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REPORT 9

CORRELATION OF THE MIDDLE AND LATE QUATERNARY SUCCESSIONS OF THE LAKE LAHONTAN, LAKE BONNEVILLE, ROCKY MOUNTAIN (WASATCH RANGE), SOUTHERN GREAT PLAINS, AND EASTERN MIDWEST AREAS

By R. B. MORRISON and JOHN C. FRYE

PREPARED IN COOPERATION WITH THE DESERT RESEARCH INSTITUTE

MACKAY SCHOOL OF MINES
UNIVERSITY OF NEVADA

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STATE OF NEVADA

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FOREWORD

This report, "Correlation of the middle and late Quaternary successions of the Lake Lahontan, Lake Bonneville, Rocky Mountain (Wasatch Range), Southern Great Plains, and Eastern Midwest areas", makes public the results of a cooperative study conducted during 1963 and 1964 by the Mackay School of Mines and the Desert Research Institute of the University of Nevada.

Dr. Roger B. Morrison, who has studied the Pleistocene stratigraphy of the Great Basin for nearly two decades, has collaborated with Dr. John C. Frye, a long-time student of Pleistocene geology of the Midwest and Great Plains, to produce a much-needed correlation of the formations and time units used in these widely separated but critical Quaternary areas. While doing the field work for this project, Dr. Frye was supported by the Desert Research Institute and Dr. Morrison was supported in part by the Mackay School of Mines.

VERNON E. SCHEID, Director
Nevada Bureau of Mines

July 1965
Mackay School of Mines
University of Nevada

CORRELATION OF THE MIDDLE AND LATE QUATERNARY SUCCESSIONS OF THE LAKE LAHONTAN, LAKE BONNEVILLE, ROCKY MOUNTAIN (WASATCH RANGE), SOUTHERN GREAT PLAINS, AND EASTERN MIDWEST AREAS

By R. B. MORRISON and JOHN C. FRYE

ABSTRACT

This paper proposes a detailed interregional correlation of middle and late Quaternary successions of the Lake Lahontan and Lake Bonneville areas of the Great Basin, the central Rocky Mountains (represented by the Wasatch Range), the Southern Great Plains, and the Eastern Midwest (Illinois and adjoining areas). Further consideration of the relations of these successions is appropriate because of the extensive restudy and the radiocarbon dating that has taken place in the Great Basin and Eastern Midwestern areas in the past decade. Summaries of the latest stratigraphic, radiocarbon, and climatic data are presented for each of the five areas. The Lake Lahontan area is more fully described than the other areas because particularly intensive study of its stratigraphy and lacustrine history was undertaken as part of the correlation investigation. Many additional large oscillations of Lake Lahontan were discovered. Three formations and a soil-stratigraphic unit ("soil") are newly named and defined for this area. The radiocarbon chronologies of Lakes Lahontan and Bonneville are evaluated stratigraphically to provide comparative chronologies for the Wisconsinan fluctuations of both lakes, and of the Rocky Mountain and Midwestern (continental) glaciers.

Interregional correlations of Quaternary successions preferably are made, as in older successions, by classifying and correlating strata as time-stratigraphic units. Fundamental inadequacies of long-distance correlation of geologic-climate units are discussed. Arguments are given in behalf of retaining the revised time-stratigraphic classification of the Quaternary of the Eastern Midwest, and a provincial time-stratigraphic classification is proposed for the Great Basin. Evidence is presented for inferring that weathering profiles (in the sense of soil-stratigraphic units; here termed "geosols"), which occur in the successions of all the areas, provide valid time-stratigraphic markers for long-range correlation. Those geosols formed in response to special, infrequent combinations of climatic factors that produced relative erosional stability and accelerated chemical weathering. The only possible cause of the weathering optima is periodic marked increase in temperature. The climatic thermal maxima are assumed to have been caused by maxima of solar energy, and should have been world-wide and synchronous. They contrasted most with intervening climates (when weathering was inappreciable) at middle and high latitudes. Consequently, the weathering optima not only were restricted time intervals (which the stratigraphic record affirms), but also were essentially snychronous throughout these latitudes. For this reason, geosols are much more nearly time-parallel than any of the common sedimentary deposits. Because they also are distinctive and

relatively ubiquitous, they generally are the best key beds for long-range Quaternary time-stratigraphic correlation.

The basic correlation framework is provided by matching the stronger geosols in the successions of each area as closely as possible in terms of relative age and relative development. Of particular importance is the establishment of essential contemporaneity of the Sangamon Soil of the Midwest and Great Plains with the Dimple Dell and Cocoon Soils of the Great Basin, and similarly, the soil of Farmdalian age in the Midwest with the Promontory and Churchill Soils. Units between the stronger geosols are correlated by matching those units that record depositional cycles (or parts of cycles) of similar relative age, magnitude, and climatic genesis. Despite certain anomalous dates from the western basins, the abundant radiocarbon dates from the Great Basin and Midwest are of great utility. Considerable attention is given to various implications of the correlations, and to problems needing further investigation.

INTRODUCTION

Stratified sediments of Quaternary age, and particularly of late Pleistocene and Recent age, profide the most sensitive indicators of past climates within the entire geologic column. This is the result not only of their proximity in time and completeness of record, but also of the sharply fluctuating climatic conditions that obtained during the Pleistocene. In the United States there were four basically different depositional environmental situations, each of which reflects this climatic history in its own distinctive way. Probably because workers in each of these provinces have tended to concentrate their efforts on deposits of only one type, there have developed four essentially independent chronologies for these four environments, namely: (1) areas covered by glacial ice and directly derived outwash and eolian deposits; (2) deposits of through-flowing streams and associated eolian deposits in regions beyond the direct influence of Pleistocene glaciers; (3) deposits in lakes, and those formed by stream and wind action in regions of internal drainage; and (4) marine deposits. In this paper the writers propose a correlation of late and middle Pleistocene sequences of the first three named types of deposits in five areas of the midwestern and western United States.

A new look at interregional correlations is appropriate at this time because the stratigraphy of all three regions has recently been intensively restudied, and because many radiocarbon dates have become available during the past decade from the Midwestern and Great Basin regions. Although brief resumes of the latest stratigraphic information from these regions are included, no attempt is made here to discuss the local data extensively, except for the Lake Lahontan area. Rather, correlation charts are presented to show our current judgments on the most probable interregional correlations. Frye has taken full responsibility for the data on the Midwest and southern Great Plains areas, and Morrison has the primary responsibility for the Wasatch Mountains, Lake Bonneville, and Lake Lahontan areas, although both authors jointly examined key stratigraphic localities in the latter three areas.

Some of the stratigraphic information was obtained in the course of field studies made in connection with this project, particularly in the Lake Lahontan area, and also to some extent in the Lake Bonneville area. The study was sponsored by the Desert Research Institute and the Mackay School of Mines of the University of Nevada.

STRATIGRAPHIC DATA

As background for the proposed interregional correlations, we present summaries of the local stratigraphic, radiocarbon, and climatic data from each of the five areas considered here, including previously unpublished data for the three western areas. The interpretations of the history of glacial and lake oscillations follow directly from the basic stratigraphic data; the interpretations of the climatic history obviously involve higher degrees of inference. Considerable "subjective control of an objective effort" has been necessary in selecting radiocarbon dates that presumably are valid in determining a precise chronology for the Lake Bonneville and Lake Lahontan areas, both because of the numerous conflicts among radiocarbon dates and because of discrepancies between the radiocarbon dates and the relative chronologies derived from the geologic stratigraphy.

Lake Lahontan area

GENERAL FEATURES

Lake Lahontan is here defined as the late Pleistocene (post-Sangamon), pre-altithermal (hence pre-Recent) fluctuating lake that inundated a number of adjoining intermontane basins, mainly in western Nevada, to form the largest pluvial lake in the western Great Basin (fig. 1). Lake Lahontan time includes two main deep-lake periods (called lacustral intervals) that were separated by a long interval of complete or near-complete desiccation; each deep-lake interval had numerous lake oscillations of considerable magnitude (fig. 2). Two long pre-Sangamonian (pre-Lake Lahontan) deep-lake periods also have been identified in this region. A few new facts about them, particularly of the younger pre-Lahontan lake, were discovered, but their history is much more obscure than that of Lake Lahontan because their deposits are rarely exposed.

Investigation of the lacustrine and climatic history of the Lake Lahontan area by means of detailed stratigraphic study was a principal subordinate objective of this project. Field studies were made principally in the bluffs along the lower Truckee River between Wadsworth and Nixon, and subordinately in the bluffs along the Humboldt River near Rye Patch. These studies developed new data that supplement the studies made by Morrison in the southern Carson Desert (Fallon) area for the U. S. Geological Survey (Morrison, 1961a, 1964a), and permit not only fuller and more detailed subdivision of the Quaternary stratigraphic successions, but also have furnished evidence of many additional large lake oscillations than were recognized from the earlier investigation. Three formations and a geosol are newly named and defined. The Quaternary stratigraphy of the Lake Lahontan area is presented here more fully because of new data, previously unpublished except for a brief summary of principal conclusions (Morrison, 1965c) and for descriptions of the Rye Patch Dam locality and several localities along the Truckee River between Wadsworth and Nixon that are published in the guidebook for INQUA Field Conference I (Northern Great Basin-California) (Morrison and others, 1965).

