reed swamps, were present in topographically low areas, particularly in association with lakes and along depositional axes. Freshwater lakes were present at times at depositional centers or along depositional axes, and when they enlarged, they expanded across the lower topographic parts of the basin floor. Saltwater lakes appeared during a late early Eocene climate change to hot and arid conditions, and these lakes persisted into the early middle Eocene. The saltwater lakes periodically retreated to salt pans located at depositional centers of the lake basin, where bedded evaporites (trona and halite) were deposited. When the saltwater lakes dried up and disappeared, the floor of the former lake basin became mudflats on which playa lakes occasionally formed. Tuff beds and tuffaceous rocks are common in the lower Eocene and become increasingly more abundant in the middle and upper Eocene.

## PALEOGEOGRAPHY

The Wasatch, Bridger, and Washakie Formations are composed of mostly fluvial flood-plain deposits that have two distinct colors: (1) red or variegated, and (2) gray and green. The red or variegated colors are most common along the margins of the basin, where topographic relief was low to moderate, soils


Stratigraphic units
Bed No.
Lithology
in./yr or °F
15
30
45
60
75
Climate
LATE EOCENE
MIDDLE EOCENE
EARLY EOCENE
Washakie Formation
Adobe Town Member
Kinney Rim Member
Green River Formation
Laney Member
Sand Butte Bed
LaClede Bed
Cathedral Bluffs Tongue
Wilkins Peak Mbr.
Tipton Shale Member
Niland Tongue
Luman Tongue
Wasatch Formation
Main body
708
703
698
877
872
664
681
659
644
637
635
626
620
614
606
594
588
575
565
561
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130
125
122
116
104
95
88
79
85
53
35
33
27
14
4
FEET
500
0
Precipitation
Temperature
77 cyclic climate changes
Cool temperate
Warm temperate
Subtropical; tropical
Hot arid; warm temperate
Subtropical
Warm temperate

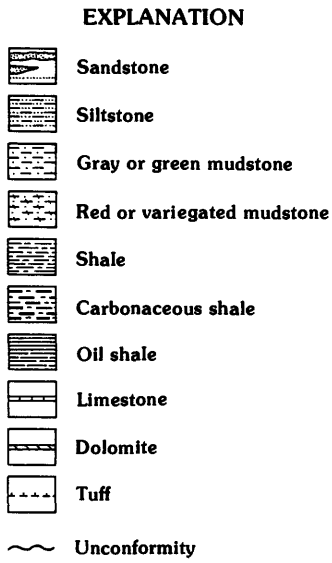


FIGURE 89 (above and facing page).—Average annual precipitation and temperature ranges and types of Eocene climates in Washakie basin. Bed numbers and lithologies are from the Washakie basin reference section (Chapter D, pl. 2). Data modified from Brown (1928), Axelrod (1968), and Leopold and MacGinitie (1972).

were well drained, and iron compounds in the soils were oxidized. The gray and green colors are most common toward the basin center, where topographic relief was little or none, soils were permanently water saturated, and iron compounds in the soils were reduced. The flood-plain deposits of the Wasatch, Bridger, and Washakie Formations intertongue with and generally envelop the lacustrine rocks that make up the Green River Formation.

The flood plains of the Wasatch, Bridger, and Washakie Formations occasionally contained ponds in which gray, brown, or tan fossiliferous limestone was deposited, in beds seldom more than 2 ft thick. The flood plains occasionally also contained marsh areas where thin carbonaceous siltstone or carbonaceous shale beds were deposited that contain poorly preserved fossil wood and leaf fragments.

A structural and topographic depression formed along the southern part of the greater Green River basin during the early Eocene. This depression, called the Uinta Mountain trough, paralleled the northern flank of the Uinta Mountains and extended eastward to the southwestern part of the Washakie basin. From there the depression continued northeastward across the Washakie basin, where it turned northward into the southern part of the Great Divide basin. This depression, or trough, or branches or segments of it, persisted in the greater Green River basin throughout the remainder of the Eocene, and it formed the primary depositional axis for Eocene sedimentation.

