Lakes represent closed systems which are faithful recorders of local climate. The basinal facies of the Green River Formation (intermontane Eocene complexes in Colorado, Utah and Wyoming), studied by Bradley (1929), show long cyclic alternations in which varved fresh water lake deposits either passed through a saline phase into dolomitic playa flats or changed directly into such playas, in oscillations of the *precipitation-evaporation* balance, apparently driven mainly by the precession cycle.

Other studies of Milankovitch cyclicity in lacustrine settings are those by Van Houten (1964) and by Olsen (1986) in the Triassic-Jurassic lake-playa sequences of the Newark rift basins in eastern North America. In these settings, deposited near the equator but likewise affected by cyclic flooding and desiccation, the long cycles of the Milankovitch frequency band (eccentricity cycles) emerge better than they do in the Green River Formation, and Fourier analyses demonstrate the presence of obliquity cycles as well.

Varves are far more common in lakes than in marine settings, and in both of these lake complexes varves have provided significant help in estimating the periods of the longer cycles. A disadvantage of lacustrine studies is the difficulty of tying them into global biostratigraphy-geochronology.

—The Editors

CYCLICITY IN THE GREEN RIVER FORMATION (LACUSTRINE EOCENE) OF WYOMING

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ABSTRACT: Basinal facies of the Green River Formation have two main modes, lacustrine and playa. The lacustrine mode (Tipton and Laney members) accumulated mainly varved oil shale. Here annual cycles are recorded as varves. Variations in varve thickness demonstrate El Niño (ENSO)-type and sunspot cycles (Ripepe et al., this volume). Milankovitch-scale cycles are not obvious in lithic variations, but gamma ray logs record 1) precessional variations with a mean period (varve-timed) of 19.5 ka, and 2) a bundling of these in the ca. 100 ka eccentricity cycle. In the playa mode (Wilkins Peak Member), the lithic succession oil shale–trona–dolomitic marlstone records the precessional drying up of a lake and is again bundled in sets of 5, by the 100 ka eccentricity rhythm. The Tipton Member persisted for 450 ka, the Wilkins Peak Member for ca. 1 Ma.

INTRODUCTION

In the Late Cretaceous-Paleogene Laramide phase, the deformation of western North America encroached upon the craton, raising scattered mountain blocks between subsiding basins. In Eocene time, these basins received widespread alluvial deposits (Wasatch and Bridger Formations) surrounding lake-playa basin complexes. The deposits of these complexes, in places up to 1000-m thick, contain much black, laminated "oil shale" interbedded with dolomitic marlstone and tongues of detrital matter.

A voluminous literature records varied interpretations of these deposits. Bradley (1929, 1931, 1948) viewed them mainly as products of large meromictic fresh-water lakes, which only occasionally dried-up into salt pans. Subsequently, the drilling of many core holes (Anonymous 1980) found a far greater prevalence of evaporite sediments than is preserved on the leached outcrop (Trudell et al. 1970). Furthermore, Eugster and others (Eugster and Surdam 1973; Eugster and Hardie 1975; Wolfbauer and Surdam 1974; Surdam and Wolfbauer 1975; Smoot 1978) recognized the unfossiliferous, mudcracked dolomitic marlstones as playa sediments. The pendulum of changing opinions swung to the point at which the existence of large lakes was questioned, but it has now settled into a moderate position (Surdam and Stanley 1979): long oil shale sequences such as represented in the Gosiute complex of Wyoming (Figs. 1, 2) by the Tipton and Laney members represent large and persistent lakes, which only rarely dried out to give way to salt pans and playas. Other members such as the intervening Wilkins Peak Member, consisting of intimately interbedded oil shale, trona beds and dolomitic marlstone, represent times during which playas prevailed but gave way rather frequently to shorter-lived lakes, which commonly passed through a salt-pan stage in the return to the playa phase.

The nature of the lakes has been controversial. Beyond the near-shore deposits (Bradley 1929; Surdam and Stanley 1979), the large lakes accumulated a remarkably uniform sediment: finely laminated, organic-rich marls, now compacted to oil shale (Figs. 3, 4, 5A). (We note that the oil shales of the Green River Formation also include other

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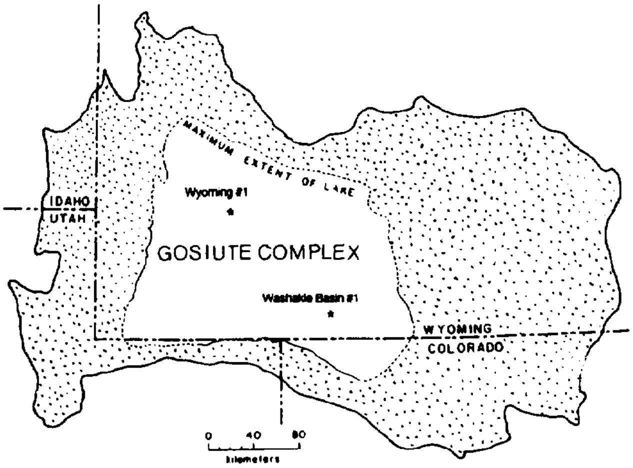

FIG. 1.—Map of Gosiute playa-lake complex within larger intermontane basin. Other such complexes to west and south are also included in the Green River Formation.