The Rye Patch and lower Truckee River areas are exceptionally favorable for stratigraphic study of the fluctuations of Lake Lahontan for two reasons:

(1) These areas are dissected to unusual depth; in each area as much as 200 feet of Quaternary deposits are exposed. This dissection is a consequence of late Quaternary tectonism that has locally reversed the usual progressive burial of older deposits by younger in a closed-basin system. The part of the Humboldt River Valley near Rye Patch Dam was strongly upwarped, partly in pre-Lake Lahontan, and partly in Lake Lahontan time. On the other hand, the Wadsworth-to-Pyramid Lake trough was intermittently downfaulted during Lake Lahontan time, and the basin of Pyramid Lake (which is the sink of the Truckee River) was the most strongly downfaulted. This caused marked lowering of base level and consequent strong dissection by the Truckee River.

(2) These areas were deltas, confined within fairly narrow intermontane basins, on two of the four largest rivers that fed Lake Lahontan. The relatively abundant supply of sediment from the rivers (as well as from mountain washes) has tended to produce thicker stratigraphic units in the successions of alternating lacustrine and subaerial sediments that record the various lake fluctuations. Many of these units are sufficiently distinctive in lithology so that they can be traced for miles in their respective areas, and some can be correlated between the two areas on the basis of lithology. Thus, these areas have

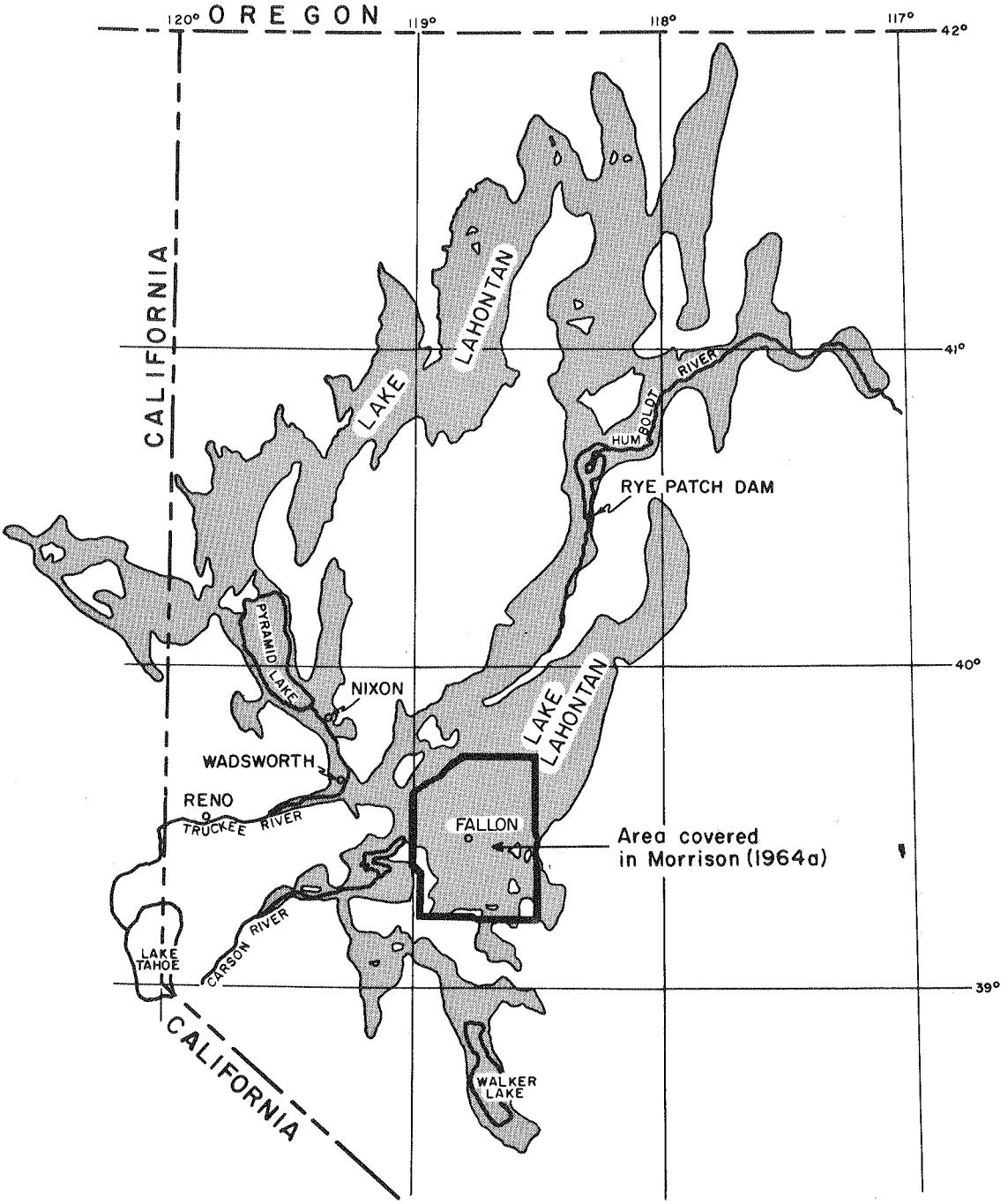

FIGURE 1. Index map of Lake Lahontan area showing locations described in text.

a fuller and more distinctive record of the smaller lake fluctuations than one can find in areas where only local sediment was available (such as most of the Carson Desert).

Both Russell (1885) and Antevs (1925) gave considerable attention to the superbly exposed thick successions in the two areas, and published descriptions of a number of stratigraphic sections in them. The study of these areas for the present project, however, is the first that utilizes modern concepts and methods of Quaternary stratigraphy (including soil stratigraphy). Available funds and professional time have been too limited to permit detailed study throughout these areas; only a mere sampling has been possible of

what appear to be the most informative localities. The work to date has produced many data that significantly supplement previous classifications of the Quaternary deposits and the interpretation of lacustrine history of this region. However, many important details remain to be discovered.

The field study in the Truckee River area consisted of general and detailed reconnaissance mapping of key localities by Morrison, supplemented by detailed measurement of stratigraphic sections at several of these localities mainly by Mrs. Margaret M. Wheat, assisted occasionally by Mr. Martin D. Mifflin and Mr. Alex Kraiscovits, all of the University of Nevada. Field work in the Humboldt River area was confined to a radius of a mile from Rye Patch Dam, and consisted of general reconnaissance mapping and measurement of several stratigraphic sections, by Morrison, Frye, Wheat, and Mifflin. The authors are particularly indebted to Mrs. Wheat and Mr. Mifflin for their assistance in noting and interpreting the stratigraphic evidence for various previously unrecognized lake fluctuations.

BASIS OF ROCK-STRATIGRAPHIC CLASSIFICATION

The rock-stratigraphic classification of Quaternary deposits in the Lake Lahontan area is designed to reflect the broad outline of the record of alternating lacustral and interlacustral intervals. The formations are of two lithogenetic types, lacustrine and subaerial (the latter type locally includes some very shallow lake sediments). The lacustrine formations are defined to represent the main lacustral periods, when the lakes generally were at intermediate and high levels. The subaerial formations represent, in given cases either of: (1) sediments coeval with and interwedging with those of a lacustrine formation; (2) deposits laid down during an interlacustral interval, and therefore intermediate in age between the preceding and following lacustrine intervals; (3) both of these conditions. Because the various formations record main depositional-climatic cycles or parts of these cycles, the formations also are geologic-climate units, although not specifically designated as such. The lacustrine formations (and also the subaerial ones of class 1 above) are analogous to deposits of a Glaciation in the western U. S.; likewise, subaerial formations of class 2 are analogous to those of an Intergalciation. Each lacustrine formation records a number of lake cycles of relatively short duration (albeit commonly of considerable amplitude) that are analogous to the stades of a Glaciation.

In spite of their cyclic pattern, individual lacustrine or subaerial formations generally have certain distinctive physical characteristics that enable the geologist to distinguish them one from the other, and to differentiate and map them in the same manner as conventional rock-stratigraphic units, rather than on inferred climate during deposition or on assumed age differences. The main differences are between lake and subaerial sediment relations, and therefore the formations are most clearly differentiated within the elevation range of interwedging lacustrine and subaerial formations. The subaerial formations at elevations above the lake maxima are differentiated by lithology of alluvial gravel, by proportions of alluvium and eolian sand, and by soils, but their boundaries commonly are less sharply defined.

