THE STRATIGRAPHIC AND SEDIMENTOLOGIC FRAMEWORK OF THE GREEN RIVER FORMATION, WYOMING

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ABSTRACT

During deposition of the Green River Formation, ancient Lake Gosiute started as a fresh-water lake, then evolved to a saline, alkaline lake and finally ended as a fresh-water lake. This evolution reflects the change from a closed-basin hydrologic regime to an open-basin hydrologic regime. As a result, sedimentation in the Lake Gosiute system was strongly influenced by the relationship between evaporation and inflow of water into the basin. In the Green River Formation, stratification sequences, sedimentary strucutures, and mineralogy of lithofacies provide important insights into the evolution of the system and into the competing factors that determined the type of sediment accumulated in the lake and fringing environments. Carbonate sedimentation was strongly influenced by lacustrine transgressions and regressions across a very low topographic gradient. Terrigenous rocks reflect progradation of beach and deltaic shorelines during wetter climatic intervals when detritus that had been produced and stored in upland areas during preceding drier intervals was transported to the lake.

Hydrochemistry of Lake Gosiute during the deposition of Wilkins Peak Member was controlled by ground water discharge, whereas during the deposition of the Tipton and Laney Members it was controlled largely by surface water. Calcite precipitated in the lake as a result of mixing calcium-rich inflow and saline-alkaline lake waters. Dolomite formed as a result of periodic flooding and drying of the playa fringe (carbonate mud flat), where carbonate muds were saturated with saline-alkaline lake waters and underwent evaporative pumping. Some surface waters reaching the playa-lake were preconcentrated by dissolution of efflorescent crusts generated by capillary draw of connate waters in alluvial plain and mud-flat sediments. Trona and halite precipitated from brine pools as the lake shrank during periods of intense aridity. During more humid periods the lake expanded and oil shale was deposited.

The stratigraphic framework of the Green River Formation reflects the dynamic nature of Eocene Lake Gosiute. All members of the formation are characterized by a diversity of lithofacies and repetitive stratification sequences.

INTRODUCTION

A widespread lake complex existed in western United States during middle Eocene time. In southwestern Wyoming, sediments now known as the Green River Formation were deposited in an interior basin occupied by ancient Lake Gosiute. The Eocene Green River Formation is perhaps the most famous accumulation of lacustrine sediments in the world because it contains enormous deposits of oil shale and trona. Ever since the classic work of Bradley (1929, 1931), it has been under almost continuous scrutiny by geologists. The most modern work is documented in Bradley (1963, 1964, 1973), Deardorff (1963), Culbertson (1966, 1971), Bradley and Eugster (1969), Deardorff and Manion (1971), Surdam and Parker (1972), Roehler (1973), Eugster and Surdam (1973), Wolfbauer and Surdam (1974), Eugster and Hardie (1975), Surdam and Wolfbauer (1975), Surdam and Wray (1976), Buchheim and Surdam (1977), Stanley and Surdam (1978), Surdam and Stanley (1979), and Surdam and Stanley (1980).

According to Bradley and Eugster (1969), Lake Gosiute at its highest stand covered an area of approximately 39,000 km², and at its lowest stand about 3,900 km² (Fig. 1). The size of the lake changed numerous times throughout the 4 million years it existed. During this time

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the lake was characterized by three major stages, each of which corresponds to a member of the Green River Formation. The major stratigraphic units, from bottom to top, are the Tipton Shale Member, Wilkins Peak Member, and Laney Shale Member (Fig. 2).

Recent studies of the Green River Formation suggest that Lake Gosiute was in fact a playa-lake complex or, in other words, the oil shale and associated sediments were the result of lacustrine deposition in a closed basin (Eugster and Surdam, 1973). By its nature a closed-basin, lacustrine complex is a dynamic feature; the area of the lake, depth of water, and salinity vary greatly according to seasonal inflow and evaporation (Langbein, 1961). Thus, the Green River Formation should contain abundant evidence of repeated fluctuations in lake level and shoreline position.

The purpose of this paper will be to review the stratigraphic framework of the Green River Formation in Wyoming, and to describe the distribution of lithofacies in the formation, the vertical and lateral patterns of stratification and bedding features, and the distribution of chemical, organic and terrigenous components. From these data it is possible to evaluate in detail the history of Eocene Lake Gosiute.

LAKE GOSIUTE

The Green River Basin extends for approximately 150 miles from the Wyoming Range-Overthrust Belt area eastward to the Rawlins Uplift. It is bounded on the north by the Gros Ventre Range, the Wind River Range, and the Granite Mountains, and on the south by the Uinta Mountains and their eastward extension.

Bradley (1963) estimated that the hydrographic basin of Lake Gosiute had an area of about 48,500 square miles. The rocks exposed in the drainage basin consisted of Precambrian granite and Paleozoic and Mesozoic sedimentary rocks; no older chemogenic deposits were present. The lake was situated approximately 1,000 feet above sea level (MacGinitie, 1969). It developed on a broad, nearly featureless, alluvial plain that had an original dip of less

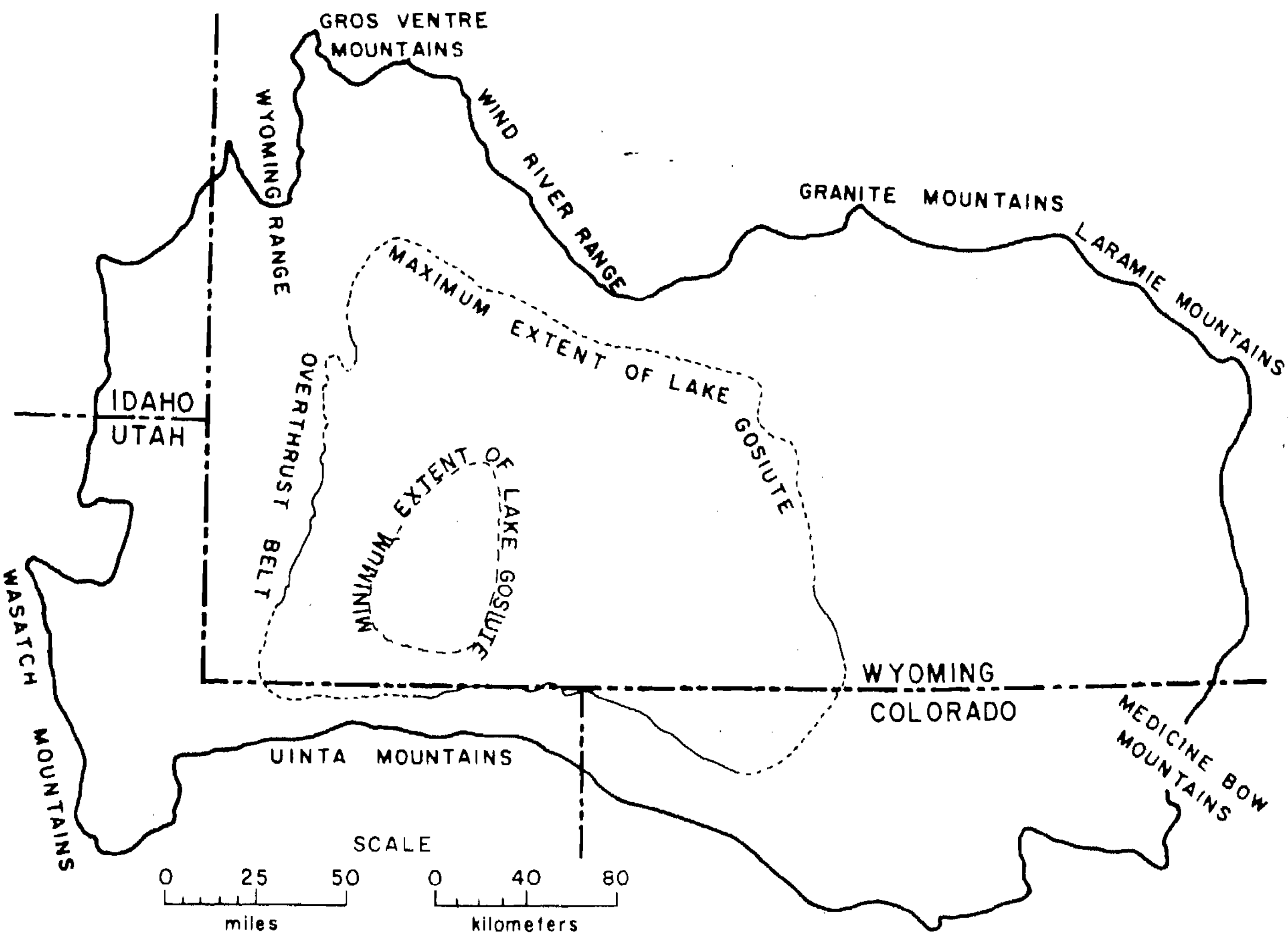

Figure 1: Location of ancient Lake Gosiute in southwestern Wyoming and adjacent areas of Utah and Colorado and outline of its hydrographic basin. Also shown are the minimum and maximum extent of the lake (after Bradley and Eugster, 1969).

than "1 or 2 feet per mile except in a rather narrow belt adjacent to the mountains" (Bradley, 1964, p. A16).

MacGinitie (1969) made a comprehensive study of the flora of the Green River Formation and concluded that the climate was warm temperate to subtropical, with annual temperatures in the range of 60° to 70°F, with a lack of frost, and with high equability. The average annual precipitation at lake level was probably 24 to 30 inches, being somewhat higher (45 in. or more) in the watershed. Maximum rainfall probably occurred in late spring and early summer and was followed by diminishing rainfall and near-drought conditions in the late summer and fall. The presence of high mountain ranges encircling a broad basin floor with low relief, the large area of the watershed and lack of a basin outlet, and the pronounced seasonal aridity of the climate suggest that playa-lake conditions existed in the Green River Basin during Ecoene time.

The initial Green River sediments were deposited in lakes, ponds, and swamps that developed on the subsiding Wasatch plain. They were common in an east-west depression along the Uinta Mountain front and in a large area east of the present Rock Springs Uplift (Roehler, 1965). The continued uplift of the surrounding mountainous areas enhanced the structural downwarping of the basin, and these smaller bodies of water coalesced to form a relatively large, shallow lake. This early stage of Lake Gosiute is represented by the Luman Tongue of the Green River Formation (Fig. 2). The Luman rocks consist of low-grade oil shale, coquinal limestone, sandstone, shale, and coal beds, which were deposited under shallow lacustrine and paludal conditions. The Luman Stage of Lake Gosiute extended from the southern Bridger Basin northeastward across the site of the present Rock Springs Uplift into the Great Divide and Washakie Basins (Roehler, 1965). At the close of Luman time, climatic (or perhaps structural) changes in the basin resulted in a decrease in the size of Lake Gosiute and a corresponding increase in fluviatile and red-bed deposition throughout most of the basin.