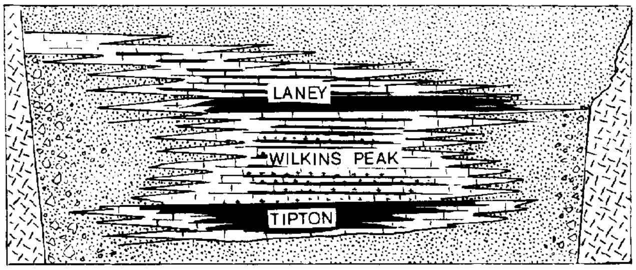

FIG. 2.—Stratigraphy of Green River Formation (Gosiute complex, Wyoming), diagrammatic. Marginal mountain blocks shed alluvium into intermontane basin, enclosing a central (Gosiute) complex of lake and playa deposits, which, together with similar deposits in basins to west and south, comprise the Green River Formation. The Tipton Member and the basal part of the Laney Member, shown in black, are persistent, varved lacustrine oil shale units. The Wilkins Peak Member and the upper portions of the Laney Member record many oscillations between playa and lake in the central parts, and many transgressive-regressive shore line cycles on the margins. Vertical scale about 1 km, horizontal scale two to three hundred kilometers. Adapted from Surdam and Stanley 1980.

types such as microbial mat deposits of shallow ponds, shown in Figs. 5B and 6.) The lamination implies not only freedom from wave action, but also from the activity of scavenger organisms, which would have found these muds highly nutritious. Blurring of varves at intervals (Fig. 4) suggests that at times minute scavengers such as insect larvae may have been present episodically. What excluded such scavengers?

Bradley (1929), viewing the lakes as fresh-water bodies, sought the answer in the thermal stratification so common in modern lakes. In the absence or rarity of seasonal overturns, the supply of organic matter would have generally kept the hypolimnion depleted of oxygen, excluding animals from the deeper bottoms. There is good evidence for fresh water: near-shore deposits contain beds with fresh-water snails and bivalves (Bradley 1929, 1931; Surdam and Stanley 1979), and the oil shales contain fish coprolites (Fig. 5A, B) and skeletal remains (Figs. 3A, 6) of fishes, commonly complete from head to tail. The coprolites include both those of predatory fishes, composed largely of scale and bone debris and lithified in early diagenesis (Fig. 5A), and those of mud-eaters, composed largely of carbonate, and diagenetically compacted into flat lenses (Fig. 5B).

But such fish-bearing layers are exceptional—mostly the laminated marls lack all but microscopic fossils, and we must conclude that generally not only the hypolimnion but also the epilimnion was devoid of a normal lacustrine fauna. This indicates that the lakes were generally undrained and hypersaline, and that fishes invaded them, from the tributary rivers, only when exceptionally heavy inflow established a fresh-water epilimnion. Salinity stratification of such lakes has been discussed (Boyer 1982; Smith and Robb 1973; Desborough 1978). Bottom anoxia is not required to exclude bottom-burrowers from saline waters.

Figure 1 shows the location of the Gosiute complex, and Figure 2 illustrates the stratigraphy. Above a basal unit of near-shore limestones (Luman tongue), the *Tipton Shale Member* consists mainly of lean to moderately rich, partly illitic, partly calcareous "oil shale". The *Wilkins Peak Member* in the middle contains oil shales interbedded with dolomites and evaporites. These units interfinger laterally with the upper parts of the alluvial Wasatch Formation. The *Laney Member,* mainly oil shale, lies at the top and interfingers with the basal units of the Bridger alluvium.

The cyclicities discussed are developed at seven levels. High-frequency cycles in the Tipton and Laney members include the annual cycle expressed in varving (1), the grouping of varves into El Niño (ENSO)-type (5.8) year cycles (2), their grouping into sunspot cycles (3), and their grouping into 30-year cycles (4). Low-frequency cycles from the Milankovitch frequency band are seen in the Tipton and Wilkins Peak members, and include the precessional 20 ka cycle (5) and the ca. 100 ka eccentricity cycle (6). Cycle categories 1, 5, and 6 are discussed here, while 2, 3 and 4 are dealt with in Ripepe et al. (this volume).

VARVING

Oil shales are defined as rocks (not necessarily argillaceous) with a kerogen content high enough to yield appreciable amounts of oil on distillation. In the Green River Formation oil yield results mainly from the presence of laminae of kerogen (Figs. 3, 4), some tens of microns thick, alternating with thicker layers of clay or of carbonate—a mixture of dolomite and calcite.

Bradley (1929) found the thickness of such kerogen-mineral couplets to range from ca. 0.014 mm in rich oil shales to 0.5 mm in lean ones and to 9.8 mm in some sandstones. By analogy with modern sediments such as Lake Zurich in Switzerland, Bradley took these couplets to be annual varves. In the distal settings in which detrital input was small, the sediment was supplied mainly by 1)