ANALYSIS OF LAKE HISTORY

The lake maxima during the various lacustral intervals were determined by mapping the deposits of each significant lake cycle and observing their relations to shore features. The lake minumums were found by noting subaerial features developed on or intercalated

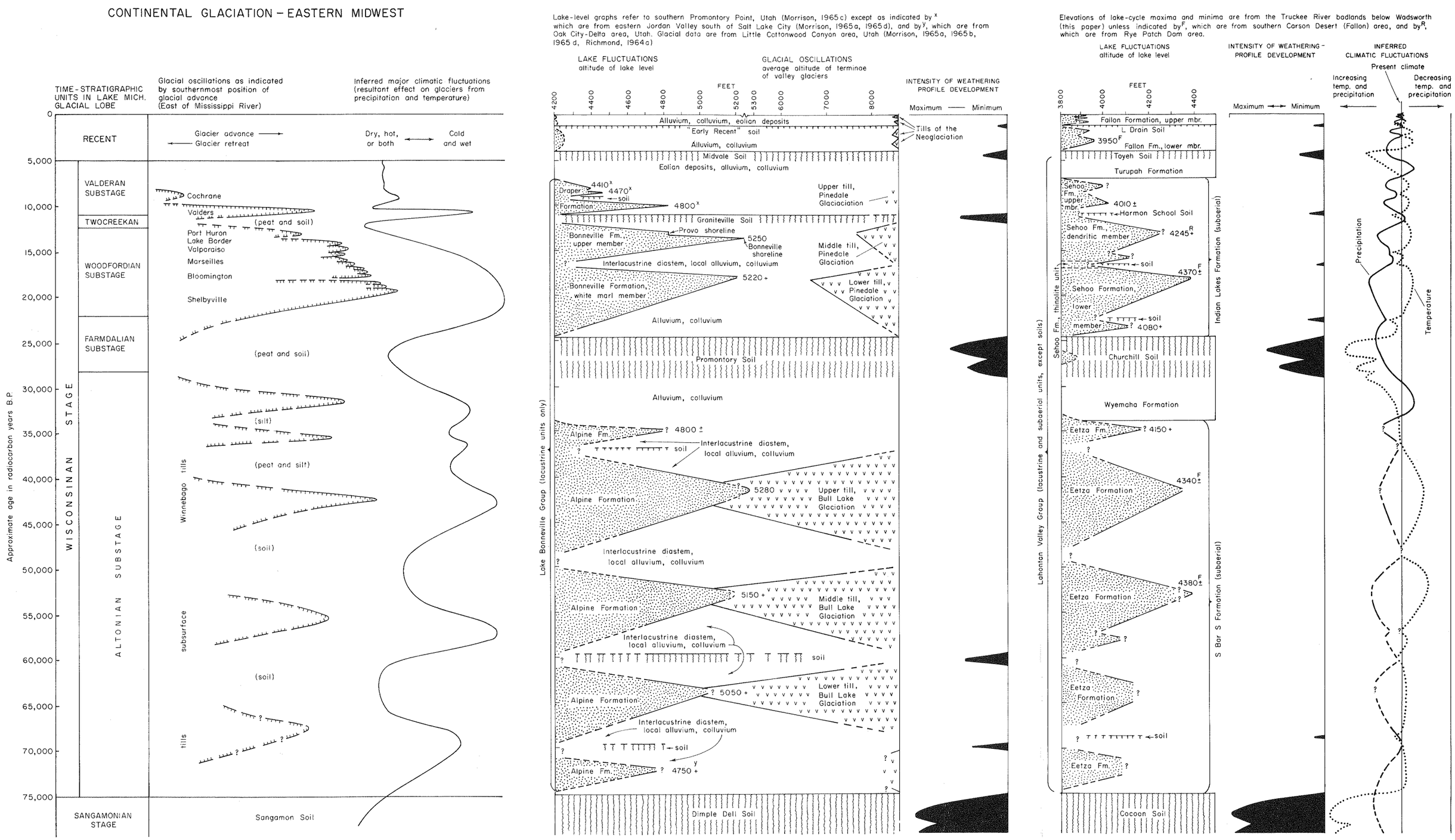

FIGURE 2. Comparison of the post-Sangamonian stratigraphy and inferred history of the oscillations of glaciers and pluvial lakes in the Eastern Midwest, Lake Bonneville, Wasatch Mountains, and Lake Lahontan areas.

with the lake sediments, and tracing those of a given age to their lowest altitude limit. These subaerial features include alluvial, colluvial, or eolian sediments, unconformities representing subaerial erosion, weathering profiles, mud cracks, sand dikes and dikelets, root casts and moulds, land-plant and march-plant remains in place, and coprolites. Subaerial exposure, or at least a major drop in lake level, is indicated by shore and near near-shore deposits such as algal tufa and lake gravel interbedded with deep-lake sediments. Tracing the subearial features was increasingly difficult toward the lower parts of the basins, therefore the lake minimums were at least as low as here indicated, and may have been still lower.

PRE-LAKE LAHONTAN UNITS

Stratigraphic units of pre-Lake Lahontan age were described in the reports of Morrison (1961a, 1964a) on the southern Carson Desert as, (a) pre-Lake Lahontan lacustrine sediments (a single exposure), (b) the Paiute Formation (alluvial and colluvial gravel), and (c) the Cocoon Soil (youngest). Studies in connection with the present project have expanded and refined the classification of the units (fig. 6). Two lacustrine units, the "older lacustrine unit" and the Rye Patch Formation, are now recognized. Each intertongues with, and is overlain by, a subaerial unit, respectively the Lovelock and Paiute Formations, that bears a strongly developed soil-stratigraphic unit (geosol)[1/]. The older lacustrine unit is correlated with the Kansan Stage, the Rye Patch Formation with the Illinoian Stage. The older geosol, the Humboldt Valley Soil, is correlated with the

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1/ Modern stratigraphic studies of Quaternary deposits in temperate and near-temperate regions show that the successions include sequences of weathering profiles that can be treated as stratigraphic units. A category of such weathering-profile stratigraphic units has recently been established and named "soil-stratigraphic units" (Amer. Commission on Stratigraphic Nomenclature, 1961). Morrison (1964b and in press) has proposed the name "geosol" as the fundamental soil-stratigraphic unit, to replace this usage of the term "soil" in order to avoid ambiguouity of meaning. He defines a geosol as

> "... a laterally traceable and mappable layer of distinctly chemically-weathered, predominantly mineral matter, formed immediately beneath and generally parallel with the land surface, that maintains a consistent stratigraphic (age) relationship to older and younger deposits with which it is associated, and is defined and used on the basis of this relationship within reasonably exact limits".

Geosols therefore are distinct stratigraphic entities; they have certain attributes like, and others unlike, those of both rock-stratigraphic units and unconformities. They may occur either buried by younger deposits (buried geosols) or exposed continuously at the land surface since they formed (relict geosols). Geosols may differ in their physical and chemical characteristics from one location to another because of changes in environmental weathering factors, such as climate, vegetation, drainage, and parent material. These lateral changes are called soil facies. The various geosols in Quaternary successions commonly differ from one another in degree of development. Each geosol, however, maintains the same general degree of development relative to the other geosols in the succession wherever it occurs in an area, in spite of changes in soil facies. For this reason, the more strongly developed geosols are excellent stratigraphic markers for differentiation and correlation of Quaternary deposits and landforms.

Yarmouth Soil, the younger geosol, the Cocoon Soil, with the Sangamon Soil of the Great Plains and Midwest.

The stratigraphic relations of all these units are best displayed in the bluffs of the Humboldt River near Rye Patch Dam and along the Truckee River between Wadsworth and Nixon, Nevada. The following summary refers mainly to the successions exposed in these areas.

Pre-Lake Lahontan lacustrine units

Older lacustrine unit. The older pre-Lake Lahontan lacustrine unit has been recognized only in small exposures at two localities: in the deepest gravel pits in western Wyemaha Valley, about 15 miles southeast of Fallon Nevada; and in the trench of the Truckee River a few miles above Nixon, Nevada; it is not known to be exposed along the Humboldt River. Snail shells from this unit at the first locality represent the extinct freshwater species "Paludestrina" and Lymnaea cf. L. bonnevillenis Call (identified by D. W. Taylor, U. S. Geological Survey) and are suggestive of middle Pleistocene age. A sample of these shells (L773-B) gave a C^{14} age of 40,000 years, and two determinations by the Th^{230} - U^{234} method gave an age of 330,000 $^{+110,000}_{-50,000}$ and 400,000 $^{+200,000}_{-70,000}$ years, respectively (Kaufman, 1964).

Rye Patch Formation. The younger pre-Lake Lahontan lacustrine unit is exposed in the deepest gravel pit in western Wyemaha Valley and in a few places along the Truckee River above Nixon, but its best known exposures are in the vicinity of Rye Patch Dam, in the bluffs of the Humboldt River valley. This unit is herewith newly named the Rye Patch Formation, and its exposures within a quarter-mile radius of the dam are designated as its type locality. The Rye Patch Formation is defined as the deposits of the ancient middle Pleistocene lake that existed in the approximate area which was subsequently inundated by Lake Lahontan, and which are younger than the Humboldt Valley Soil and older than the Cocoon Soil. The unit here is a maximum of about 30 feet thick. Its most conspicuous feature is a resistant, calcium carbonate-cemented bed of pebble gravel in its middle part that crops out on the west side of the river a few feet above the level of the dam spillway. This bed, 5 to 8 feet thick, is a shallow-water deltaic deposit. Imbrication of the gravel suggests a northerly source, but its bedding also commonly is inclined northward 5 to 20 degrees. This bed dips slightly upstream, opposite its original dip, as a result of up-arching of the Rye Patch Dam area. Benearth the cemented gravel bed is a zone 5 to about 15 feet thick, of lacustrine silt, clay, and locally sand and vitric volcanic ash; some beds have penecontemporaneous involution. Overlying the cemented gravel bed is another zone, about 12 feet thick, exposed west of the dam, of mainly lacustrine silt and clay with an intercalated thin bed of colluvium bearing a moderately strong weathering profile. This weathering profile, together with the alternations from deep-water silt and clay to deltaic gravel and back to silt and clay, show that the lacustral interval represented by the Rye Patch Formation had at least three lake cycles that rose well above 4,190 feet altitude, separated by lake recessions substantially below this level. The highest lake level during Rye Patch time is not definitely known. Mr. Mifflin (oral communication, 1964) reports possible lacustrine shore terraces, bearing a geosol at least as well developed as the Cocoon Soil, at elevations 80 $\pm$ 30 feet above the highest shoreline of Lake Lahontan at several places about the

periphery of Lake Lahontan, but these occurrences have not been investigated by the authors.