The restricted stage was short-lived and soon Lake Gosiute expanded greatly. The rocks deposited during this stage constitute the Tipton Shale Member of the Green River Formation (Fig. 1) and consist primarily of oil shale and dolostone.

With the onset of more arid conditions, the lake was reduced to a very small area. By this time, the lake waters had become so concentrated that trona, and sometimes halite, precipitated. Periodically, during less arid times, the lake level rose and beds of oil shale were deposited. The alteration of oil shale and trona deposition occurred at least 60 times during this interval (Eugster and Surdam, 1973). These rocks, together with the marlstones and mudstones spatially associated with them, constitute the Wilkins Peak Member of the Green River Formation (Fig. 2).

At the close of the Wilkins Peak time, the climate

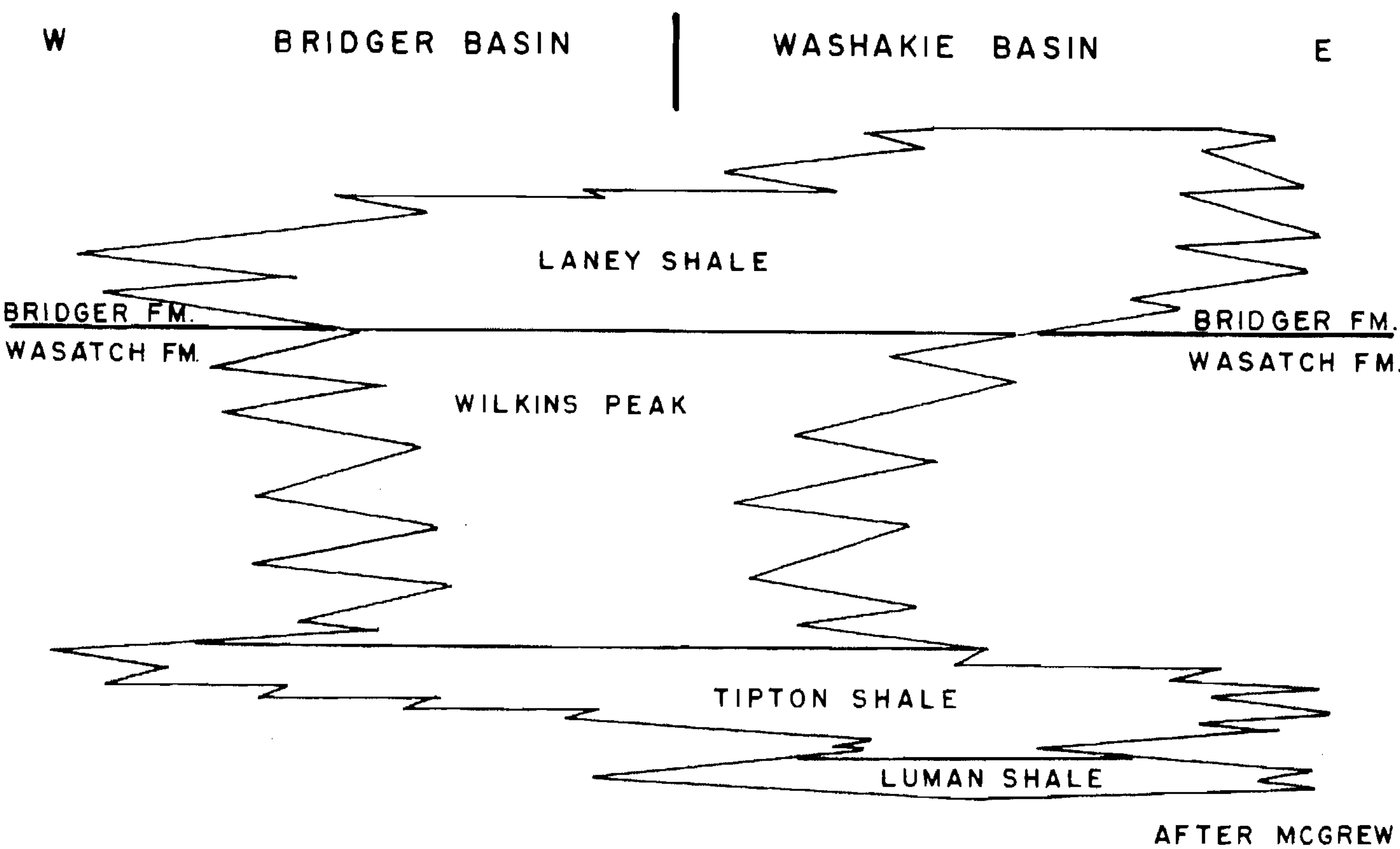

Figure 2: Schematic stratigraphic diagram for the Green River Formation of southwestern Wyoming. The Wilkins Peak Formation contains the trona deposits. From Surdam and Wolfbauer, 1975.

became more humid and a large, shallow lake again developed. During this stage, the siltstones, marlstones, and sandstones of the Laney Shale Member of the Green River Formation were deposited (Fig. 2). At this time Lake Gosiute and the related mud flats surrounding it may have covered an area of approximately 15,500 square miles (Bradley, 1963). Lake Gosiute came to an end during middle Eocene time, as the basin filled with sediment (Surdam and Stanley, 1980).

STRATIGRAPHY OF THE TIPTON SHALE MEMBER

The stratigraphy of the Wilkins Peak Member of the Green River Formation is well documented (Culbertson, 1961, 1966, 1971; Stuart, 1963; Bradley, 1964). For the purposes of this paper, however, a few comments concerning the stratigraphy of the Tipton Shale Member are necessary. In general, the Tipton sequence can be subdivided into three distinct zones (Fig. 3).

Zone 1

The lowest 1.5 to 31 meters of the Tipton Shale Member consists of limestone, siltstone, and low-grade oil shale. At or very near the base of the Tipton are one or more thin limestone or sandstone units, which contain an abundance of the snale *Goniobasis* sp. These beds are collectively referred to as the *Goniobasis* marker unit. Ostracodes, the snail *Viviparus* sp., and the clam *Lampsilis* sp. can also be found in this unit. Above the *Goniobasis* marker unit of Zone 1 is primarily shale, siltstone, and low-grade oil shale.

It is interesting to note the occurrence of *Lampsilis* sp. in the *Goniobasis* marker unit because La Rocque (1960) has stated that this type of clam requires the presence of fish to complete its life cycle. The larvae attach themselves to the gills of fish where they live for a considerable period of time. Therefore the clams must live in an environment that is also favorable for the fish. This suggests that the geographic area characterized by the presence of *Lampsilis* sp., in the *Goniobasis* marker unit, in the lowermost Tipton, represents established lacustrine conditions. Outside the *Lampsilis* sp. area, *Physa* sp. sometimes can be found. The presence of this lung breather signifies very shallow water and emergent vegetation.

At or very near the top of Zone 1 is an algal stromatolite that varies in thickness from 2.5 to 62 centimeters (Fig. 3). This unit can be traced from the Church Buttes uplift eastward to the Green River and from there into the Great Divide and Washakie Basins.

Zone 2

Above 1 is a 19 to 50 meter thick interval that consists

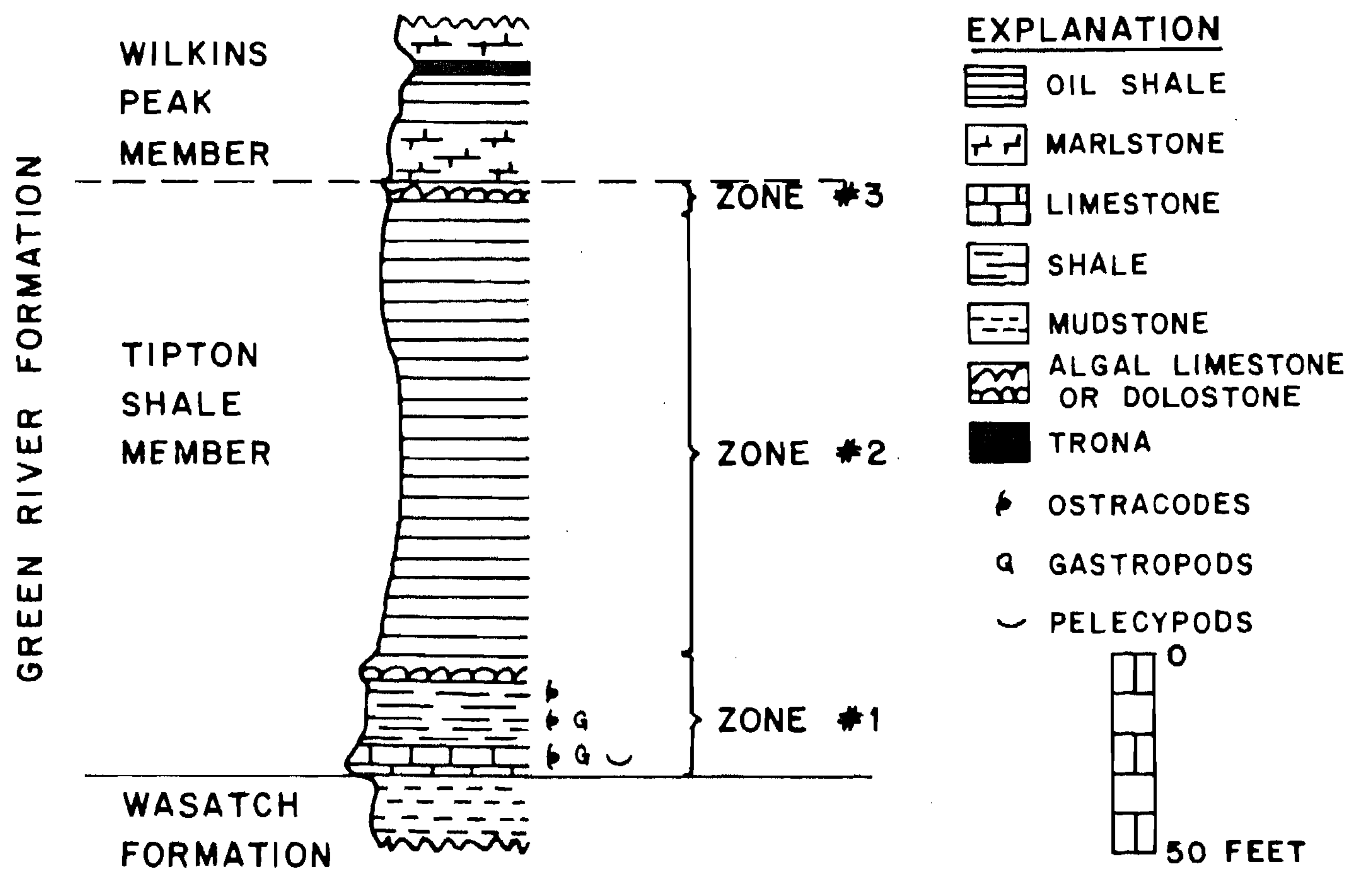

Figure 3: Schematic stratigraphy of Tipton Member of Green River Formation. Zone 1, 5 to 100 ft thick; Zone 2, 60 to 160 ft thick; Zone 3, 3 to 20 ft thick. Lowermost limestone beds represent "Goniobasis marker."

of oil shale and tongues of fluviatile sandstone (Fig. 3). These rocks contain very few fossils. Rare occurrences of fish remains have been found in the oil shale in the southern Green River Basin, whereas the scattered remains of ostracodes and insect larvae have been noted elsewhere. Most generally, however, fossiliferous material is absent. The greatest concentration of oil shale in this zone is found in the southern Bridger Basin and in the southwestern Washakie Basin. In general, these oil shales average 15 to 25 gal/ton.