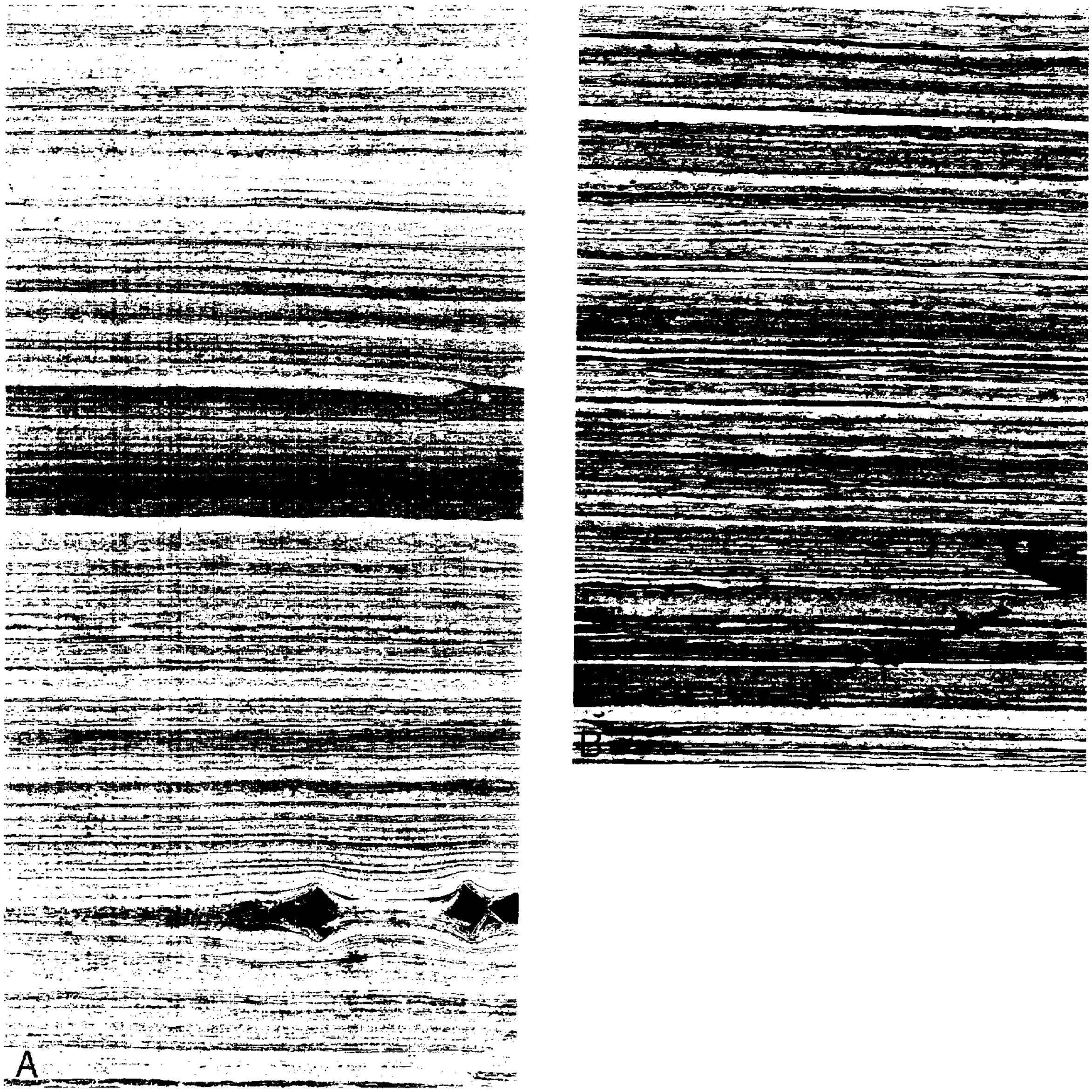

FIG. 3.—Photomicrographs of hypolimnial oil shales; direct prints from acetate peels, kerogen laminae dark, × 5. **A)** Laney Member, Bore Hole Wyoming #1, Green River Basin, 570.1 feet, showing varving, microfault (middle right) and obliquely transected fish (bottom). **B)** Laney Member, Core Hole Washakie Basin #1, 577′. Note in both the common occurrence of double kerogen layers and the grouping of varves into diffuse bundles at the ca. 1 cm level on print (2 mm level in core), attributed to a combination of ENSO-type and sunspot-generated cycles. Scarcity of fish and coprolites suggests that water was generally saline.

organic particles and 2) chemical precipitates, mainly of carbonate. He assumed that a rain of organic particles formed the background component, peaking in late summer. Detrital layers, found mainly in the lower parts of the formation, might represent either spring floods or episodes of dust storms. Bradley (1929) considered the carbonate laminae as chemical precipitates in the epilimnion, resulting from photosynthetic activity (carbon dioxide withdrawal) during algal blooms, in early summer. This remains the most likely cause, although the possibility that some carbonate layers represent dust transport from playas (Eugster and Surdam 1973) cannot be dismissed. The extreme regularity of this lamination, having formed millions of couplets in the course of Green River time, is indeed hard to attribute to any oscillatory mechanism other than that of the annual cycle, and the product shows good similarity to varying in modern meromictic lakes (e.g., Kelts and Hsü 1978; Dickman 1985).

The kerogen laminae (Figs. 3, 4) are discrete and sharply bounded, brown in transmitted light, and on the order of ten μm thick. Some sets of such laminae are believed to extend continuously for tens of kilometers (Trudell et al. 1970; Dean, personal communication).