The Ramsey Ranch Member of the Wasatch Formation was deposited in the Uinta Mountain trough. The member is composed of mostly gray and green rocks of mixed flood-plain, paludal, and lacustrine origins. Interbedded with and surrounding the member are mostly gray and green or red or variegated flood-plain deposits that are characteristic of the remaining parts of the Wasatch Formation. Forest swamps were present intermittently along the length of the Uinta Mountain trough, and from these numerous subbituminous coal beds formed. The lacustrine rocks are composed mostly of oil shale and limestone; they comprise the embryonic stages of development of Lake Gosiute. The Eocene climate was warm temperate at the beginning of deposition of the Ramsey Ranch Member, but it began to moderate during deposition of the member. The precipitation and temperature increased and the climate changed to subtropical. By the end of deposition of the Ramsey Ranch Member, the lakes that occupied the Uinta Mountain trough began to coalesce and enlarge. Eventually, they expanded to form a single, large, deep, freshwater lake that occupied about 6,650 $mi^2$ of the Uinta Mountain trough during deposition of the Luman Tongue of the Green River Formation.

The lacustrine sediments deposited in the Luman Tongue formed mostly oil shale. They were deposited within the Uinta Mountain trough for more than 1 million years. By the end of that time, the precipitation and temperature had decreased, the climate again had become warm temperate, the lake had contracted, and sediments of swamp and flood-plain origins had invaded the lake margins. The sediments deposited in the Uinta Mountain trough during an extended warm temperate period that followed make up the Niland Tongue of the Wasatch Formation.

The climate in the greater Green River basin again became subtropical at the end of deposition of the Niland Tongue. This climate change caused a renewed expansion of Lake Gosiute, by again inundating the Uinta Mountain trough. After filling the trough, the freshwaters of the lake slowly expanded outward onto the floor of the greater Green River basin. At its maximum expansion, the lake covered nearly three-quarters of the basin, an area of about