During deposition of Zone 2 in the northern Bridger Basin, oil shale deposition was interrupted by the influx of a large body of sand that entered the basin from the north. This fluvatile tongue is the easternmost extension of the New Fork Tongue of the Wasatch Formation. The sandstone is characterized by an assemblage of sedimentary structures diagnostic of shallow-water and subaerial depositional conditions. Near the close of Zone 2, the influx of sand diminished.

Zone 3

Zone 3 marks the transition from the Tipton Shale to the Wilkins Peak Members of the Green River Formation (Fig. 3). Zone 3 is characterized by several beds of algal stromatolites that can be traced from the northern Bridger Basin, around the northern end of the Rock Springs Uplift, and into the Great Divide and Washakie Basins. These same units may be correlative with the algal beds described by Lawrence (1962) along the extreme western edge of the Bridger Basin near the boundary between the Fontenelle Tongue (= Tipton Shale Member) and the middle tongue (= Wilkins Peak Member) of the Green River Formation. The Wilkins Peak Member overlies the algal beds of Zone 3.

Transition from Tipton to Wilkins Peak Time

Bradley (1929a) recognized and first described in detail "algal reefs" (stromatolitic limestone units) in the Green River formation. Two regionally significant stromatolite units occur in the Tipton Shale Member (Fig. 3; Surdam and Wolfbauer, 1975), and nine to twelve such units are noted in the Laney Shale Member (Trudell and others, 1973); whereas stromatolitic limestones are rarely present in the Wilkins Peak Member. Bradley (1929) noted that these algal beds are important because they denote very shallow water and the proximity of shore. The stromatolite units are intimately associated with rocks containing mudcracks, flat-pebble conglomerates, saline crystal casts, ooliths and pisoliths, and coquinas containing pulmonate gastropods; all indicative of subaerial exposure or shallow-water deposition. Both the external morphology and the internal fabrics of the algal stromatolites in the Green River Formation are similar to recent near-intertidal columnar stromatolites and associated cryptalgal fabrics at Shark Bay, Western Australia, described by Logan et al (1974).

The two stromatolitic algal horizons in the Tipton Shale Member, one at the top of Zone No. 1 and the other Zone No. 3 (Fig. 3), are useful in a basin analysis of the Green River Formation sediments. These stromatolites are exposed continuously along the White Mountain scarp from Boars Tusk (T23N, R105W) south to Rock Springs, Wyoming, a distance of approximately 55 kilometers (Fig. 4). In the vicinity of Boars Tusk (Fig. 4, Section 5) the stromatolites of Zone No. 3 are up to 1 meter thick and individual algal heads measure 30 to 40 centimeters in diameter. However, scme heads are so closely packed that the upper surface of the unit has a hummocky appearance (Bradley, 1929, 1926, Fig. LXII). The amount of growth relief is difficult to ascertain, but appears to have been only a few centimeters. Southward along the White Mountain scarp, the algal heads of Zone No. 3 become smaller (15-30 cm in diameter) and less domal in character. Approximately 23 kilometers south of Boars Tusk, the stromatolites are more planar, consisting of stromatolitic algal structures 7 to 15 centimeters across (Fig. 4, Section 3). These low-relief stromatolites resemble recent forms occurring in lakes near the Coorong Lagoon, South Australia (Walter et al., 1973). Ten kilometers farther south the unit has lost most of its distinctly stromatolitic algal character. Slightly farther south, again the unit is composed of very fine-grained dolostones characterized by mudcracks, flat-pebble conglomrates, salt crystal casts, and ripple marks (Fig. 4, Section 1).

Preserved tuffaceous ash beds in this part of the Green River Formation provide a means of interpreting depositional history within a chronologic framework. The relationship between the stromatolite-dolostone lithologic unit and the tuff beds is illustrated in Figure 4. Because correlative tuff beds are time-stratigraphic units, it is readily apparent that the stromatolite unit is diachronous. The stromatolite unit is interpreted as representing a transition from a wave-swept shoreline along the northern margin of the basin at a high stand of the lake (maximum areal extent of lacustrine sediments), to a mud-flat environment in the Rock Springs area at a relatively low stand of the lake (minimum areal extent of lacustrine deposits). During this contraction of the lake the shoreline migrated 55 kilometers to the south and the time-stratigraphic position of the stromatolite unit climbed at the rate of about two stratigraphic feet per mile (ca. 33 cm per km). Bradley (1964), using other geologic evidence, estimated that the topographic gradient in the Lake Gosiute Basin during the deposition of the Green River Formation was one to two feet per mile (ca 16-33 cm per km).

A reasonable estimate of the amount of shoreline fluctuation can be determined by mapping the minimum and maximum areal extent of algal stromatolites in these diachronous lithologic units (Fig. 5). The regional distribution of the algal bed at the top of Zone 1 indicates that, during the early part of Tipton time, the lake shrank from 12,500 square miles (Bradley, 1963) to 4,500 square miles or less. The regional distribution of algal stromatolites in Zone 3 of the Tipton shows that the lake also shrank

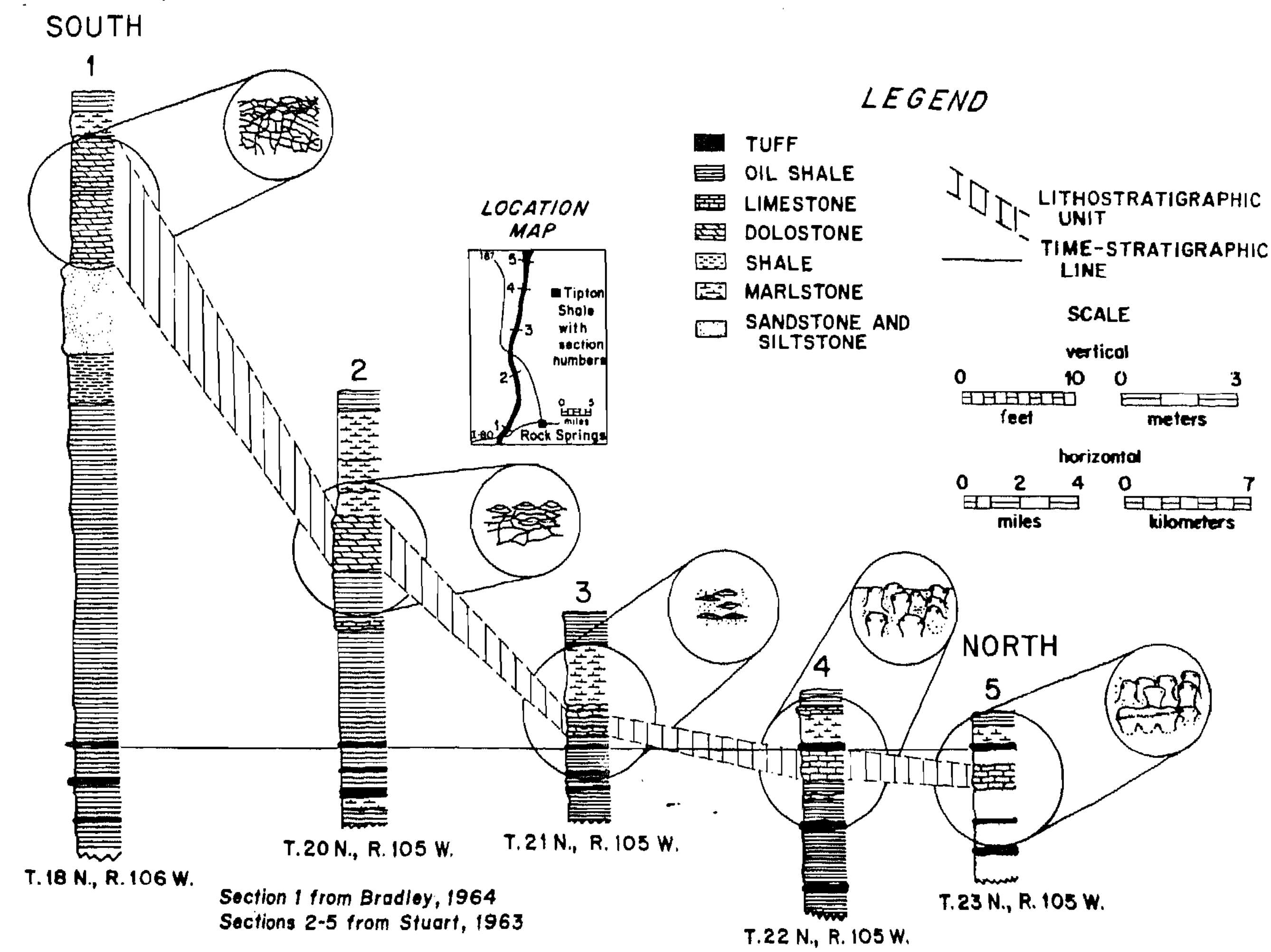

Figure 4: Straitgraphy of uppermost Tipton-lowermost Wilkins Peak section along the White Mountain scarp north of Rock Springs, Wyoming. Section 5 is so-called Boars Tusk section. Note the exaggerated vertical scale. Circled inserts enclose sketches of stromatolite forms found in Zone No. 3 in sections 2-5. Reticulate pattern in Section 1 indicates mudcracks and associated sedimentary structures. (Section 1 modified after Bradley, 1964; Sections 2-5 modified after Stuart, 1965; see Surdam and Wolfbauer, 1975.)

thousands of square miles during the transition from Tipton to Wilkins Peak deposition. The areal extent of the lowermost trona bed (No. 1) in the Wilkins Peak Member (Fig. 1), which lies just above the Tipton-Wilkins Peak contact (Culbertson, 1971), marks a minimum stand of the lake and thus delineates the maximum shoreline fluctuation during the Tipton-Wilkins Peak transition. Thousands of square miles of mud flats were exposed during each of these large shoreline fluctuations. Obviously, the Tipton Shale Member does not represent a large, deep, stable lake but, instead, was the product of an unstable lake characterized by large fluctuations in size and depth.

Seasonal changes and some small-scale fluctuations in water level can occur in large, open lakes that have a large response time. However, large-scale, long-term fluctuations are possible only in a closed basin where increased inflow and/or precipitation can be removed only through evaporation. Several mechanisms, such as structural movements, stream piracy in the hydrographic basin, and the blockage of an outlet, could account for the water-level fluctuation, but it seems highly unlikely that these mechanisms would have occurred repeatedly to cause the changes observed in the Tipton Shale Member. The regional distribution of the algal units in Zones 1 and 3 necessitates large decreases in the lake level. Such large-scale fluctuations can best be explained as a result of the effect of climatic changes on a closed basin.