As noted by Bradley (1929), a given varve is commonly

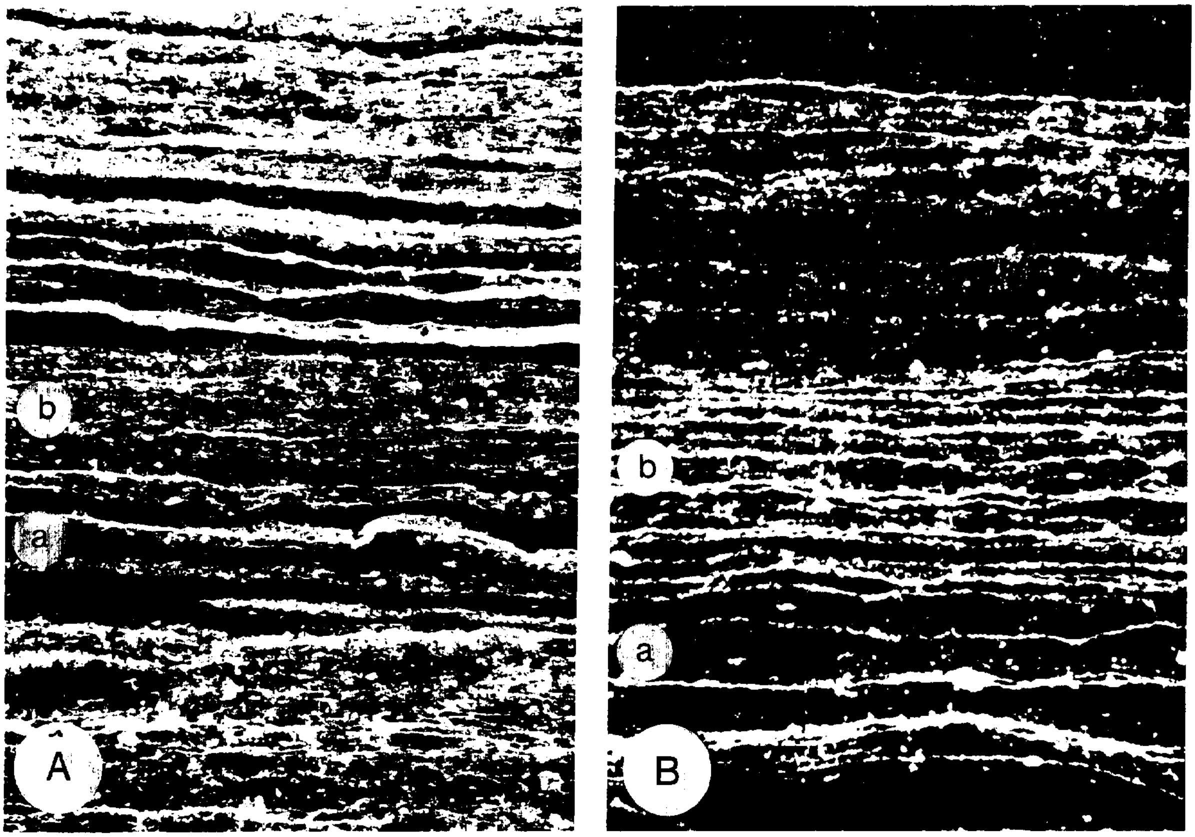

FIG. 4.—Composite structure of kergen laminae, and grouping of varves. Photomicrographs of acetate peels, × 45, showing kerogen layers in white and carbonate dark. Kerogen layers subdivided by very thin laminae or lenses of carbonate. Varves are grouped into sets, each of which consists of two subequal members, (a) and (b). The (a) members contain 4–5 distinct varves. The (b) member in A is a thick layer of kerogenic limestone in which lamination is indistinct, possibly a result of microbioturbation. In **B** it contains crowded kerogen laminae in which the differentiation of sub-varve layers and varves is problematic. A, Tipton Member, Core hole Wyoming #1, 1274.49 feet. B, Laney Member, Core hole Wyoming #1, 487.46 feet.

composite, consisting of several very thin kerogen layers separated by laminae of carbonate (Figs. 3, 4). Doublets of this sort are common, and as many as 4 sub-varves have been observed. They presumably record as many algal blooms, or possibly some storm events that brought dust from the playas. In some cases (Fig. 4), the observer counting varves is left in doubt as to which couplets are varves and which are sub-varve units, a matter that was handled in our image-analysis varve counts (Ripepe et al., this volume) by arbitrarily counting only variations above the 30-μm level.

The microbiota of the oil shales has been extensively studied by Bradley (1931). Demineralized thin-sections yielded bacteria, cyanobacteria, chlorophyte algae, euglenophytes, fungi, moss and fern spores, and pollen, as well as arcellid rhizopods, aquatic mites, and hairs, scales and other debris of insects. Chlorophyll-derived biomarkers such as phytoporphyrins and pristane have been identified (Robinson 1976).

Bradley (1929) visualized this organic matter as organic detritus produced by plankton in the epilimnion and settled to form "putrescent ooze" on hypolimnial bottoms. Bucheim and Surdam (1977), however, have argued for its origin in algal or microbial mats. The sharply bounded, discrete character of the kerogen laminae supports that view: it seems unlikely that episodic seasonal rains of mineral grains—clay or carbonate—would have retained such sharp boundaries if added to a layer of "putrescent ooze". The composite nature of the kerogen laminae and the occurrence of discontinuous patches of kerogen between the more continuous laminae speak for a binding of this ooze by microbes to for microbial mats. Such mats now range from photosynthetic ones in the shallowest puddles to heterotrophic ones on the bottoms of deep lakes and marine basins such as the Santa Barbara Basin off California.

CYCLICITY AT THE DECADE LEVEL

Similar varves tend to be grouped into sets of five to twelve, differing from adjacent sets in thickness or spacing of kerogen laminae. This produces color banding at levels of half a millimeter to one or two millimeters, apparent to the eye, and shown in Figures 3 and 5 at the scale of a centimeter. It is, however, a complex kind of banding, not easily followed as a time-series. Such sets may be