Inasmuch as the overlying Cocoon Soil is correlated with the Sangamon Soil, and the underlying Humboldt Valley Soil with the Yarmouth Soil, the Rye Patch Formation is correlated with the Illinoian Stage. It is interesting to note that the type Illinoian Stage in Illinois contains three distinct episodes of glacial advance and retreat.

Pre-Lake Lahontan subaerial units

Lovelock and Paiute Formations. Subaerial sediments of pre-Lake Lahontan Quaternary age are divided into two formations, the Lovelock Formation (oldest) and the Paiute Formation. Both formations are mostly alluvial gravel, but they grade locally into fine-grained alluvium, mainly silt and sand, in the basin interiors. They also locally include minor amounts of colluvium, eolian sand, and loess.

Each formation is defined on the basis of its relation to the two main pre-Lake Lahontan geosols, Humboldt Valley and Cocoon, which provide the only feasible markers for their differentiation. Inasmuch as each geosol was formed during a main interlacustral interval, the time of deposition of each subaerial formation started during a main lacustral (pluvial) interval and extended into the following main interlacustral interval. At elevations below the levels of the pre-Lahontan lakes these formations both intertongue with and overlie the pre-Lake Lahontan lacustrine formations. In the basin lowlands, such as the Truckee and Humboldt badlands, however, the intercalations with the lacustrine units are very local and thin, and the portions of the Lovelock and Paiute Formations that respectively overlie the lacustrine formations constitute the bulk of the subaerial units. At elevations above those reached by the ancient lakes, however, the bulky alluvial fan and pediment-gravel deposits that represent the subaerial units appear to have been mostly deposited during pluvial intervals contemporaneous with the lake deposits. The equivalents there of the subaerial units resting on the lacustrine deposits in the basin interiors may be scanty alluvium, eolian deposits, or even an unconformity at the top of the alluvial gravels.

The older pre-Lake Lahontan subaerial unit is here newly named the Lovelock Formation. Its type locality is the valley of the Humboldt River for a mile below Rye Patch Dam, where as much as 50 feet of it is exposed, underlying the Rye Patch Formation. It is named for Lovelock, the principal town in this sector of the Humboldt Valley, about 22 miles south of the type locality. The Lovelock Formation is defined as the subaerial Quaternary sediments in the Lake Lahontan and contiguous areas that are coeval with or older than the Humboldt Valley Soil. This unit at its type locality consists of poorly sorted silty to sandy and pebbly alluvium, intercalated with at least six weathering profiles, that together represent the Humboldt Valley Soil. In this low-lying situation the exposed Lovelock Formation represents only the older pre-Lake Lahontan interlacustral interval; however, this formation by definition also includes subaerial deposits correlative with at least the preceding main lacustral interval (i.e., with the older pre-Lake Lahontan lacustrine unit).

The Paiute Formation was defined in the southern Carson Desert area (Morrison, 1961a, 1964a) as alluvial and colluvial gravel of pre-Lake Lahontan Quaternary age that overlies andesitic and basaltic lavas of Pliocene and early Pleistocene(?) age with pronounced unconformity, bears the Cocoon Soil, and underlies the Eetza Formation with slight or no disconformity. Additional stratigraphic data obtained from the present study

permit of more precise definition of the lithology and lower boundary of this formation; accordingly in this paper the Paiute is restricted to include only those subaerial sediments (alluvial, colluvial, and eolian) that are intermediate in age between the Humboldt Valley and Cocoon soils, and including those that are coeval with the Cocoon Soil. Exposures of this formation near Rye Patch Dam show especially well its relations to the overlying deposits of Lake Lahontan and the Rye Patch Formation that here underlies it (Morrison and others, 1965, stop 2, Sept. 8). Other excellent exposures of the Paiute Formation beneath deposits of Lake Lahontan occur in several localities along the Truckee River between Wadsworth and Nixon (Morrison and others, 1965, stops 1 & 5, Sept. 9). In both areas the Paiute consists mainly of alluvium with minor eolian sand, and contains numerous intercalated weathering profiles that represent compounded occurences of the Cocoon Soil (see below). In these basin-interior areas nearly all of the Paiute lies between the Eetza and Rye Patch Formations, and hence represents the interlacustral interval correlative with the Sangamon interglaciation. The Paiute by definition, however, also includes the subaerial sediments that are coeval with and locally intercalated with the Rye Patch Formation (e.g., a thin bed of colluvium, on which a weathering profile is developed, in the upper part of the Rye Patch Formation near Rye Patch Dam). Hence, the Paiute is considered to range in age from Sangamonian through Illinoian. This is the sense in which it was used by Morrison (1964a).

The Lovelock Formation and the Humboldt Valley Soil, and likewise the Paiute Formation and the Cocoon Soil, have been noted as low as 3,930 feet altitude along the Truckee River. Hence, these units indicate that the lake was very low or completely dry during both of the two main pre-Lake Lahontan interlacustral periods.

Humboldt Valley and Cocoon Soils. The Humboldt Valley Soil, first called the pre-Cocoon soil (Morrison, 1965b), is the geosol that formed during the major interlacustral interval preceding the one in which the Cocoon Soil formed. As previously pointed out, at higher elevations on the piedmonts and in the highlands, the Humboldt Valley Soil generally is developed as a single weathering profile on alluvial and colluvial gravel of the Lovelock Formation. In some low-lying situations, however, this geosol is represented by more than one weathering profile, intercalated with beds of the Lovelock Formation. Such occurrences are said to be compounded. Where they can be traced upslope they invariably merge into a single very strongly developed weathering profile that is the characteristic profile of the Humboldt Valley Soil. Evidently the compounded profiles were formed in certain low-lying localities that were favorable for recurrent small increments of deposition during the Humboldt Valley soil-forming interval.

The type area of the Humboldt Valley Soil is the bluffs on both sides of the Humboldt River for 1 mile below Rye Patch Dam. This locality demonstrates well the stratigraphic relations of this geosol, which here is invariably compounded and represented by several (as many as six are known) separate weathering profiles. The soil is named for the Humboldt River Valley, which includes not only its type area but also numerous localities where this geosol is preserved as relict occurrences on the higher piedmont slopes at the edges of this valley. For example, the typical single, non-compounded profile of this geosol can be seen within 4 miles of the type area on the summits of remnants of the older set of alluvial fans along the front of the Humboldt Range to the east.

The Cocoon Soil, as originally observed in the southern Carson Desert (Morrison, 1964a), is a maximal Brown or Chestnut soil, developed on deposits as young as the youngest beds of the Paiute Formation, and underlying the earliest deposits of Lake Lahontan (Eetza Formation). No weathering profiles were observed at lower stratigraphic

levels within the Paiute Formation in the earlier work, possibly because the only exposures of this soil in the Carson Desert area are in the highlands and pediments at the edges of the basins. In the excellent basin-interior exposures investigated along the Truckee and Humboldt Rivers, the Paiute Formation generally contains many intercalated weathering profiles, ranging from weak to strong in degree of development, and separated by variable thicknesses (commonly a few inches to a few feet) of alluvium, colluvium, or eolian sand. At Rye Patch Dam ten separate weathering profiles have been identified, distributed through the total thickness of about 50 feet of the Paiute Formation. Such multiple weathering profiles within the Paiute Formation are considered to be compounded occurrences of the Cocoon Soil, for where the compounded weathering profiles can be traced upslope they merge into a single weathering profile that is considered the typical profile of the Cocoon Soil. From these relations it now is evident that the time of deposition of the Paiute Formation extended locally essentially throughout the whole Cocoon soil-forming interval.

Both the Humboldt Valley and Cocoon soils are similar in profile morphology in a given environment, and they parallel each other in environmental facies changes, although as a rule in a given environment the Humboldt Valley Soil is somewhat more strongly developed than the Cocoon Soil. In the desert lowlands these soils are very strongly developed (maximal) Brown (or locally Chestnut) soils with a deep reddish brown (generally hue 7.5 YR) and moderately to strongly structured textural (clayey) B horizon 1 to 2 feet thick, overlying a white, very strongly calcareous Cca horizon generally about 4 feet thick. In compounded occurrences the intensity of development of each weathering profile tends to decrease with the number of weathering profiles in the complex. At elevations above 4,800 to 5,300 feet (i.e., well above the highest shoreline of Lake Lahontan) they grade into Western Brown Forest and Brown Podzolic facies, with a minimal or no Cca horizon, and with considerably thicker B horizon.