Concomitant with the Tipton-Wilkins Peak transition there was a marked increase in the salinity and alkalinity of the lacustrine environment (Surdam and Wolfbauer, 1975). During this transition the deposition system characterizing Lake Gosiute evolved from one dominated by oil shale deposition to one dominated by the deposition of dolomitic mudstone.

Sedimentary Structures

The rocks of the Tipton Shale Member contain the following assemblage of sedimentary structures:

1. The sandstones and siltstones are characterized by mud cracks, ripple marks with flattened crests, ripple marks with mud racks in troughs, many burrows, and root casts, and thinly-bedded units with current lineations.
2. The carbonate rocks are characterized by mud cracks, saline crystal casts and plant debris, flat-pebble conglomerates, ooliths and pisoliths, and algal bioherms.
3. The oil shales are characterized by disrupted bedding and a lack of continuous lamination, some mud cracks and numerous incomplete desiccation polygons, and a variety of looped bedding and injection features. Continuous laminations are relatively rare.

Many of these sedimentary structures are not definitive in themselves but the total assemblage of structures strongly supports the playa-lake model for the Green River Formation.

Tipton Deposition System

The lithologic and mineralogic distribution patterns for modern closed basin deposits ("playa-lake systems") and the Eocene Green River Formation are strikingly similar (Surdam and Wolfbauer, 1975). In the Tipton Shale Member there is strong evidence demonstrating large fluctuations in the position of the shoreline and progressive increases in salinity and alkalinity of the lake water. The assemblage of observations made in the Tipton with regard to lithofacies distribution, stratification sequences and sedimentary structures is compatible only with a sedimentologic model containing as fundamental elements; (1) shallow-water deposition, (2) closed hydrographic basin,

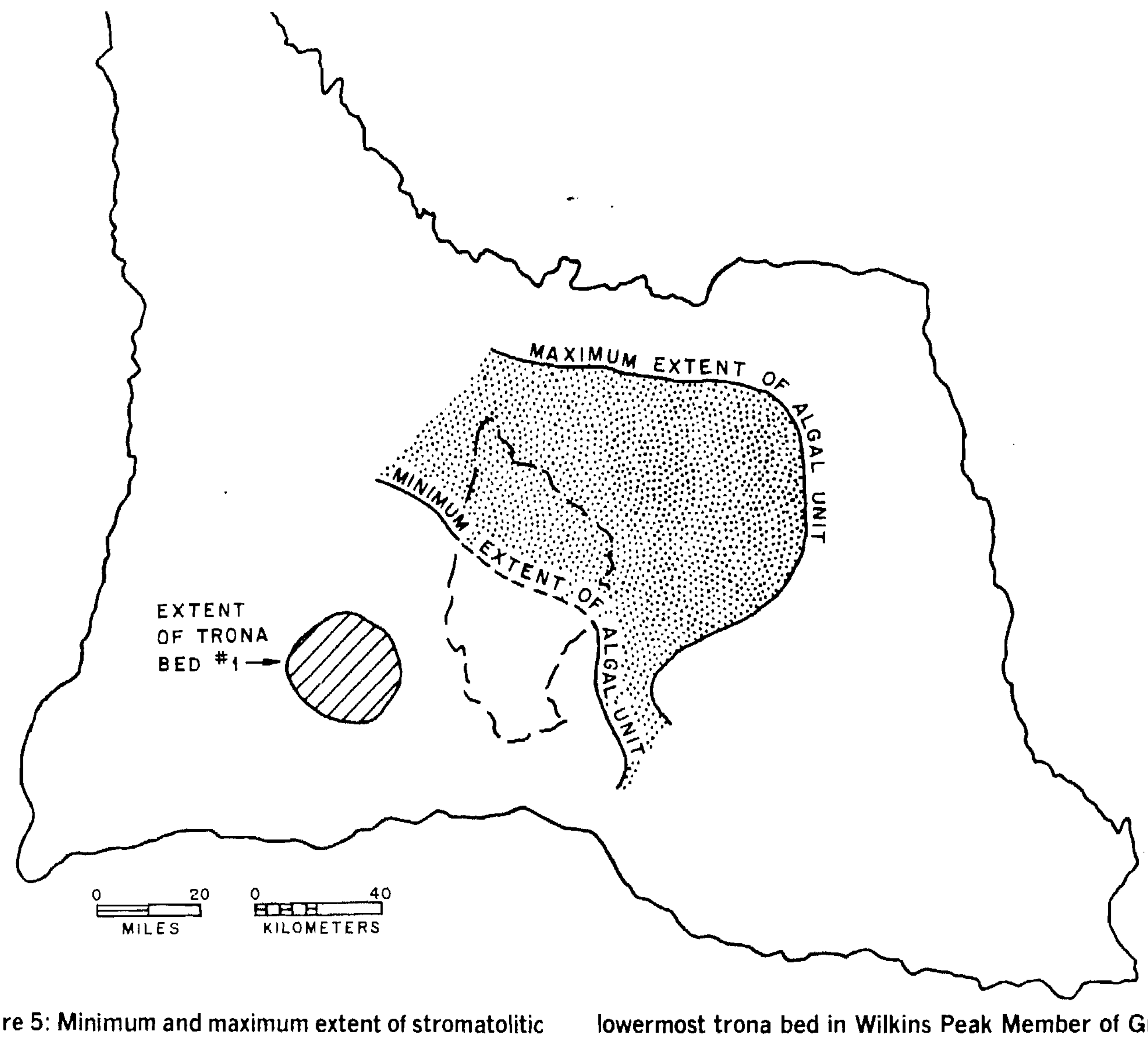

Figure 5: Minimum and maximum extent of stromatolitic algal unit in Zone 3 of Tipton Shale Member. Stippled area represents carbonate mud flats exposed as lake receded from high to low stand. Note areal extent of lowermost trona bed in Wilkins Peak Member of Green River Formation, which represents maximum shoreline recession. From Surdam and Wolfbauer, 1975.

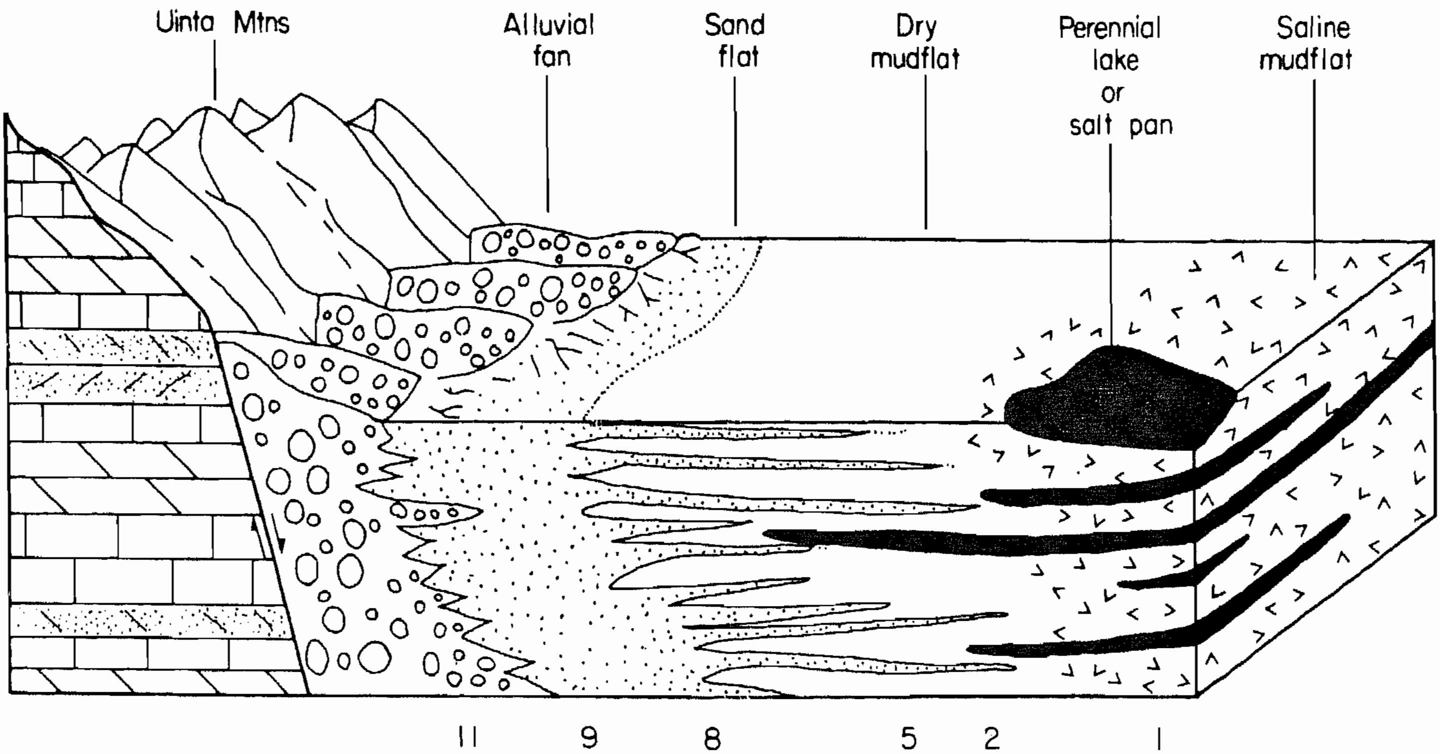

Figure 6: Schematic block-diagram showing general depositional framework and facies distribution for Wilkins Peak Member (after Smoot, 1978; Eugster and Hardie, 1975).

and (3) delicate imbalance between inflow and evaporation (Surdam and Wolfbauer, 1975).

In summary, the Tipton Shale Member represents the initial flooding of the Lake Gosiute Basin, and the subsequent evolution of the depositional system as it gradually changed from a widespread, but relatively shallow freshwater lake to a saline-alkaline lake surrounded by a broad carbonate mud flat.

THE WILKINS PEAK MEMBER

The Wilkins Peak Member, unlike the Tipton Member, is dominantly a dolomitic micrite or dolomitic mudstone unit. At the depocenter, the dolomitic micrite and lesser amounts of oil shale are intercalated with bedded trona and halite. Smoot (1978) has described the following subenvironments in the Wilkins Peak Member: alluvial fans, fringing sand-flats with broad, sheet-like basinward tongues, evaporative mud flat and an ephemeral lake (Fig. 6). The major mode of sedimentation, or resedimentation, was apparently by sheetwash across a normally subaerially-exposed, evaporative environment (Eugster and Hardie, 1975; Smoot, 1978). The carbonate sediments are mostly sand to silt-sized dolomite peloidal intraclasts that are in traction-deposited bed forms (Smoot, 1978). It is thought that these intraclasts were formed by the disintegration of dolomite surface crusts formed on the mud flat, or travertine tufa deposits, or caliche crusts. A chemical mass-balance demonstrates that all of the carbonate sediments in the Wilkins Peak could have been produced by the mechanisms characterizing modern closed-hydrographic basins (Smoot, 1978).