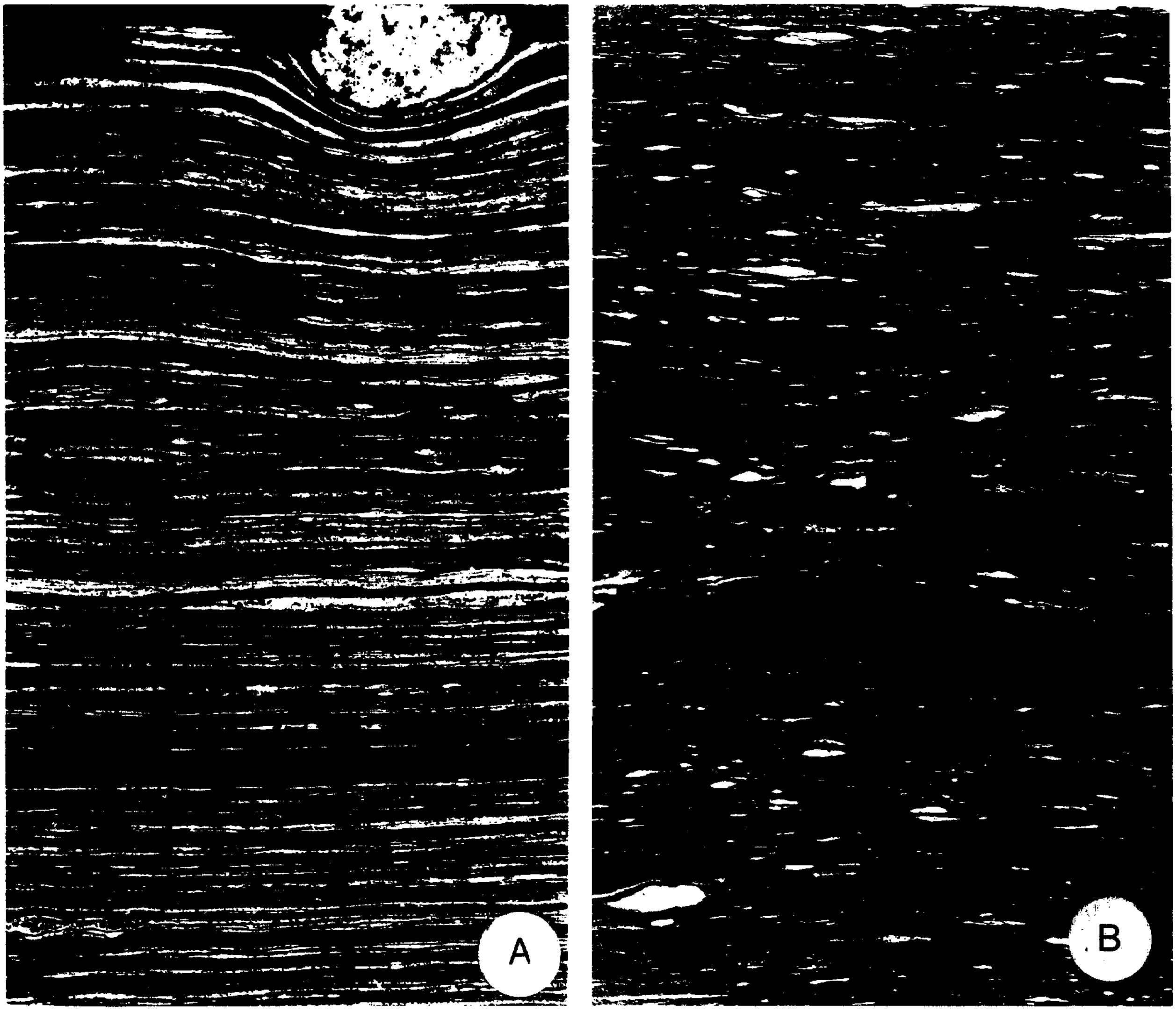

FIG. 5.—Photomicrograph of oil shales, contrasting hypolimnial (A) and shoal-water (B) types. Direct prints from acetate peels, × 5, kerogen laminae black. A) Varved oil shale with numerous carbonate coprolites (white lenses). Shell core #1 Greeno, 2363 feet. B) Tipton Member, Core Hole Wyoming #1. This is atypical of Tipton Member but common in oil shales associated with playa facies.

differentiated into a lower half having ca. 4 very distinct varves, and an upper half in which varves are blurred or crowded (Fig. 4). Computer analysis (Ripepe et al., this volume) indicates that two cycles are involved, one of which, with a mean period of 5.8 years, may be related to an El Niño (ENSO)-type of climatic change, while the other with a period of 10.8 years may well represent the sunspot cycle as suggested by Bradley (1929).

The Fourier analyses by Ripepe et al. (this volume) also show the presence of a periodicity at about 30 years—one that had also been previously identified by Bradley (1929).

CYCLICITY AT MILLENIUM LEVELS

Surdam and Stanley (1979) show a photograph of an outcrop of Laney oils shale, near Green River, Wyoming, in which exceptionally rich oil shales recur with a mean spacing of about 40 cm. Applying a mean varve thickness of 120 μm suggests a periodicity of about 3300 years. These units in turn are divided into about 5 couplets forming little ledges and recessions on the outcrop, presumably due to variations in carbonate content. By the same token, these would appear to record an oscillation in the 600 year range. We call attention to this level of cyclicity, but have not studied it.

MILANKOVITCH CYCLICITY IN TIPTON OIL SHALE

Bradley (1929) interpreted oil shale—marlstone couplets in the Parachute Creek Member of the Piceance Creek Basin, Colorado as products of the precessional cycle, and Surdam and Stanley (1979) read it as the forcing function behind the transgressions and regressions re-

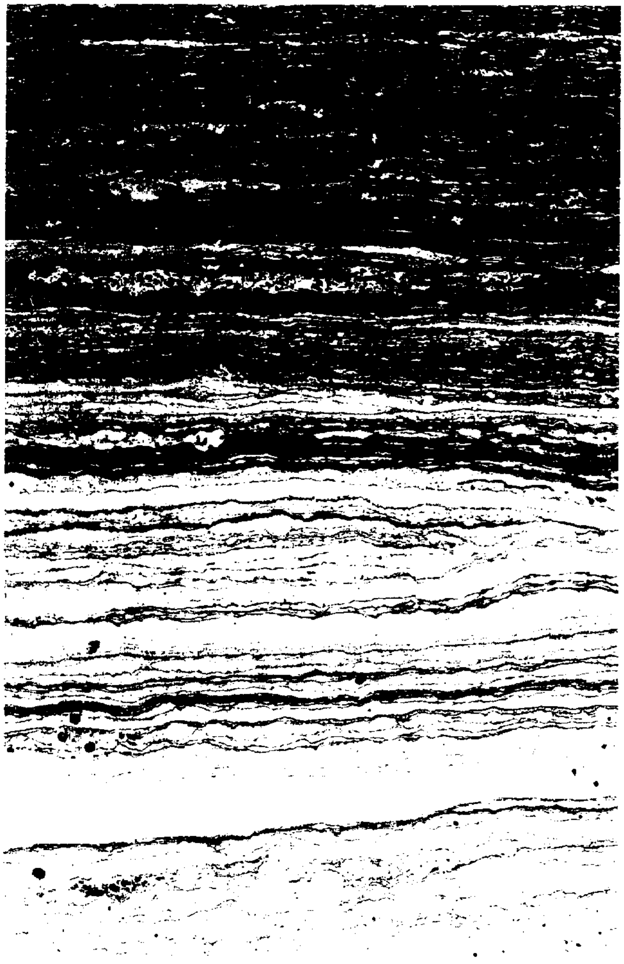

FIG. 6.—Photomicrograph of transition from dolomitic marlstone facies to oil shale. Direct print from acetate peel, × 5, kerogen laminae black. Very blistery and widely spaced kerogen laminae at base become more planar and more tightly spaced upwards, passing into crudely laminated oil shale with layers of fish debris. Flat white lenses are probably fish coprolites of carbonate mud. Laney Member, Core Hole Wyoming #1, Green River Basin, 475.5 feet.

corded in the shoreline facies of the Wilkins Peak and Laney members of the Washakie rim region in the eastern part of the Gosiute complex of Wyoming.