LAHONTAN VALLEY GROUP

The Lahontan Valley Group (named for a part of the Carson Desert; Morrison, 1961a, 1964) consists of sediments deposited in Lake Lahontan and the interwedging and immediately overlying subaerial sediments (alluvium, colluvium, eolian sand, and loess). On the basis of lithologic differences due to two major alternations from mainly deep-lake to subaerial and very shallow-lake sediments, this Group is divided into six formations: the Eetza (lacustrine), S Bar S (subaerial), Wyemaha (subaerial and very shallow lake), Sehoo (lacustrine), Indian Lakes (subaerial), and Turupah (subaerial) Formations. The S Bar S Formation is newly named and defined in this paper; the other formations were named and described in the reports on the Carson Desert study (Morrison, 1961a, 1964a).

The exposures of the Lahontan Valley Group studied along the Truckee River, locally more than 150 feet thick, range in altitude from about 3,930 to 4,200 feet; those near Rye Patch Dam from 4,140 to 4,245 feet. The lowest exposures are within about 130 feet of the present level of Pyramid Lake, but the highest fall about 150 feet short of the highest Lake Lahontan shoreline (Lahontan Beach at 4,375 to 4,400 feet altitude). Consequently, the present study has concentrated on finding evidence of the lacustrine history within the low and intermediate range of the lake oscillations; further study elsewhere will be needed to provide data on the higher lake cycles, to supplement that obtained from the Carson Desert investigation. The recessions between the various lake cycles are recoreded by diastems due to subaerial erosion, by weathering profiles, by shore and shallow-lacustrine deposits intercalated with deep-lake sediments, and by interbedded alluvium and colluvium.

Deposits of early Lake Lahontan age

The oldest formations in the Lahontan Valley Group are the Eetza and S Bar S Formations, which are essentially contemporaneous and interwedge with each other. They both directly overlie the Paiute Formation and Cocoon Soil with slight or no disconformity, and underlie the Wyemaha Formation with local disconformity. The Eetza Formation is entirely lacustrine, and the S Bar S Formation is entirely subaerial. At least two weathering profiles are intercalated with the latter.

Eetza Formation. The Eetza Formation was defined in the Carson Desert (Fallon) area by Morrison (1961a, 1964a) as the oldest formation of the lacustrine sediments in the Lahontan Valley Group; alluvial and colluvial gravel coeval with the Eetza was designated informally. In that area it is exposed only in the highlands, and here consists largely of boulder gravel to pebble gravel, with very minor sand, silt, clay, and tufa. In both the Truckee and Humboldt River badlands, however, the Eetza is mainly silt, clay, and sand, with minor gravel, characterized by predominantly light grayish tones.

In the Carson Desert area several hillshore exposures showed a tongue of subaerial sediment (alluvium or colluvium), locally bearing a weak geosol, interbedded with the Eetza Formation. This was considered to be a single tongue. It was observed at altitudes as low as 4,060 feet, and is inferred to indicate a single lake recession at least this low during Eetza time. On this basis the Eetza was subdivided into lower and upper members. The lower member was traced to the highest shoreline of Lake Lahontan, about 4,380 feet altitude, and the upper member to about 4,340 feet. However, in the Truckee River badlands below Wadsworth, evidence has been discovered of probably six and perhaps seven or eight major intra-Eetza lake recessions. Evidence gleaned to date is not sufficient to determine the maxima of the higher Eetza Lakes, and the record of the earlier lake cycles of Eetza time is incomplete because of local removal of parts of the succession by periodic episodes of degradation by the ancestral Truckee River. In this area the two thickest silt-clay zones are in the upper two-fifths of the formation, and suggest that perhaps the two longest-lasting and perhaps deepest lake cycles were in relatively late Eetza time. However, in the bluffs east of Rye Patch Dam at least three deep-lake cycles of Eetza age rose well above 4,200 feet, and are indicated by thick zones of silt and clay between and overlying extensive gravel beds. From the record at this location it appears that a deep-lake cycle occurred fairly early in Eetza time in addition to the two later deep-lake cycles. On the basis of the Carson Desert study it is probable that one of the two earlier of the deep-lake cycles recorded at Rye Patch Dam rose to the highest shoreline, but which is not known.

Data on the absolute chronology of Eetza time are very few because the deposits of this age are beyond the usual range of the radiocarbon dating method. Several samples of gastropod shells and of tufa from the upper part of the Eetza Formation have all given ages greater than 34,000 to 40,000 years. They all have slight residual activity, however, and are perhaps only a few thousand years older than the range of the age determination method. Age determinations were made on two samples of snail shells by both the C^{14} and the Th^{230}-U^{234} methods (Kaufman, 1964). One sample (L772-P gave a radiocarbon (C^{14}) age of >34,000 years and a Th^{230}-U^{234}age (2 determinations) of

215,000 $^{+60,000}_{-45,000}$ years and 288,000 $^{+100,000}_{-70,000}$ years. The other sample (L773-L) gave a radiocarbon age of >38,000 years and a Th^{230}-U^{234} age (2 determinations) of 110,000 ± 15,000 and 125,000 ± 10,000 years. The Th^{230}-U^{234} ages seem to be much too old for material from the upper part of the Eetza Formation; it is doubtful if even the lower part of the formation is this old.

S Bar S Formation. The S Bar S Formation is herein newly named, and is defined as entirely subaerial sediments, contemporaneous and intertonguing with the Eetza Formation, that overlie the Paiute Formation and Cocoon Soil with moderate or no unconformity, and underlie the Wyemaha Formation with local unconformity. It consists of alluvium, some colluvium, and very minor eolian sand. The deposits included within this formation were formerly informally designated (Morrison, 1961a, 1964a) as alluvium and colluvium of Eetza age. The type area of the S Bar S Formation is the bluffs of the Truckee River valley in secs. 15 and 16, T. 21N., R. 24E. about 5 miles north of Wadsworth. The formation takes its name from the S Bar S Ranch, located on the west side of the type area.

Below the high shores of the various lake cycles of Eetza age, the S Bar S Formation locally interwedges with the Eetza Formation. The various wedges of the S Bar S consist mainly of thin, highly lenticular beds of alluvium or colluvium that can be differentiated locally. At present they are not designated formally or informally as specific stratigraphic units. Figure 2 indicates the presently known lowest elevations reached by the various wedges. In the southern Carson Desert area a weak geosol, developed on colluvium of the S Bar S Formation, was noted locally to altitudes as low as 4,060 feet intercalated between gravels of the Eetza that probably represent the last two lakes of Eetza age that rose to the high-shore zone (above 4,300 ft). In the Truckee badlands below Wadsworth one of the lower wedges of the S Bar S locally bears a weak geosol.

Above the high shores of the Eetza lakes, the S Bar S Formation is not readily subdivided because it consists mainly of fan gravel and minor colluvium, without marked vertical differences in lithology.

Units of middle Lake Lahontan age

Two essentially subaerial units, the Wyemaha Formation and the Churchill Soil, record the longest interval of desiccation and near-desiccation of Lake Lahontan, in middle Lake Lahontan time.

Wyemaha Formation. The Wyemaha Formation was defined for the Carson Desert area (Morrison, 1961a, 1964a), where it mainly consists of eolian sand, and locally alluvium and colluvium (slope wash), although in the lowlands below about 3,980 feet altitude the subaerial facies intertongue with shallow-lake sand, silt, and clay.

In the Truckee River badlands the Wyemaha is entirely subaerial, and alluvium predominates; it is commonly 20 feet and rarely more than 50 feet thick. Generally it is very sandy, and much of it is relatively angular fan gravel derived from washes tributary to the river; locally the deposits have lithology indicating deposition from the Truckee River (see Morrison and others, 1965, stop 5, Sept. 9). These deposits have a general yellowish to light-yellowish-brown cast; their hue and gravelly character together distinguishes them from the other gravelly units in the Lahontan Valley Group. The Wyemaha comprises only part of the "medial gravel" of Russell (1885). The remainder of the "medial gravel" includes lacustrine sand and gravel of the uppermost part of

the Eetza Formation, as well as transgressive gravel and sand of the lower member of the Sehoo Formation.

Alluvium and/or eolian sand of the Wyemaha Formation is exposed at least as low as 4,000 feet altitude in the Truckee badlands a few miles south of Nixon, and as low as 3,930 feet in the southern Carson Desert, where it also was identified in the subsurface (from well logs) at least as low as 3,850 feet.