Eugster and Hardie (1979) have documented in beautiful detail the variations in the Wilkins Peak depositional system and have related these variations or depositional cycles to repeated transgressions and regressions of the lake. They describe at least 50 major alternations of wet and dry periods during the deposition of the Wilkins Peak Member. Eugster and Hardie (1975) have shown that on the fringing environments adjacent to the central lake there are three types of stratification sequences (Fig. 7). These three sequences are composed of various vertical combinations of flat-pebble conglomerate, oil shale, lime mudstone and lime sandstone (Fig. 7). At the center of the basin there is one basic type of stratification sequence; it consists of oil shale overlain by trona which is overlain by lime mudstones (Fig. 8; Culbertson, 1971).

In summary, in the Wilkins Peak, all of the stratification sequences are interpreted as being the product of repeated expansions and contractions of the lake resulting from climatic variations. During the most intensely arid times the lake shrank and trona and halite were precipitated, whereas during more humid times the lake expanded and oil shale was deposited.

A synoposis of the Wilkins Peak depositional environment was presented by Eugster and Hardie (1975) which remains accurate and unchallenged:

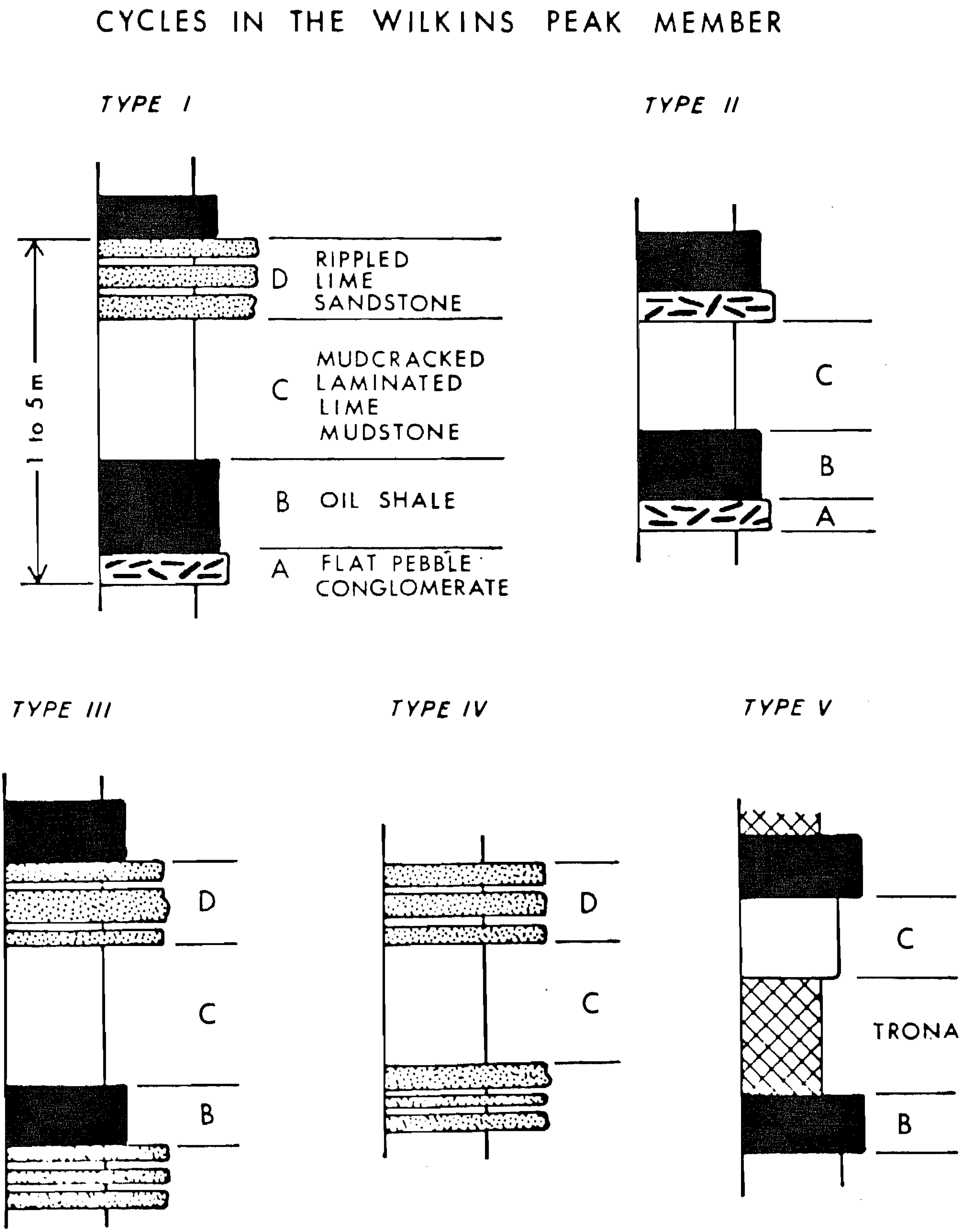

Figure 7: Four types of depositional cycles (stratification sequences) in Wilkins Peak Member (after Eugster and Hardie, 1975).

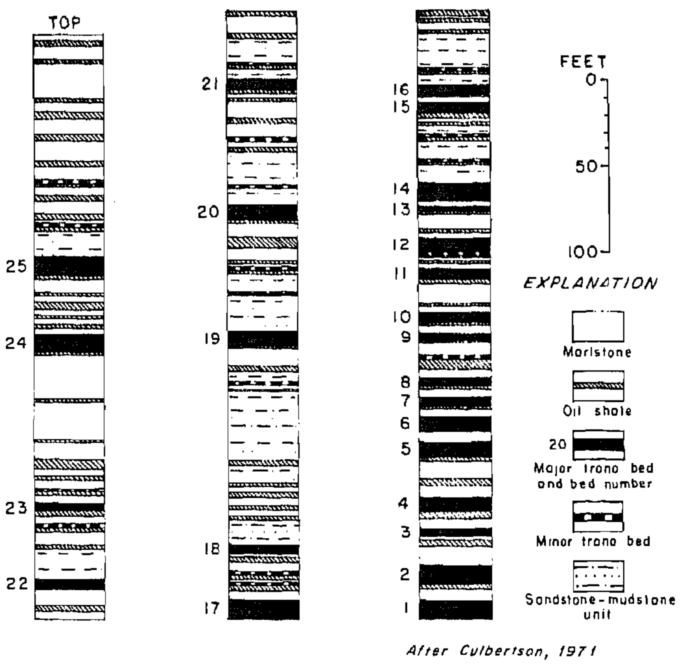

Figure 8: Composite columnar section of Wilkins Peak Member in trona area of Wyoming (after Culbertson, 1971).

"The combination of sedimentological and geochemical constraints makes the playa-lake model very attractive as the depositional framework for the Wilkins Peak Member. The need for a permanently stratified lake is eliminated. The main aspects of the playa-lake model can be summarized as follows:

1. Block faulting produced a closed basin with an arid floor, surrounded by high mountains that trapped precipitation and provided substantial perennial inflow into the basin.

2. Alluvial fans (normally mapped in the Bridger Basin as part of the Wasatch Formation) built up by outwash from the mountains and rimmed the basin, while the floor consisted of a very wide expanse of mud flats with a central body of shallow water that periodically expanded to a larger lake and shrank to a saline alkaline lake (Fig. 6). Records of these transgressions and regressions are beautifully preserved in the depositional cycles that are the characteristic feature of the Wilkins Peak Member.

3. Fluviatile processes were restricted to the edges of the basin, except for the nine long tongues of siliciclastic sand bodies that extend northward over the playa. These bodies were produced by braided streams issuing from the Uinta Mountains and represent alluvial fan material reworked during tectonic rejuvenation.

4. Soft waters with a low sulfate and chloride content were produced by weathering of silicates in the mountains. Perennial streams disappeared into the alluvial fans and recharged the ground-water system. Capillary evaporation from the water table caused concentration to increase, leading to precipitation of calcite, high-magnesian calcite, and protodolomite in that succession.

5. Alkaline-earth carbonates were precipitated as a soft, micritic mud from springs and surface inflow at the outer perimeter of the mud flats. The desiccated and mud-cracked micrite was washed toward the center of the basin as sand and silt-size mudclasts by sheet wash during periodic storms. Siliciclastic material, both weathering residues and pyroclastic debris, was added during these storms or by wind. Deposition produced laminated mudstones of intraclastic detrital nature. The laminae of many mudstones were disrupted by multiple mud cracking and by growth and dissolution of efflorescent crusts.

6. Precipitation of alkaline-earth carbonates produced high pH sodium-carbonate brines that migrated toward the hydrographic low of the playa. During dry periods, the central lake was contracted and trona precipitated from the brine. The lake was probably seasonally dry. The mud of dolomite partings in the trona sequences was washed in during storms. These storm waters also brought in solutes acquired by dissolution of efflorescent crusts.

7. At the onset of a pluvial period, rapid transgression of the shoreline produced a flat mudstone-pebble lag deposit. A more gradual and oscillatory transgression produced rippled lime sand bodies alternating with mud-cracked dolomitic mudstones.

8. Oil shale accumulated in the expanded, fresher lakes, which were still surrounded by wide mud flats. Protection from sediment influx allowed thick, bottom-dwelling, coccoid, blue-green algal mats to thrive, infrequent storms provided dolomitic laminae with the dolomite derived from the mud flats. The lakes were shallow and must at times have dried up in part to produce mud cracks and intraclast breccias.

9. The Wilkins Peak fauna and flora are compatible with a playa-lake complex. McGrew (1971) mentioned a flamingo nesting area in the northern part of the Bridger Basin where the Cathedral Bluffs tongue of the Wasatch Formation interfingers with the Wilkins Peak Member. Judging from Lakes Natron and Magadi in Tanzania and Kenya, this exactly fits our proposed setting. The adult flies and fly larvae and the aquatic insects mentioned by Bradley (1964, p. 43) also point to shallow-water bodies and wet mud flats. The subtropical climate visualized by MacGinitie

(1969) and McGrew (1971) does not conflict with a highly evaporative playa, as long as it is kept in mind that the higher portions of the alluvial fans and the mountains were forested and that in the lower parts of the fans, wherever water was available, a luxuriant flora could establish itself, just as it now has on the Rift Valley slopes above Lake Magadi.

10. Modifications by diagenetic processes was extensive. This includes reactions of interstitial brines with carbonates and silicates to produce authigenic minerals."