Precessional Cycle

Milankovitch-scale rhythmicity has not been recorded in lithic logs of the oil shales, either in cores or outcrop. It occurs, however, in gamma-ray logs (Fig. 7B, C). The Tipton Member, 47 m thick, shows 20 small-scale gamma ray oscillations. A somewhat similar signature is present in the sonic velocity log, which shows 22 oscillations, but in places the signatures do not match.

It is not clear at this stage to what extent the gamma ray oscillations record fluctuation in uranium and thorium connected with the organic matter, potassium linked to clays, or dilution of organic content by clays and/or carbonate. Mismatches with the sonic velocity log suggest that in some cases the signature derives from carbonate content, in others from clay enrichment. The spacing of peaks or troughs varies markedly, but the mean is 2.35 m. The mean varve thickness of 120 μm yields a mean period of 19,358 years, a remarkable match for the ca. 20-ka precessional cycle.

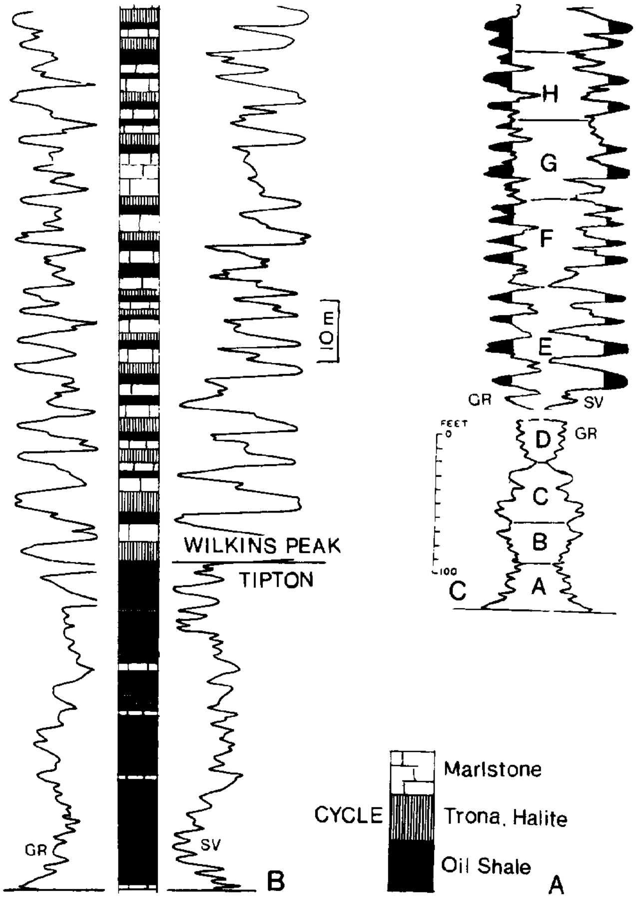

FIG. 7.—Cyclicity in the Tipton and Wilkins Peak members, Green River Basin. A) Basic desiccation cycle proceeding from lacustrine deepwater oil shale through a trona-halite precipitating salt pan phase into the playa phase of dolomitic marlstone. B) Basal 129 m of Green River Formation in Green River Basin (omitting Luman tongue). Stratigraphy composite, based on a number of core holes. GR: Gamma ray log; SV: Sonic velocity log. Digitations interpreted as precessional (20-ka) cycles recording alternating drier and moister climates. Tipton time was dominantly lacustrine, and the cycle mainly drove a variation in carbonate content. During Wilkins Peak time the playa prevailed, and the cycle brought brief (average 8000 year) lacustrine episodes, passing through a salt-pan stage (trona-halite) into the playa phase. C) log plots illustrating the grouping of precessional cycles into 100 ka "Schwarzacher bundles" A, B, C . . .) that reflect ca. 100-ka modulations of the precessional cycles by the eccentricity cycle. Plot for Tipton Member (AS-D) is a mirror plot of gamma ray log; Plot for Tipton Member (E-H) opposes gamma ray and sonic velocity logs. Basic data from Dana and Smith 1972.

Eccentricity Cycle

These small-scale oscillations ride on a longer and more evenly spaced wave, which appears to the eye when the gamma ray log is mirror-plotted (Fig. 7C). Each undulation of this wave bears 5 precessional cycles, fixing the period at 100 ka—that of the short (E1, 2) cycle of orbital eccentricity. Thus the gamma ray log of the Tipton Member reveals responses to two components of the precession-eccentricity syndrome or precession index, the most powerful of the climatic forcing functions in mid-latitudes (Berger 1988; Berger and Pestiaux 1984).

MILANKOVITCH CYCLICITY IN THE PLAYA-DOMINATED PHASE (WILKINS PEAK)

Precessional Cycles

The Wilkins Peak Member is characterized by about 50 cycles which are either oil shale-marlstone couplets or oil shale-trona-marlstone triplets (Fig. 7A). These record climatic oscillations which led to an alternation of lake and playa, and commonly passed through a trona-halite yielding salt pan phase in the transition. In the upper part of the member this cyclicity is disrupted by intercalations of detrital tongues, but the lower 82 m are free of such disturbance, consisting of 22 such cycles (Fig. 7) with mean thickness of 3.7 m.

These lithic cycles are dramatically recorded in the bore hole logs (Fig. 7B, C). In the gamma ray log, the trona-halite beds yield the lowest values (plotted as peaks), and the oil shales the highest values, the marlstones being intermediate. In the sonic velocity log, the trona beds form velocity peaks, the oil shales velocity lows. These cycles are somewhat thicker than the precessional cycles in the Tipton oil shale, but appear as their continuation. They are also somewhat thicker than the oil shale-marlstone couplets of the Parachute Creek Member of the Green River Formation in the Piceance Creek Basin, of Colorado (Bradley 1929), which lack the trona member.