Churchill Soil. The Churchill Soil is a relatively mature geosol that developed during the mid-Lake Lahontan desiccation interval. In the southern Carson Desert, where it was first described and named (Morrison, 1961a, 1964a), it was observed merely as a single weathering profile, older than the Sehoo and Indian Lakes Formations, and formed on deposits ranging as young as the youngest subaerial beds of the Wyemaha Formation; hence it was considered to postdate the Wyemaha. In the basin-interior exposures along the Truckee and Humboldt Rivers, however, this geosol commonly is represented by two or three weathering profiles, intercalated with a few inches to several feet of alluvium, colluvium, or eolian sand of the Wyemaha. Traced into higher areas, the various soils of the complex merge into a single profile, which is the usual profile of this geosol. The compounded weathering profiles record local minor increments of deposition during the Churchill soil-forming interval. Thus, it now is evident that minor deposition of Wyemaha deposits continued locally throughout most of Churchill time. Where the compounded Churchill Soil has been preserved without significant subsequent erosion, the upper weathering profile always is the more strongly developed. It is chosen as the boundary between the Wyemaha and older deposits, and those of Sehoo-Indian Lakes age.

The Churchill Soil, where it has been developed as a single weathering profile, typically is a strongly developed Brown soil, with a deep brown, slightly clayey B horizon 9 to 18 inches thick, either massive or with weak to moderate prismatic or blocky structure, overlying a strongly calcareous Cca horizon 2 to 3 1/2 feet thick, — the usual facies of this soil in the basins and lower mountains of the Lake Lahontan area. At elevations above about 5,500 feet the soil changes to pedalfer facies, generally Brown Podzolic soils.

Age. Several samples from the upper part of the Wyemaha Formation in the lowlands of the Carson Desert have yielded finite radiocarbon ages ranging from 27,500 to 33,500 years (Broecker and Kaufman, 1965). A sample (L483G) of the Cca horizon of the Churchill Soil from its type locality gave an age of 26,300 $\pm$ 1,000 years (W. S. Broecker, written communication, 1962). On the basis of the available radiocarbon dates and stratigraphic evidence, the Churchill soil-forming interval is estimated to have begun 30,000 $\pm$ 2,000 years ago to have ended about 25,000 $\pm$ 2,000 years ago. It probably was considerably more than 1,000 years in length, likely several thousand but probably not much more than 5,000 years long. Deposition of the Wyemaha Formation probably began several thousand years earlier than did the soil development.

Units of late Lake Lahontan age

Two formations, the Sehoo and Indian Lakes Formations, represent late Lake Lahontan time. These, like the Eetza and S Bar S Formations, are interwedging, contemporaneous units. The Sehoo is entirely lacustrine and the Indian Lakes is subaerial except for minor swamp and very shallow lake sediments in sink areas. The various wedges of the Sehoo Formation record a succession of at least six lake cycles of this age, and below the high shorelines of the Sehoo-age lakes these are in places intercalated with wedges of the Indian Lakes Formation and/or unconformities and weak weathering profiles. Both formations overlie the Wyemaha Formation and Churchill Soil with slight or no disconformity, and underlie the Turupah Formation with local disconformity.

Sehoo Formation. In the study of the southern Carson Desert (Morrison, 1961a, 1964a), the Sehoo Formation was divided into lower, dendritic, and upper members on the basis of three major lithologic divisions (wedges) that were inferred to record three successive lake cycles that reached maximum altitudes of 4,370, about 4,190, and about 3,990 feet respectively. Recent studies have shown, however, that each of these members records not one but two lake cycles. These six lake cycles of Sehoo age were separated by lake recessions to at least as low as 4,000 feet, and perhaps several to lake levels as low as those of modern time.

In addition to lacustrine gravel, sand, silt, and clay, the Sehoo contains an abundance of tufa. All these facies are distinctive among the three members and their subdivisions in minor lithologic details. The tufa deposits occur at certain stratigraphic horizons, and generally those of a certain age are morphologically distinct from those of other ages, thereby making the various types of tufa stratigraphic markers. Most of the tufas were deposited by algae, and such types range from dense stony (lithoid) to spongy forms and to the aborescent variety called dendritic tufa (which is characteristic of the dendritic member of the Sehoo). Also present and distinctive of certain stratigraphic horizons that record lake-recessional intervals is the inorganically deposited crystalline variety called thinolite.

Indian Lakes Formation. The Indian Lakes Formation consists of subaerial sediments, mainly alluvium with some colluvium and very minor eolian sand, equivalent in age to the Sehoo Formation and locally interwedging with it below the high shorelines of the Sehoo lakes. In the lowlands of the Carson Desert this formation also includes minor amounts of very shallow lake and marsh sediments, but such sediments have not been identified in the Truckee badlands area. The various wedges of this formation found between the members and lake-cycle units of the Sehoo Formation are designated informally.

Lake oscillations of Sehoo age. The first lake cycle of Sehoo age is recorded by the lower unit of the lower member of the Sehoo Formation, which is well exposed along the Truckee River within 7 miles south of Nixon (see stops 4 and 5, Sept. 9 in Morrison and others, 1965). This unit has not been traced higher than about 4,080 feet altitude, and it is doubtful if the lake cycle that it records rose much higher than this. The subsequent lake recession is recorded by a local wedge consisting of a few inches to several feet of colluvium and alluvium of the Indian Lakes Formation that locally bears a moderately strong weathering profile, and also by a minor unconformity and by deltaic shore gravel; by these criteria it has been traced to elevations as low as 4,000 feet along the Truckee River.

The second lake cycle is represented by the main part of the lower member, which is the thickest lake-cycle unit of the Sehoo, and which in the basin lowlands also contains the highest proportion of silt and clay. In the Carson Desert this unit was traced to the highest shoreline of Sehoo age, at 4,370 feet altitude (here only 10 feet below the "Lahontan Beach" of Russell (1885), the highest Eetza shoreline). Algal tufa deposits that are correlated with this unit and in places interbedded with it, locally extend to within 15 feet of the highest Sehoo shoreline in the southern Carson Desert (and slightly higher in the Pyramid-Winnemucca Lake area). For some unexplained reason, however, the radiocarbon ages of all samples of tufa from the high-shore zone (4,300 to 4,370 feet altitude) are considerably younger than expected (perhaps by 6,000 to 8,000 years) on the basis of the local stratigraphic relations, on certain "landmark" radiocarbon dates, and on the interregional correlations proposed in this paper. This problem is discussed further in the next section.

The lake recession of this second cycle, called the thinolite recession, was marked by extensive deposition of thinolite in both the Carson Desert and Pyramid-Winnemucca Lake areas. This recession is proven to have gone at least as low as 3,990 feet altitude in the Carson Desert and at least as low as 3,960 feet in the Truckee River valley.

The third and fourth lake cycles are recorded by the dendritic member of the Sehoo Formation. Both were marked by deposition of slightly different varieties of dendritic tufa. The first dendritic lake may have risen no higher than to about 4,100 feet altitude, judging from preliminary data from the Truckee badlands. Subsequently, the lake has been proven (by unconformity caused by trenching by the Truckee River) to have receded in this area to as low as 4,040 feet and probably considerably lower. The maximum of the second dendritic lake (fourth cycle) was difficult to ascertain exactly in the southern Carson Desert, because in that area the lake maximum is only poorly marked by distinctive deposits or shore-morphologic features. It was therefore conservatively placed at 4,190 ± feet altitude (Morrison, 1961a, 1964a). However, subsequent observations near Rye Patch Dam and near Lovelock have positively identified deposits assigned to this lake cyle (including dendritic tufa) as high as 4,245 feet altitude, and it seems likely that they may extend somewhat higher.

The lake recession between the times of deposition of the dendritic and upper members of the Sehoo is recorded by a local wedge of alluvium and colluvium of the Indian Lakes Formation, by an unconformity, and by the weak L Drain Soil. It is known to have receded to at least as low as 3,900 feet in both the southern Carson Desert and Truckee River areas. At this time the inner valley of the Truckee River north of Wadsworth was dissected to nearly its present depth and configuration. This valley was inundated by the last two lake cycles of Sehoo age, as recorded by the upper member of the Sehoo Formation. The first of these late Sehoo-age lakes rose to about 4,010 feet altitude, and the second perhaps to about 3,990 feet; a recession of unknown magnitude intervened between these lake cycles. A separate lake existed during late Sehoo time in the Carson Desert - Lovelock area because of intervening topographic divides. Only a single lake maximum has been identified in this area, at about 3,990± 10 feet altitude.

Radiocarbon chronology of the lake fluctuations of Sehoo age. To date, about 65 radiocarbon age determinations have been made from samples from various parts of the Sehoo Formation, making this unit one of the most intensively dated in the United States. All of the determinations were made on carbonate materials (snail and ostracod shells, algal tufas of various kinds, and thinolite). In addition, 5 radiocarbon dates have been obtained from subaerially-deposited organic materials of Sehoo age (wood, rat dung, and bat guano). Nearly all of these determinations were made under the direction of Dr. W. S. Broecker, of Lamont Geological Observatory, Columbia University, in connection

with a project (supported mainly by grants from the National Science Founcation) to explore the validity of radiocarbon dating of the deposits of Lakes Lahontan and Bonneville, particularly carbonate deposits. Morrison supplied many of the samples and much of the stratigraphic information from both pluvial lake areas for this study.