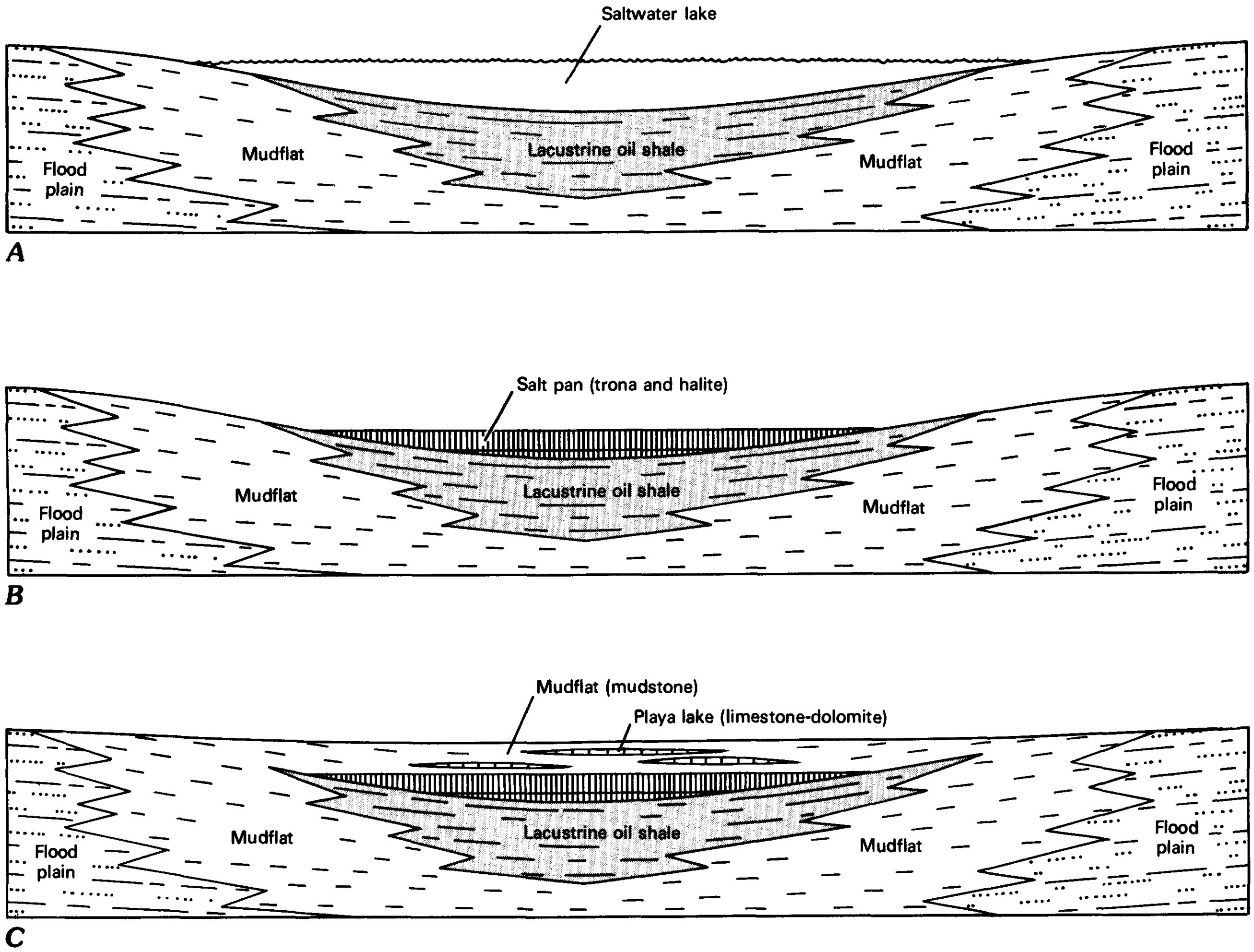


FIGURE 90.—Three stages of cyclic deposition in Lake Gosiute during deposition of Wilkins Peak Member of Green River Formation. *A*, lake expansion; *B*, lake contraction; *C*, lake extinction.

15,000 $mi^2$. The lacustrine sediments deposited in this expanded lake make up the Scheggs Bed of the Tipton Shale Member of the Green River Formation.

The Wind River Mountains were uplifted during late stages of deposition of the Scheggs Bed. Ensuing erosion in the mountains caused a broad wedge of course clastic sediments, mostly sandstone, to spread southward into Lake Gosiute. This wedge of clastic sediments, forming the Farson Sandstone Member of the Green River Formation, rapidly filled the northwest part of the lake with as much as 400 ft of delta and beach deposits, thereby reducing the size of the lake by nearly 6,500 $mi^2$. During the lake infilling, a band of gray, green, and brown flood-plain deposits intertongued with and replaced the lacustrine sediments of the Farson Sandstone Member along the northwest margins of the basin. These flood-plain deposits compose the Alkali Creek Tongue of the Wasatch Formation.

Deposition of the Rife Bed of the Tipton Shale Member of the Green River Formation followed deposition of the Scheggs Bed. The contact of these units is sharp, and it coincides with an abrupt climate change to hotter and drier conditions, the closing of the outlet of Lake Gosiute, and an abrupt change in the lake waters from fresh to saline. Lake Gosiute again contracted to the area of the Uinta Mountain trough, where it occupied an area of about 7,000 $mi^2$ for nearly 500,000 years. Organic mud (oil shale) was deposited in deep waters across the central part of the Rife lake, and algal limestones and thin sands were deposited along its shorelines.

The climate of the basin was periodically very hot and very dry in the late early Eocene and early middle Eocene during deposition of the Wilkins Peak Member of the Green River Formation. Alternating cyclically with the hot and dry periods were periods when the climate was warm and temperate.

Expansion, contractions, and extinctions of Lake Gosiute occurred 77 times as a result of these cyclic climate changes. During lake expansions, lacustrine oil shale was deposited; during lake contractions to salt pans, bedded evaporites (trona and halite) were deposited; and during lake extinctions, mudflat mudstone and playa lake limestone-dolomite were deposited. During lake contractions, red or variegated flood-plain deposits that compose parts of the Cathedral Bluffs Tongue of the Wasatch Formation were deposited across evacuated parts of the lake basin.