Bradley (1929) interpreted the Parachute Creek couplets as precessional, by calculating the duration of the oil shale portion on the basis of mean varve thickness, and by extrapolating the sedimentation rate to the succeeding marlstone unit, adding a "fudge factor" for more rapid deposition of the marlstones (which he thought of as lacustrine). In the light of newer knowledge, we question the propriety of this procedure. The dolomitic marlstones accumulated on playas alternately wet and dry, shrinking and expanding, alternately accumulating sediment and losing it to wind erosion, and undergoing major diagenetic changes. They are products of regimes radically different from those that gave rise to varved lacustrine muds. To extrapolate accumulation rates from one of these systems to the other seems unwarranted.

Nevertheless, the continuity of the Wilkins Peak cycles with the precessional cycles of the underlying Tipton oil shale strongly suggests precessional origin. The mean thickness of these cycles is 3.7 m and the oil shales in them average 66 cm thick. Application of a mean varve thickness of 120 μm yields a duration of 8000 years for the lacustrine phase, leaving 12,000 years for the accumulation of the trona and dolomite members. We have some misgivings about this calculation, for the oil shales of these units include not only regularly varved shales of the Tipton and Laney types but also poorly laminated or highly lenticular deposits (such as illustrated in Fig. 5B), oil shale breccias, and cross-laminated units. They also commonly contain evaporite minerals. We suggest that some of these oil shales represent microbial mat accumulations in shallow saline ponds subject to desiccation, and that their depositional rates may have differed markedly from those of the varved type. Nevertheless, a precessional origin seems likely.

Eccentricity Cycle

The proof lies in the presence of 5:1 bundling. As in the Tipton Member, these lesser cycles in the Wilkins Peak Member are segmented into sets (Schwarzacher bundles) of 5, best shown by viewing the well logs in combination (Fig. 7C). This segmentation involves two factors: at the bundle boundaries, gamma ray fluxes remained at intermediate levels, as did sonic velocities. This is partly due to the absence of the trona member, but not all trona-lacking cycles are thus affected.

Thus the Wilkins Peak cycle pattern, like that of the Tipton Member, shows a higher frequency cycle riding on one of lower frequency, in ratio 5:1. This is the ratio of the 20-ka precession to the 100-ka eccentricity cycle, and is found in the "Schwarzacher bundling" of many stratigraphic sequences (Fischer 1986; Fischer et al. 1990, this volume).

Geochronology

The Tipton Member at this location is composed of four bundles and one additional precessional cycle and thus represents a history of 420 ka. The portion of the Wilkins Peak Member studied consists of 4 bundles, and two additional precessional cycles, representing 440 ka. The 50 precessional cycles observed in the entire Wilkins Peak Member suggest a duration of 1 million years.

CONCLUSIONS

The Green River Formation in the deeper parts of the Green River Basin contains an extraordinary record of climatic rhythms, arranged in an hierarchy of six levels, as follows:

1) The annual rhythm, recorded in carbonate-kerogen varves with a mean thickness of 120 mu.
2) A ca. 6-year rhythm, expressed in variations of varve thickness, and attributed to meteorological variations of the ENSO type. This rhythm is discussed by Ripepe et al. (this volume).
3) A ca. 11-year rhythm, expressed in variations of varve thickness, attributed to the sunspot cycle. This is discussed by Ripepe et al. (this volume).
4) A ca. 30-year rhythm in varve thickness, of unknown origin. This is dealt with in Ripepe et al. (this volume).
5) The ca. 20,000-ka precessional rhythm. In the oil shale facies (Tipton Member) this finds its clearest expres-

sion in gamma ray flux but is also seen less perfectly in the sonic velocity log. In the playa-dominated facies (Wilkins Peak Member), this cycle is represented by oil shale–marlstone couplets and oil shale–trona–marlstone triplets, which represent desiccation cycles leading from lake to playa.

6) The ca. 100 ka eccentricity cycle. This shifted the base-line of the precessional gamma-ray cycles in the Tipton Member, and the base-line of the desiccation cycle in the Wilkins Peak Member. We infer that the bounding precessional cycles, characterized by moderate gamma ray flux and absence of a trona member, denote drier times when the lake did not reach its normal size.

No evidence was found for the existence of a ca. 40-ka (obliquity) cycle or a 400-ka (long eccentricity) cycle. Additional rhythms with periods close to 600 and 3000 years may be present but remain unstudied.

In the area studied, the Tipton Member represents a time span of 420 ka, the lower Wilkins peak one of 440 ka. The entire Wilkins Peak Member probably spans about a million years.

Surdam and Stanley's (1979) interpretation of regressional shoreline cycles in the Wasatchie rim area as precessional cycles seems well justified.

DISCUSSION

The varving is a response to seasonal change. Simple varves with one kerogen layer and one carbonate layer suggest a single carbonate-precipitation algal bloom per year, whereas composite varves suggest the presence of several such blooms. The possibility of carbonate layers resulting from seasonal dust storms cannot be excluded.

Modulations of varve thickness presumably indicate variations in the intensity of plankton blooms, but again we cannot be sure that some varves were not bloated by dust. Such variations seem to have responded to three forcing functions—one with ENSO timing, one related to sunspot activity, and the 30-year cycle of unknown nature. Presumably these forced weather patterns, such as precipitation and river influx, the amount of available sunlight, and wind activity, but the relative roles played by these factors remain open.

The Milankovitch cycles presumably reflect changes in precipitation-evaporation balance that drove the lake through oscillations in salinity and lake level. Presumably trona beds developed when the water mass was large enough to yield volumes of trona and halite precipitating brines, and remained absent when lake volume was smaller.