Broecker and Kaufman (1964) concluded from this investigation that radiocarbon ages of pluvial lake carbonates less than 25,000 years old are in almost all cases reliable to within ± 1,000 radiocarbon years. However, these workers virtually ignored the stratigraphic assignments of the samples in making their appraisal; their evaluation was based almost entirely on geochemical considerations. Unfortunately, we cannot concur with their conclusion as to the relatively high reliability of radiocarbon dates from pluvial lake carbonate deposits, on the basis of our own evaluation of the radiocarbon ages combined with the stratigraphic associations of the samples from Lakes Lahontan and Bonneville. A full analysis of the problems involved cannot be given here but a summary is presented in Morrison and Varnes (1965).

As pointed out in the above paper, nearly all the subaerial (non-pluvial lake) and the interglacial very-shallow-lake-level age determinations from the Lake Lahontan and Lake Bonneville areas seem to fit well the Midwestern radiocarbon chronology (see Frye and Willman 1960, 1963; Frye, Willman, and Black, 1965) in the manner that this chronology has been linked to the Lake Lahontan area by the interregional correlation scheme outlined in this paper (based on both soil stratigraphy and matching the records of similar climatic cycles that are manifest in the depositional successions of the various areas). Specifically, the finite radiocarbon dates from the upper Wyemaha and Churchill Soil (mentioned above) seem to "fit". Another, probably important, age that "fits" is 28,000 years (average of 2 runs) from lithoid tufa (sample L687A) from the extreme base of the Sehoo Formation at the southern edge of the Carson Sink. This sample came from a location where, on the basis of detailed stratigraphic study involving numerous measured stratigraphic sections, logged boreholes, and relations to a key volcanic ash bed, the basal Sehoo appears to overlap timewise into the terminal Wyemaha-Churchill interval. It should also be noted that the radiocarbon age is similar to that from the Cca horizon of the Churchill Soil at its type locality (26,300 ± 1,000 years); this is as it should be on the basis of the stratigraphic relationships in this area.

Succeeding the latter two determinations in the assemblage of radiocarbon age determinations occurs a perhaps significant gap of nearly 7,000 years. This gap has persisted in spite of attempts to bridge it by samples of radiocarbon-dateable materials from stratigraphic horizons thought to be only slightly younger. Moreover, nowhere in the lowlands of the southern Carson Desert is there evidence of unconformity in this part of the stratigraphic succession.

Following this gap, in the interval from 19,500 to 8,500 years fall all the remaining radiocarbon age determinations from samples of Sehoo age. Several clear age-reversals, in terms of stratigraphic succession, occur in this assemblage (Morrison, 1965g). Particularly significant is the fact that all the age determinations from the high-shore zone (4,300 to 4,370 feet altitude) fall between 11,800 and 9,500 years, in spite of the fact that all these determinations are from algal tufa from deposits correlated with the lower member of the Sehoo Formation (in some cases occurring buried, intercalated with shore gravel of this member). On the basis of the detailed stratigraphic study of the southern Carson Desert (Morrison, 1964a) the lower member, including these tufa deposits, was inferred to record the highest lake maximum of Sehoo age, at about 4,370 feet altitude. No stratigraphic evidence has been found in the course of subsequent studies that invali-

dates this conclusion. Obviously, either the stratigraphic interpretation or the radiocarbon age determination from the high-shore tufas is in error. Data adequate to resolve this dilemma are not available at present.

The 7,000-year gap in radiocarbon ages from the earlier Sehoo, together with other considerations, however, suggests the possibility that all the radiocarbon ages from carbonate materials from the Sehoo are considerably too young, particularly those from the higher shores. The most obvious hypothesis to explain radiocarbon ages that are too young is to assume that contamination by younger carbonaceous material has occurred (for example, by replacement of carbon in carbonate). This possibility has been well explored (Broecker and Orr, 1958;) Broecker and Kaufman, 1965) and does not appear to be a significant factor in the majority of cases. However, there is a possibility, not yet adequately explored, that during the rise of a pluvial lake after an interlacustral interval, enrichment of C^{14} with respect to C^{12} somehow takes place in the lake water, perhaps as a result of gravitative fractionation of the isotopes. Such a mechanism might explain the apparently too-young ages from carbonates on the intermediate and higher-level shores. Because of the serious uncertainties in the higher-shore radiocarbon dates, we prefer for the present to disregard these dates, relying instead on certain "landmark" dates from the subaerial deposits and lower interlacustral lake levels. To fill in the lacustrine chronology between these "landmarks", Morrison has used the pertinent portions of the relative-age sequence of lake fluctuations that have been inferred from his detailed stratigraphic studies. Among the "landmark" radiocarbon ages used are those from the following samples: (1) the above-cited sample (L687A) of tufa at the extreme base of the Sehoo; (2) two samples (L662L and L483P, averaging 17,550 years) of thinolite from the thinolite unit of the Sehoo, marking the "thinolite" lake recession, between the times of deposition of the lower and dendritic members; and (3) three samples (L676A, L245, and C281) of subaerial organic materials from caves that immediately overlie the youngest lacustrine deposits in these caves. On the basis of this chronologic scheme it is apparent that the radiocarbon ages of the tufas from the high-shore zone are 6,000 to 8,000 years too young. The highest Sehoo lake maximum is inferred to have occurred in early (pre-dendritic) Sehoo time, about 18,000 years ago. Such a date is consistent with the maximum extent of continental glaciation in the Midwest.

This interpretation contrasts with that of Broecker and Kaufman (1965), who postulate that the highest lake maxima of Sehoo time occurred twice during the dendritic Sehoo, about 12,000 and about 9,500 years ago; a major lake recession is inferred between these two lake maxima. This interpretation is based on two clusters of radiocarbon ages from the high-shore zone, centering around 12,000 and 9,500 years. At least some of the tufa samples from both clusters seem to be from identical stratigraphic horizons, however. Moreover, the major lake recession between these two lake cycles about 11,000 years ago is based on samples of subaerial organic material from caves at comparatively low elevations -- yet in no case are these subaerial beds overlain by lacustrine deposits, as would be expected if the caves had been inundated by the postulated second lake rise to the highest Sehoo shoreline 9,500 years ago.

Units of post-Lake Lahontan age

Turupah Formation. The Turupah Formation is an entirely subaerial unit, the youngest formation in the Lahontan Valley Group. In both the Carson Desert and Truckee badlands areas it consists mainly of eolian sand, with minor local tongues of alluvium and colluvium. It overlies the Sehoo and Indian Lakes Formations with local disconformity, and bears the Toyeh Soil (where this geosol has not been eroded). This unit is coeval with a widespread disconformity in the basin lowlands that records pronounced deflation. In the Carson Desert, both the Turapah and this disconformity extend to the lowest parts of the basin floor, and indicate a long period of desiccation after the final drying up of Lake Lahontan. The Turupah is correlated with the early part of the altithermal age of Antevs (1948, 1952).

Toyeh Soil. The Toyeh Soil (Morrison, 1964a) is one of the most widely distributed and best-preserved geosols of the Lake Lahontan area. It marks the top of the Lahontan Valley Group. It is a submature (moderately developed) Desert (formerly Gray Desert) soil, found on deposits as young as the upper part of the Turupah Formation, and is overlain by the Fallon Formation with slight or no disconformity. The Toyeh is less than half as well developed as the Churchill Soil. It is characterized by a pale gray "vesicular" A-horizon 1 to 4 inches thick; a light-brown, light-brownish gray, or brown, generally non-textural (non-clayey) B-horizon, about 5 inches thick, generally massive (unless salt-affected), overlying a light-gray to light-brownish-gray Cca horizon that is moderately to weakly calcareous and 6 to 14 inches thick. In poorly-drained lowlands this geosol locally is salt-affected and grades into solonetz-type facies. At elevations above about 4,300 feet the Toyeh Soil grades into pedalfer facies, such as Western Brown Forest, Gray-brown Podzolic, Brown Podzolic, and Prairie (Brunizem) Soils.

According to radiocarbon and archaeologic dating this geosol formed during an interval about 1,000 $\pm$ 500 years long that ended about 4,000 to 3,800 years ago. This interval is correlated with the late part of the altithermal age of Antevs. The Toyeh Soil and its equivalents elsewhere in the Great Basin has been proposed as the logical marker for the boundary between the Pleistocene and Recent Epochs (Morrison, 1961c, 1965f.

FALLON FORMATION

The Fallon Formation consists of subaerial sediments (alluvium, colluvium, and eolian sand and loess) of Recent age, that in the lowermost basins, such as the Carson Desert, inter-tongue with shallow-lake sediments. It overlies the Turupah Formation and Toyeh Soil with slight or no disconformity (but locally is markedly disconformable upon the Sehoo and even older units because of widespread intense deflation during Turupah time). Its type locality is the lowlands of the Carson Desert near Fallon (whence it takes its name), although it is widely distributed throughout the entire region, in both highlands and lowlands.

A weakly developed geosol, the L-Drain Soil (Morrison, 1964a) is locally intercalated with the Fallon Formation. The portion of the Fallon that is older than this geosol is designated as the lower member, and the portion younger as the upper member. In the Carson Desert-Lower Humboldt Valley area the lower member includes two wedges of shallow-lake deposits that extend to maximum altitudes (marked also by high shorelines) of about 3,950 (oldest) and 3,930 feet. The upper member in this area includes three lacustrine wedges whose maxima were at 3,922, 3,919, and 3,919 feet altitude. Intervening subaerial tongues extend to or nearly to the lowest parts of this basin, indicating

complete or almost complete lake desiccation between each of these five Fallon-age lake rises. The longest, driest, and warmest recession was between the second and third Fallon-age lakes, when the L-Drain Soil was formed.