LANEY MEMBER

The Laney Member of the Green River Formation comprises the youngest and most extensive lacustrine rocks deposited in Eocene Lake Gosiute (Fig. 2; Bradley, 1964). The relationships of the Laney Member to the Wasatch, Bridger, and Washakie Formations, and to other members of the Green River Formation are described by Bradley (1964), Culbertson (1969), and Roehler (1973), who also recognized a lower oil shale and an upper sandstone and mudstone division of the Laney. The Laney ranges in thickness from 0 to 630 meters, but toward the margin of the depositional basin it intertongues with the Wasatch and Bridger Formations. In the central part of the basin the Laney rests on the Wilkins Peak Member, and toward the periphery it rests on the Wasatsh Formation or on the Cathedral Bluffs Tongue of the Wasatch (Bradley, 1964). The Bridger and Washakie Formations overlie the Laney.

The Laney Member consists of four lithofacies that are characterized by one or two major rock types and in some cases by numerous minor rock types. These lithofacies are: (1) laminated carbonate, (2) sandstone and mudstone, (3) evaporite, and (4) molluscan-ostracodal calcareous mudstone (Figs. 9 and 10). The distribution of the four lithofacies is shown in Figures 9 and 10; tuff and evaporite marker beds provide datum planes for correlation of stratigraphic sections across the depositional basin. The distribution of lithofacies in Figures 9 and 10 reflects the evolution of terrigenous, organic, and chemical sedimentation in the depositional basin. Within each lithofacies are vertical successions of beds that define stratification sequences produced by lateral shifts of adjacent alluvial, littoral, and sublittoral lacustrine environments. These stratification sequences are related to changes in lake level

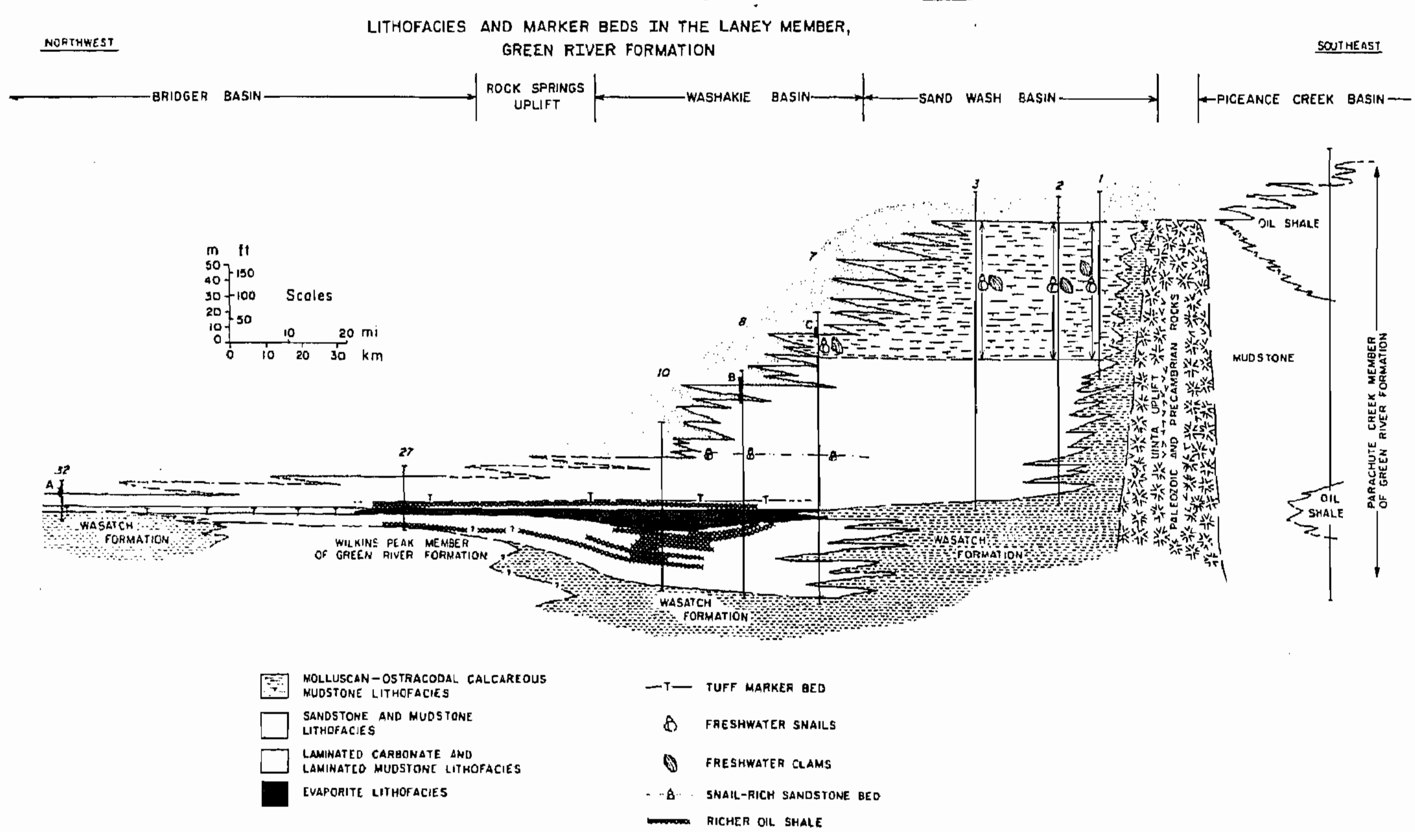

Figure 9: Lithofacies and marker beds from northwest to southeast in Laney Member, Green River Formation, Wyoming and Colorado, showing that during deposition of Laney, lake evolved from a playa (evaporite lithofacies) to a freshwater lake (molluscan-ostracodal calcareous mudstone lithofacies). Sections are as follows: 32, LaBarge, Wyoming; 27, Green's Canyon, Wyoming; 10, Spring Draw, Wyoming; 8, Pioneer Field, Wyoming; 7, Shell Creek, Wyoming; 3, The Nipple, Colorado; 2, Little Snake River, Colorado; 1, Elk Gap, Colorado. Data from Piceance Creek basin is from Roehler (1974). From Surdam and Stanley, 1979.

that produced transgressions and regressions of the lake, or to progradation of shorelines into the lake. Other changes in lithofacies and in stratification sequences reflect sublittoral lacustrine changes in biota, bedding features, and sediment types related to subtle changes in the physical, chemical, and/or biological features of the lake waters. For example, contacts between the laminated carbonate, evaporite, and molluscan-ostracodal calcareous mudstone lithofacies are sharp and parallel to tuff beds, which suggests that they are time datums related to some change in the sublittoral lacustrine environment. Hanley (1974, 1976) has shown that mollusks of the Green River Formation are freshwater types that cannot live in waters with salinities of more than a few parts per thousand. Mollusks are abundant in the molluscan-ostracodal calcareous mudstone lithofacies, locally in the sandstone and mudstone lithofacies, and in one horizon of calcareous mudstone in the laminated carbonate lithofacies (Fig. 9). Mullusk-bearing beds are commonly massive or platy, whereas rocks devoid of mollusks are laminated and/or contain saline mineral casts and molds. The synchronous change in bedding, biota, and mineralogy from the laminated carbonate to the evaporite lithofacies, and from the laminated carbonate to the molluscan-ostracodal calcareous mudstone lithofacies, therefore, can be ascribed to sublittoral lacustrine changes in the lake that influenced sedimentation. These sublittoral lacustrine lithofacies are successive chronostatigraphic units that are not lateral facies equivalents.

STRATIFICATION SEQUENCES

Laminated Carbonate Lithofacies

The laminated carbonate lithofacies is composed of repetitive successions of rock types (stratification sequences) that can be identified in the Bridger, Washakie, Great Divide, and Sand Wash Basins. Kerogenous laminated carbonate (oil shale) characterizes stratification sequences in the geographic center of Lake Gosiute, but dolomicrite and ostracodal, oolitic-pisolitic, and/or stromatolitic limestone also occurs in increasing amounts toward the margin of the lake. In the Washakie Basin, as many as 16 stratification sequences occur below the evaporite lithofacies (Fig. 10). These sequences range in thickness from a few centimeters to several meters and average 2 meters. They can be traced for 50 kilometers along the northern and western parts of the Washakie Basin.

In the Washakie Basin, the basal part of each stratification sequence fills mud cracks and is characterized

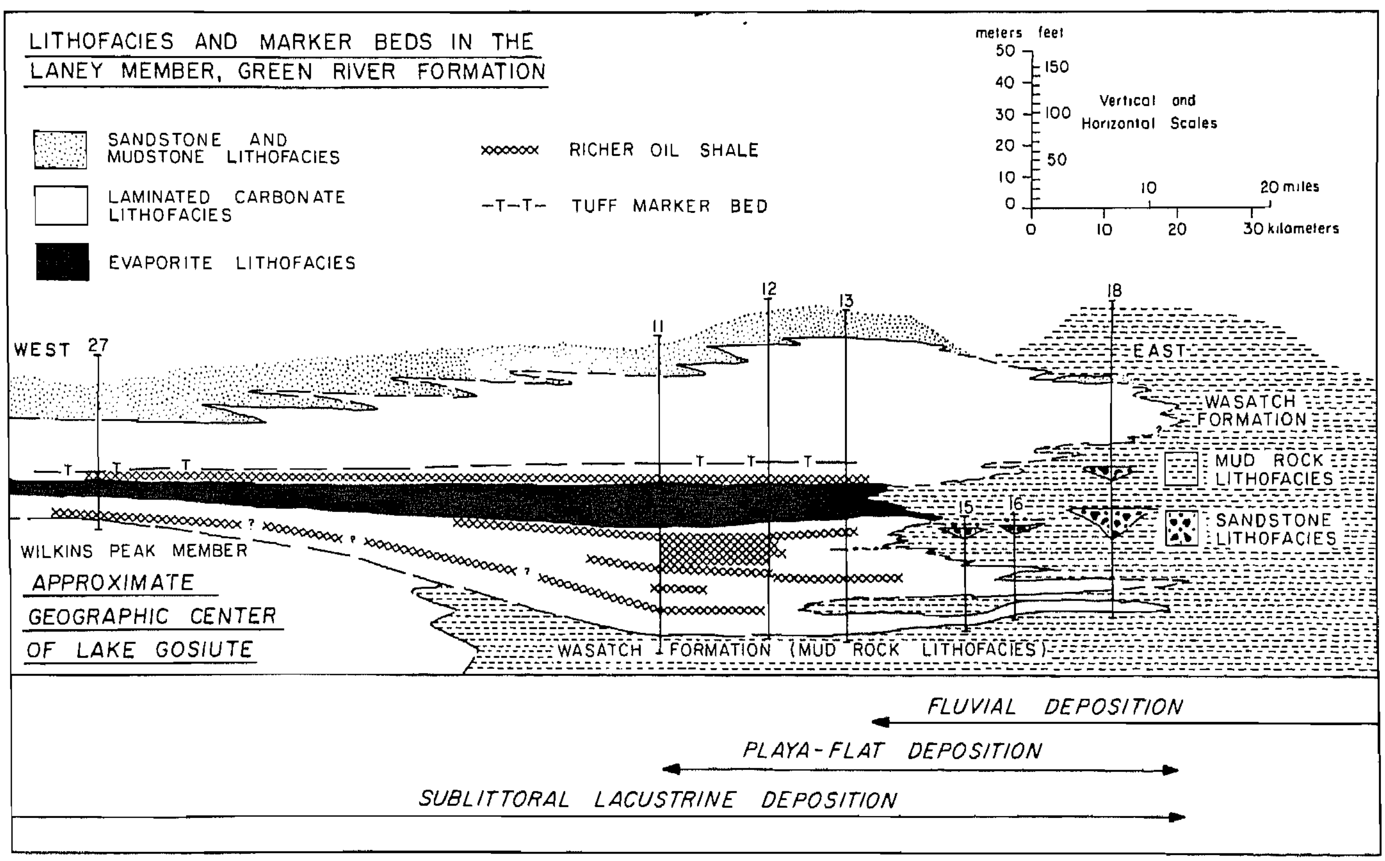

Figure 10: Lithofacies and marker beds from east to west in Laney Member, Green River Formation, Wyoming, showing Distribution of fluvial, playa-flat, and sublittoral lacustrine deposition. Sections (all in Wyoming) are as follows: 27, Green's Canyon; 11, Sand Butte; 12, LaClede Station; 13, J. O. Dugway; 15, Tipton Road; 16, Red Desert; 18, North Barrel Springs.