The climate during deposition of the upper part of the Wilkins Peak Member changed from hot and dry to subtropical and then to tropical. As the precipitation increased as a result of these changes, cyclic deposition ended, the outlet of the lake opened, the lake waters changed from saline to fresh, and the LaClede Bed of the Laney Member of the Green River Formation was deposited.

Lake Gosiute reached its maximum size and depth during deposition of the LaClede Bed. The lake covered more than 15,400 $mi^2$. Sediments deposited in the lake exceeded 800 ft in thickness and locally represent the thickest interval of sustained oil-shale deposition in the greater Green River basin. Algal reefs were represent in the shallow nearshore waters of the lake and most of the shorelines consisted of beach and delta sand.

The Godiva Rim Member of the Green River Formation intertongues with and replaces the lower part of the LaClede Bed along the eastern margins of the greater Green River basin. The Godiva Rim Member is composed of gray mudflat mudstone and flood-plain sandstone with some interbedded brown and gray lacustrine oil shale, limestone, and sandstone.

The Rock Springs uplift was a major anticlinal structure at the end of the Cretaceous Period. It was subsequently peneplained, and by the end of the Paleocene Epoch, it was buried and obliterated. Lower Eocene rocks were consequently deposited in uninterrupted fashion across the buried uplift area. Renewed uplift of the Rock Springs anticline took place in the early middle Eocene during late stages of deposition of the LaClede Bed of the Laney Member. This uplift raised the center of Lake Gosiute to form an island, which was soon connected to the northern shores of the lake to form a peninsula. Lake Gosiute then slowly retreated southward from the east and west arms of the lake until it was once again restricted to its depositional axis located along the southern margins of the basin. The newly uplifted crest of the Rock Springs anticline was then subjected to subaerial erosion and the sediments derived from there constitute the Sand Butte Bed of the Laney Member of the Green River Formation. The erosion surface on which the Sand Butte Bed rests is called the Tower unconformity.

The Sand Butte Bed was deposited in a 3,500 $mi^2$ area of the central part of the greater Green River basin that includes the Rock Springs uplift and adjacent areas. The northern part of the Sand Butte Bed intertongues with the Bridger Formation and the Hartt Cabin Bed of the Laney Member. The southern part of the bed intertongues with the LaClede Bed of the Laney Member. The bed is composed of mostly fluvial channel and interchannel sandstone and interbedded tuff in the northern part of the Rock Springs uplift. These rocks grade southward across the uplift into lacustrine shoreline and delta sandstone and then into lacustrine oil shale. The Sand Butte Bed is irregularly lenticular in cross section and has thicknesses that range from less than 1 to nearly 900 ft.

The Hartt Cabin Bed of the Laney Member of the Green River Formation is composed of rocks of mixed lacustrine and fluvial origins. It was deposited during the drying-up stages of Lake Gosiute as the lake expanded and contracted but eventually retreated from the central and southern parts of the greater Green River basin into the southeast corner of the basin. As the lake retreated, mostly sand and lime of shallow lacustrine origin intertongued with and were replaced by gray and green sand and mud of flood-plain origin. Where deep, open-water parts of the lake persisted near the east end of the Uinta Mountains, organic mud (oil shale) was deposited as the final remnants of the LaClede Bed of the Laney Member. At times, the Hartt Cabin Bed occupied as much as 6,100 $mi^2$ of the floor of the greater Green River basin. The thickness of the bed varies greatly, from less than 1 to about 800 ft, because of its intertonguing and unconformable relationships with adjacent formations.

The Bridger and Washakie Formations were deposited during the closing stages of Lake Gosiute and after deposition of the Green River Formation. They are composed of mostly gray and green tuffaceous flood-plain deposits consisting of sandstone and mudstone and some conglomerate, limestone, shale, siltstone, carbonaceous shale, and carbonaceous siltstone. The Bridger Formation has a maximum thickness of about 2,100 ft and the Washakie Formation has a maximum thickness of about 3,200 ft.

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