Lack of evidence for an obliquity cycle is not surprizing, because in other pre-Pleistocene cycle sequences such as the Triassic-Jurassic Newark sequence (Olsen 1986) or the mid-Cretaceous of Italy (Fischer et al., this volume) the evidence for this is restricted to Fourier spectra. The ca. 400-ka eccentricity cycle may not be in evidence because the time series in any one facies (lacustrine or playa-dominated) are not sufficiently long to reveal it.

How much of the Green River Formation can be segmented into such cycles remains to be seen.

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REFERENCES

Anonymous, 1980, A bibliography of publications dealing with oil shale and shale oil from U.S. Bureau of Mines, 1917–1974, the ERDA Laramie Energy Research Center, 1975–1976, and the DOE Laramie Energy Research Center, 1977–1979: Springfield, VA, National Technical Information Service, U.S. Department of Commerce, 58 p.

Berger, A., 1988, Milankovitch theory and climate: Reviews of Geophysics, v. 26, p. 624–657.

Berger, A., and Pestiaux, P., 1984, Accuracy and stability of the Quaternary insolation, *in* Berger, A., Imbrie, J., Hays, H., Kukla, G., and Saltzman, B., eds., Milankovitch and Climate: Dordrecht, D. Reidel, p. 83–112.

Boyer, B.W., 1982, Green River laminites: does the playa-lake model really invalidate the stratified-lake model?: Geology, v. 10, p. 321–324.

Bradley, W.B., 1929, The varves and climate of the Green River epoch: U.S. Geological Survey Professional Paper 158, p. 87–110.

Bradley, W.B., 1931, The origin of the oil shale and its microfossils of the Green River Formation of Colorado and Utah: U.S. Geological Survey Professional Paper 168, 58 p.

Bradley, W.B., 1948, Limnology of the Eocene lakes of the Rocky Mountain region: Geological Society of America Bulletin, v. 59, p. 635–648.

Bucheim, H.P., and Surdam, R.C., 1977, Fossil catfish and the depositional environment of the Green River Formation, Wyoming: Geology, v. 5, p. 196–198.

Dana, G.F., and Smith, J.W., 1972, Oil yields and stratigraphy of the Green River Formation's Tipton Member at Bureau of Mines sites near Green River, Wyoming: U.S. Bureau of Mines Report of Investigations 7681, 46 p.

Desborough, G.A., 1978, A biogenic-chemical stratified lake model for the origin of oil shale of the Green River Formation: an alternative to the play-lake model: Geological Society of America Bulletin, v. 89, p. 961–971.

Dickman, M., 1985, Seasonal succession and microlamina formation in a meromictic lake displaying varved sediments: Sedimentology, v. 32, p. 109–118.

Eugster, H. P., and Hardie, L.A., 1975, Sedimentation in an ancient playa-lake complex: the Wilkins Peak Member of the Green River Formation in Wyoming: Geological Society of America Bulletin, v. 86, p. 319–334.

Eugster, H.P., and Surdam, R.C., 1973, Depositional environment of the Green River Formation in Wyoming: a preliminary report: Geological Society of America Bulletin, v. 84, p. 1115–1120.

Fischer, A.G., 1986, Climatic rhythms recorded in strata: Annual Reviews of Earth and Planetary Sciences, v. 14, p. 351–376.

Fischer, A.G., de Boer, P. L., and Premoli Silva, I., 1990, Cyclostratigraphy, *in* Ginsburg, R.N., and Beaudoin, B., eds., Cretaceous Resources, Events and Rhythms, Dordrecht, Kluwer Academic Publishers, p. 139–172.

KELTS, K., AND HSÜ, K.J., 1978, Freshwater carbonate sedimentation, *in* Lerman, A., ed., Lakes—Chemistry, Geology, Physics: New York, Springer-Verlag, p. 295–323.

OLSEN, P.E., 1986. A 40-million year lake record of Early Mesozoic orbital forcing: Science, v. 234, p. 842–848.

RIPEPE, M., ROBERTS, L.T., AND FISCHER, A.G., 1991. Varves, El Niño and sunspot cycles in (Eocene) Green River oil shales revealed by image analysis: Journal of Sedimentary Petrology, this volume.

ROBINSON, W.E., 1976, Origin and characteristics of the Green River Oil Shale, *in* Yet, T.F., and Chilingar, G.V., eds., Oil Shale: New York, Elsevier, p. 61–79.

SMITH, J.W., AND ROBB, W.A., 1973, Aragonite and the genesis of carbonates in Mahogany oil zone shales of Colorado's Green River Formation: U.S. Bureau of Mines Report of Investigations 7727, 21 p.

SURDAM, R.C., AND WOLFBAUER, C.A., 1975, Green River Formation, Wyoming: a playa-lake complex: Geological Society of America Bulletin, v. 86, p. 335–345.

SURDAM, R.C., AND STANLEY, K.O., 1979, Lacustrine sedimentation during the culminating phase of Eocene Lake Gosiute, Wyoming (Green River Formation), Geological Society of America Bulletin, v. 90, p. 93–110.

SURDAM, R.C., AND STANLEY, K.O., 1980, The stratigraphic and sedimentologic framework of the Green River Formation, Wyoming: Wyoming Geological Association Guidebook No. 31, p. 205–221.

SMOOT, J.P., 1978, Origin of the carbonate sediments in the Wilkins Peak Member of the lacustrine Green River Formation (Eocene), Wyoming: International Association of Sedimentologists, Special Publication 2, p. 109–127.

TRUDELL, L.G., BEARD, T.N., AND SMITH, J.W., 1970, Green River Formation lithology and oil shale correlations in the Piceance Creek Basin, Colorado: U.S. Bureau of Mines Report of Investigations 7357, 11 p. and appendices.

WOLFBAUER, C.A., AND SURDAM, R.C., 1974, Origin of non-marine dolomite in Eocene Lake Gosiute, Green River Basin, Wyoming: Geological Society of America Bulletin, v. 85, p. 1733–1740.