by flat-pebble conglomerate, algal breccia, domal or laminar algal stromatolitic limestone, pisolitic and oolitic limestones, and/or ostracodal limestones. These kinds of rocks make up basal beds as much as 20 centimeters thick in stratification sequences found in the westernmost Washakie Basin, but they increase in thickness and abundance toward the lake margin. Commonly, the basal bed grades upward from ostracodal limestone to oolitic and/or pisolitic limestone to stromatolitic limestone, although in many sequences one or more of these rock types is missing. Ostracodal and oolitic limestone is commonly a grain-supported calcarenite cemented by sparry calcite; locally it is crossbedded. Some of the ostracodal and oolitic limestone layers are modified to upward-coarsening pisolitic limestone that can be traced for more than 30 kilometers along the northern side of the Washakie Basin. These pisolitic beds are characterized by many of the features of pisolites formed in the vadose zone (Dunham, 1969), such as inverse size grading, polygonal shape, micrite support of pisoliths, and large pisoliths without foreign nucleii. Although these pisolitic beds are interpreted as being the product of pedogenic modification, we do not believe that all pisolitic limestone in the Laney Member is of vadose origin, for some of it is similar to pisolitic limestone of algal origin described by Bradley (1929, Pl. 47).

The basal part of the depositional sequence is overlain by kerogenous laminated carbonate that in the past has been called varved oil shale (Bradley, 1964). Although some of the laminae are mud cracked or display loop structures, disrupted laminae, or discontinuous laminae, most of the laminated carbonate is characterized by "varve-like" continuous laminate that range in thickness from 0.001 to 0.04 millimeters. Fish fossils are common in the laminated carbonate; kerogen content varies widely but is generally high, as much as 70 liters per metric ton, and it commonly decreases upward into overlying dolomicrite. The kerogenous laminated carbonate is overlain by dolomicrite, with a thin, gradational contact. The dolomicrite is characterized by mud cracks, poorly developed laminations or massive bedding, and an absence of fossil fish. Saline mineral casts and molds and magadi-type chert are common, particularly in the uppermost part of the dolomicrite. The top of the dolomicrite is mud cracked and overlain by another depositional sequence. Wave ripple-bedded arkosic sandstone and/or green montmorillonitic mudstone locally substitute for the kerogenous laminated carbonate, and toward the lake margin, these two rock types substitute for both the laminated carbonate and the dolomicrite. In the easternmost exposures, the laminated carbonate lithofacies is replaced by oolitic, ostracodal, and/or carbonate lithoclastic calcarenite layers underlain by mud-cracked montmorillonitic mudstone and overlain by montmorillonitic mudstone.

The stratification sequences in the laminated carbonate lithofacies of the Washakie Basin cannot be traced westward into the central part of Lake Gosiute. However, using characteristic tuff beds as time lines, close stratigraphic correlations can be made between the Laney rocks in the western part of the Washakie Basin and Laney outcrops near the town of Green River, as shown by sections 11 and 27 in Figure 10. Near the geographic center of Lake Gosiute (sec. 27, Fig. 10) the sequence consists of alternating thinner beds of kerogen-rich (rich oil shale) and thicker kerogen-poor (lean oil shale) varve-like laminated carbonate. Fossil fish are abundant, particularly in the kerogen-rich beds (Buchheim and Surdam, 1979). The sequence in this part of the lake is characterized by an absence of ostracodal, oolitic-pisolitic, and stromatolitic limestone; dolomicrite; and mud cracks.

Carbonate stratification sequences in the laminated carbonated lithofacies record repeated fluctuation in lake level, with concurrent expansion and/or reduction in the influence of marginal lacustrine and lacustrine environments on sedimentation. The systematic variations in ostracodal, oolitic, pisolitic, and stromatolitic limestone at the base of the stratification sequences are interpreted to result from slight variations in wave action and from changes in depth of water. These strandline deposits rest on mud-cracked dolomicrite with magadi-type chert and saline mineral casts; features that suggest genesis of the dolomicrite on a carbonate mud flat fringing the lake. Overlying the strandline deposits are sublittoral lacustrine, laminated carbonate rocks that grade upward into the mud-flat dolomicrite. This sequence is interpreted to represent repeated transgression and regression of the lake across the carbonate mud flat that fringed the lake. The repetitive succession of kerogen-rich and kerogen-poor laminated carbonate in the central part of the lake basin (section 27, Figs. 9 and 10) is interpreted as resulting from continuous sub-littoral lacustrine deposition with variations in kerogen content and mineralogy resulting from alternating high and low stands of the lake. Introduction of arkosic sands and montmorillonitic clays into the lake deposits is largely restricted to the margin of the basin, and commonly occurs in the kerogenous laminated carbonate part of the sequence or during the transgressive high stands of the lake.

Evaporate Stratification Sequences

In the evaporite lithofacies, stratification sequences are difficult to identify because this lithofacies is not well exposed. In addition, during the deposition of the lithofacies, the basin was deluged by pyroclastic debris which masks stratification sequences. Commonly, the rocks of this facies consist of 50 per cent vitric material altered to analcime. Although not well exposed, we have observed alternating ripple-laminated lithic sandstone composed of peloids of dolomicrite and mud-cracked dolomicrite sequences that are similar to type III stratification sequences of Eugster and Hardie (1975). However, the evaporite lithofacies contains many well preserved sedimentary structures including mud cracks, saline mineral casts and molds, ripples with flattened crests, flat-pebble conglomerates and bedded saline minerals and saline mineral nodules. The assemblage of sedimentary structures and minerals in the evaporite lithofacies is similar to that described by Bradley and Eugster (1969) and Eugster and Hardie (1975) in the Wilkins Peak Member, an ancient playa-lake complex. The evaporite facies of the Laney represents sedimentation dominated by mud-flat and brine-pool processes resulting from substantial periods of pronounced aridity.

Molluscan-Ostracodal Mudstone Stratification Sequences

These rocks are characterized by the presence of a variety of well developed stratification sequences (Kornegay, 1976). The most common sequence involves the repetition of two lithologies: platy fossiliferous calcareous mudstone and kerogen-rich laminated mudstone. The platy character of the molluscan and ostracodal-rich mudstone is a consequence of intensive bioturbation of sediment by mollusks. This rock-type is interpreted to represent deposition in an oxygenated, fresh-water, sublittoral, lacustrine environment. In contrast, the presence of fine laminations and the absence of fossils in the inter-bedded kerogen-rich mudstone reflects deposition in a more stagnant and/or in a more saline environment. Mud cracks are common in the platy fossiliferous calcareous mudstone, suggesting that the lake was not only fresh, but shallow during the deposition of this lithology (Kornegay, 1976, Plate 1). The repetition of these two lithologies record an alteration in the nature of sublittoral sedimentation, probably resulting from changing salinity and supply of terrigenous clay.

Sandstone and Mudstone Depositional Sequences

The transition from lacustrine to alluvial rocks in the Laney Member is characterized by (1) shoreline-deltaic and (2) Gilbert-type delta sequences (Stanley and Surdam, 1978) that are defined by vertical stratification sequences and the interfingering of terrigenous and carbonate lithofacies. Locally, these sequences are partly or wholly obliterated by large load casts, slump folds, and sandstone pillows produced by foundering of deltaic, water-saturated sands into lacustrine, kerogen-rich muds. The most common stratification sequence is the shoreline-deltaic sequence that consists of parallel-laminated oil shale, parallel-laminated mudrock, wave ripple-bedded fine-grained sandstone, and large-scale crossbedded fine- to medium-grained sandstone. This sequence occurs throughout the Green River, Washakie and Sand Wash Basins, and locally, the thickness of the sequence from oil shale to large-scale cross beds ranges up to 2 meters. The thickness and bedding features of the sequence suggest progradation of the delta-shoreline into a very shallow lake margin (depth less than 2 m), whose bottom was nearly flat and featureless. Locally, progradation of distal shoreline-deltaic sediments is followed by transgression of the lake so that an incomplete "offshore" vertical sequence is preserved and so that parallel-laminated mudrock and wave ripple-bedded fine-grained sandstone is then overlain by lacustrine, laminated oil shale. In addition, wave-rippled bedded fine-grained sandstone occurs in carbonate sequences associated with stromatolites, oolites, and laminated oil shale. This sequence is a variant of the mud flat fringe-lake, transgressive- regressive depositional sequence where the supply of siliclastic sands to the lake margin corresponds with the onset of lake-level rise during a wetter climatic time. The sandstone occurs in the stratigraphic position of kerogen-rich oil shale that contains abundant fossil fish. Ripple bedding in this sandstone suggests that sorting and dispersal of sand along the shore probably reflect wave influence of lake bottom sediment during the transgression.

Gilbert-type delta deposits are recognizable at only a few localities in the Laney Member in the northern Green River Basin and in the northern and northwestern Washakie Basin where complexes of coalescing Gilbert-type deltas mark the transition from lacustrine to alluvial rocks. Within these complexes are several southward prograding deltas stacked on one another and coalescing laterally (Stanley and Surdam, 1978). For the Laney Member we could find no delta foreset sequences with a thickness greater than 25 meters, and most were less than 10 meters. This relief, and the nearly constant thickness of foreset beds lakeward, suggest that the lake was shallow with a small variation in depth (Stanley and Surdam, 1978). Depths of up to 25 meters suggested by some thicknesses of foreset beds probably reflect local deep areas in the lake that were filled by prograding deltas. The more common thicknesses of less than 10 meters and more prevalent occurrence of the shoreline-deltaic sequence, which indicates depths less than 2 meters, probably are more representative of lake bathymetry adjacent to river mouths. Gilbert-type deltaic rocks in the Laney are composed of cycles consisting of a constructional and destructional phase (Stanley and Surdam, 1978). The constructional phases are represented by an upward-coarsening sequence produced by lakeward progradation of delta topset and foreset beds over pro-deltaic sediments. During the destructional phase, erosion and reworking of delta plain and slope beds resulted in the formation of an erosional surface and, locally, a sandstone shoreline veneer. The most characteristic feature of the Gilbert-type deltaic sequence is foreset bedding with a depositional dip of up to 20 degrees. These foreset beds grade upward into flat-lying sandstone and mudrock topset beds, and grade downward into flat-lying mudrock bottomset beds.

DEPOSITIONAL ENVIRONMENTS

Bradley (1964), Culbertson (1966), and Roehler (1973) recognized the lacustrine and marginal lacustrine origin of carbonate and terrigenous rocks in the Laney and that these rocks represent a high stand in the history of Lake Gosiute. The regional and temporal relationships of lithofacies and the repetitive depositional sequences identified in them provide more detail about the nature of the lake and adjacent environments during a high stand of the lake and during the culminating phase of lacustrine sedimentation in Lake Gosiute. Unlike the Wilkins Peak Member of the Green River Formation, which was deposited during the preceding low stand of the lake, the Laney contains little evidence for lake-wide, continuous sedimentation dominated by carbonate mud-flat and brine-pool processes, which are characteristic of playas and playa-lakes as described by Eugster and Surdam (1973), Bradley (1973), and Eugster and Hardie (1975). Such lake-wide conditions of evaporation existed only during deposition of the evaporite lithofacies (Figs. 9 and 10), although laminated carbonate depositional sequences indicate episodic development of a broad carbonate mud flat fringing the lake during deposition of the laminated carbonate lithofacies. The persistence of kerogenous laminated carbonate rocks that contain fossil fish in the central part of the lake basin and the overlying molluscan-ostracodal calcareous mudstone rocks indicate the presence of a permanent lake in the basin except during deposition of the evaporite lithofacies. This lake varied from fresh to saline and underwent episodic and/or periodic fluctuations in water level that produced large areal expansions and reductions of the lake. These transgressive-regressive phases of the lake are represented by depositional sequences of the laminated carbonate lithofacies, in which strandline and carbonate mud-flat deposits are traceable for up to 40 kilometers from the margin of the lake toward the lake center. The strandline and mud-flat deposits are parallel to tuff beds, a relationship that implies rapid transgression and regression of the lake over vast areas of flat and nearly featureless carbonate mud flat fringing the lake.

The lateral persistence of the transgressive- regressive sequences, and particularly the subaerial exposure of a vast area of the lake floor when the fringing carbonate mud flats were present, requires a nearly flat and featureless lake bottom. The thickness of these depositional sequences ranges up to 4 meters and averages 2 meters. These thicknesses are comparable to those of the prograding shoreline-deltaic stratification sequences in the sandstone and mudstone lithofacies that show no significant change in thickness. The thickness of these sequences suggests water depths of only a few meters. In the center of the lake, depths must have been greater because subaerial exposure is indicated only during deposition of the evaporite lithofacies. Maximum depths of water during Laney deposition may be indicated by the Gilbert-type deltas in the upper, less saline, phase of the lake. These suggest water depths of up to 25 meters; however, they commonly require a depth of only 3 to 10 meters (Stanley and Surdam, 1978). The Gilbert-type delta deposits are rare and may reflect progradation of terrigenous material into local and isolated deeper parts of the lake. Even in the upper phase of the lake, most prograding shoreline deposits indicate water depths of less than 3 meters (Stanley and Surdam, 1978).

SUMMARY

As a consequence of the study of the Laney Member, it is now possible to construct a complete model of the depositional environment of the Green River Formation of Wyoming. The observations outlined in the discussion of the Laney (Surdam and Stanley, 1979), coupled with those of Eugster and Hardie (1975) on the Wilkins Peak Member and those of Surdam and Wolfbauer (1975) on the Tipton Shale Member, suggest that the Lake Gosiute system is best described as a shallow lake surrounded by a wide fringing mud flat in a basin that was hydrographically closed, except in the waning stages of the lake. During periods of aridity the hydrochemistry of the lake was dominated by spring discharge and brine-pool processes, whereas during humid periods the hydrochemistry was dominated by surface water discharge and resolution of efflorescent crusts. As a result, the types of sediments deposited in the basin depended on a delicate imbalance between evaporation and inflow. The Lake Gosiute system was dynamic and capable of changing sedimentologic parameters radically over relatively short periods of time. Thus, each Member of the Green River Formation in Wyoming possesses individuality, with there being significant differences not only between members, but also between different facies within members. However, these differences can be explained by one general depositional setting, in which numerous environmental variables lend significant variation to each member, each bed, and even each rock type.

THE STRATIGRAPHIC FRAMEWORK OF THE GREEN RIVER FORMATION

The regimes of early Tertiary Lakes Gosiute and Uinta (Colorado and Utah) were strongly affected by pronounced imbalance between evaporation and recharge by surface and ground water. Both evaporation and recharge were strongly affected by the climate of the closed hydrographic basins where the lakes formed. However, at unique times in the histories of the Lake Gosiute and the Lake Uinta (Colorado and Utah) basins, the regimes of these lakes were significantly modified by enlargement of the drainage basins to include water from basins farther north.

Evidence for changes in the size of drainage basins includes southward dispersal of volcani-clastic sands containing baslatic to dacitic volcanic rock fragments from the Absaroka volcanic field in northwestern Wyoming (Fig. 11). The southward progradation of the resulting sandstone units from the Wind River Basin into the greater Green River Basin, and from there into the northern Piceance Creek Basin, records the successive depositional filling of closed hydrographic basins so that water and sediment were transported by streams over the lowest divides into the adjacent basins (Surdam and Stanley, 1980). Filling of these basins allowed large volumes of surface and ground water to be added first to Lake Gosiute and then to Lake Uinta. The added water resulted in (1) a rise in the lake level, (2) the development of nutrient-rich lakes where algal productivity led to the deposition of precursors of oil shale, and (3) in the case of Lake Uinta, a change in water chemistry such that brines precipitated sodium rather than calcium sulfate minerals.

Basin filling and enlargement of the drainage systems were probably a consequence of tectonic activity and stability of the basins and adjacent uplifts, although climatic conditions that increased sediment yield and runoff in the hydrographic basins also could have hastened their filling. However, it is difficult to explain patterns of

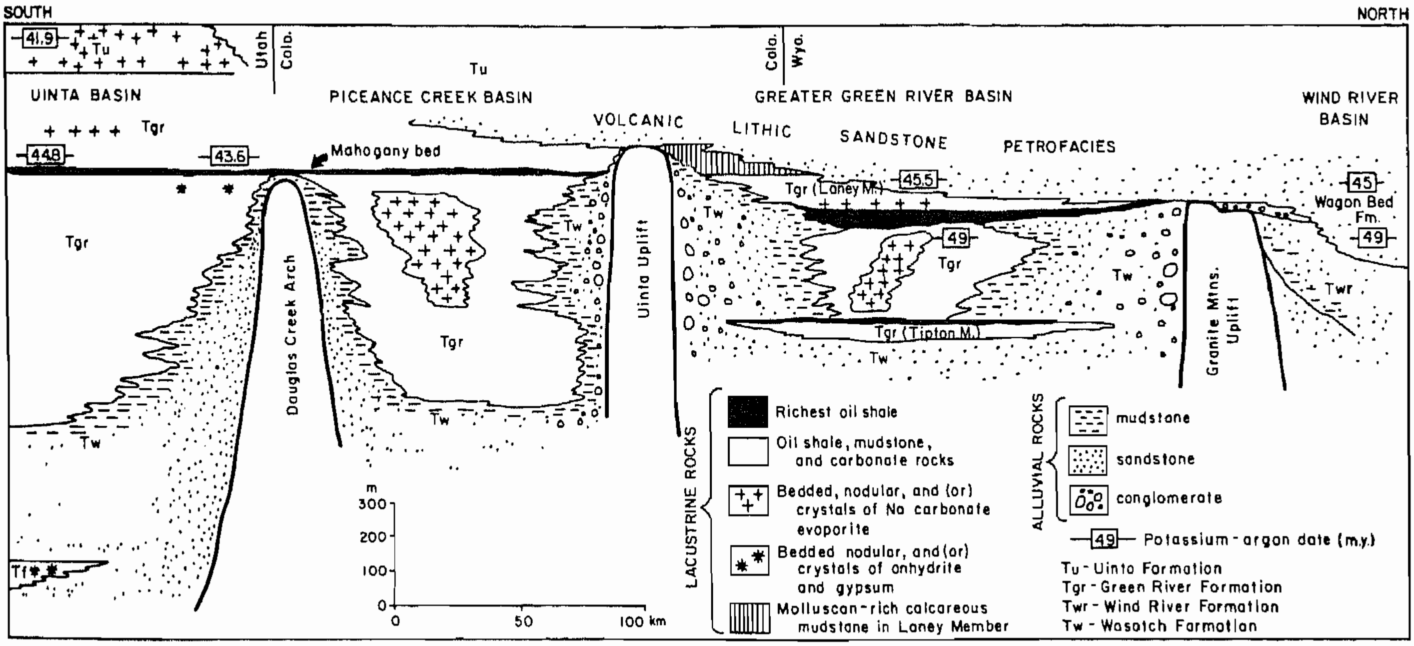

Figure 11: Generalized stratigraphic reconstruction of the Green River Formation and coeval rocks in the Wind River, greater Green River, Piceance Creek, and Uinta Basins, showing the relationship of the volcanic lithic sandstone petrofacies to rich oil-shale horizons, distributions of evaporite minerals, and uplifts. Potassium-argon dates in the Wind River Basin are on samples from the Wagon Bed Formation (Love, 1970, Table 5). Potassium-argon dates in the greater Green River Basin are on samples from the upper part of the Wilkins Peak Member (49 m.y. B.P.) and the upper part of the Laney Member (45.5 m.y. B.P.), and those from the Uinta Basin are from just above the Mahogany bed (43.6 m.y. B.P.) and from the saline facies (44.8 m.y. B.P.) of the Uinta Formation (Mauger, 1977).

evaporite minerals, oil shale, mudstone, and sandstone formed in Lakes Gosiute and Uinta if climate was the dominant factor.

Figure 11 shows the regional stratigraphic framework of the Green River Formation. In addition, Figure 11 emphasizes the stratigraphic correlation of the Formation from the Greater Green River Basin to the Piceance Creek Basin to the Uinta Basin. We believe that the oil shale in the Laney member is correlative with alluvial and pond deposits of the Wagon Bed Formation in the Wind River Basin, and that the Mahogany oil-shale bed is correlative with the lacustrine molluscan calcareous mudstone and the marginal lacustrine sandstone and mudstone of the Laney in the southern greater Green River Basin.

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