The lacustrine tongues of the Fallon Formation have scarcely been studied in the Pyramid Lake -Winnemucca Lake area. A well-marked shoreline at about 3,950 feet altitude in this area, bearing the L-Drain Soil, is believed to be correlative with the first Fallon Lake (also at 3,950 feet altitude) in the Carson Desert.

The Fallon Formation was deposited during the last 4,000 or so years. The first Fallon lake maximum occurred about 3,500 years ago, the last one about 100 years ago. The L-Drain soil-forming interval probably lasted less than 250 years.

Lake Bonneville area

Lake Bonneville comprises the series of lake fluctuations of post-Sangamonian, pre-altithermal (hence pre-Recent) age, and was the largest late Pleistocene pluvial lake in North America (fig. 3). At its maximum it inundated nearly 20,000 square miles in a number of contiguous intermontane basins in the northeastern Great Basin, mainly in western Utah, and attained a maximum depth of about 1,100 feet.

Interpretations of the history of the lake fluctuations by various geologists have differed considerably; those of the principal earlier workers are summarized in Morrison (1964a, 1965b). Detailed stratigraphic studies, especially since 1962, mainly by Morrison, have considerably modified the earlier interpretations. Many additional lake oscillations now are recognized than in the studies of a few years ago, and correlations with the Rocky Mountain glacial succession have been revised significantly. Morrison's latest interpretation of the stratigraphy and history of lake fluctuations in the Lake Bonneville area is given in two papers (1965b, 1965c) and will not be repeated here. It should be noted that data presented in these papers substantially modify his earlier (1965a) stratigraphic classification, interpretation of lake history, and correlation with the Rocky Mountain glacial succession, publication of which unfortunately was delayed so that it coincided with the later papers. The stratigraphic terminology used at present, and the inferred lake fluctuations are given in figure 2.

RADIOCARBON CHRONOLOGY OF LAKE BONNEVILLE

About 80 radiocarbon age determinations have been made from the sediments of Lake Bonneville and associated subaerial deposits (fig. 4). Most of these determinations were made under the direction of Dr. W. S. Broecker at Lamont Geological Observatory, Columbia University, in connection with his investigation of the validity of radiocarbon dates from pluvial lakes. Many of the same problems appear in connection with the Lake Bonneville dates as with those from Lake Lahontan, but generally to somewhat less degree.

In general, nearly all the radiocarbon dates derived from subaerial units are reasonably consistent with the lake-cycle chronology based on our interregional correlation scheme. Among the "landmark" radiocarbon dates that we chose to use as main tie-points for the framework of the radiocarbon chronology of Lake Bonneville, are the following:

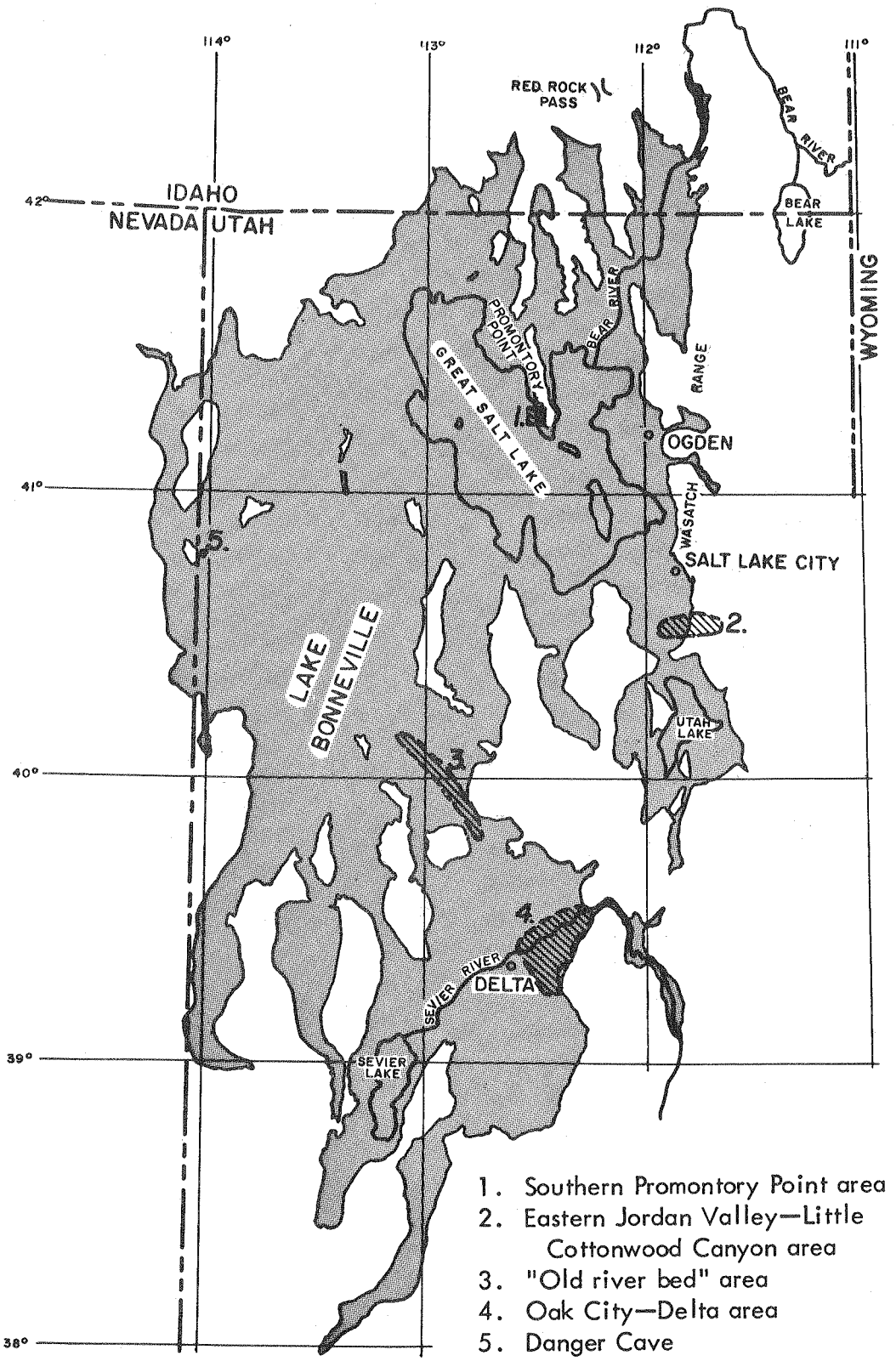


FIGURE 3. Index map of Lake Bonneville area showing locations described in text.

(1) Two samples of wood from the base of the white marl member of the Bonneville Formation, at Little Valley, Promontory Point; sample W-876 from about 4,775 feet altitude gave a date of 20,600 ± 500 years, and sample L-775N, from about 4,650 feet gave 20,800 ± 300 years. These dates are believed to be fairly reliable for the transgression of the white marl lake cycle at these altitudes.

(2) Two samples (L-775I and L-775J) of snail shells from a lens of lake-reworked alluvium between the white marl and upper members of the Bonneville Formation, also from Little Valley, at about 4,890 feet altitude gave ages of 15,300 ± 400 and 15,400 ± 300 years, which are considered to be fairly reliable for the transgression of the later lake cycle of Bonneville Formation time -- the lake cycle that rose to the Bonneville shoreline proper and overflowed at Red Rock Pass.

(3) Two samples (L679A and L774D) of land-snail shells from alluvium of inter-Bonneville-Draper age at about 4,780 feet altitude from the Delta, Utah area, which gave dates of 11,900 ± 400 and 11,600 ± 200 years. These date the recession between the last cycle of Bonneville Formation time and first cycle of Draper age, when the Graniteville Soil was formed.

(4) A sample of the Cca horizon of the Promontory Soil from 4,780 feet altitude near Delta, Utah, gave an age of 23,600 ± 1,000 years. Inasmuch as this soil is correlated with the Churchill Soil and the Farmdalian substage, this date may be as much as 3,000 years too young. Perhaps this appears to be too young because the Cca horizon of the Promontory Soil has here been somewhat contaminated by younger carbon. This sample came from a buried occurrence of this soil, where it is directly overlain by the highly calcareous white marl member.

Broecker & Kaufman (1964, 1965) postulate that the "white marl" lake cycle rose to the Stansbury level (about 4,500 feet altitude) about 19,500 years ago, reached the Provo level (about 4,800 feet) about 18,000 years ago, and the Bonneville level about 14,000 years ago. This chronology not only does not agree with that indicated by our correlation scheme, but also makes use of only certain of the many radiocarbon ages available from the transgressive phase of the white marl member. By selecting other radiocarbon age determinations, cases could be made for the white marl lake transgression reaching the Stansbury level 25,500 or 22,250 years ago, and also up to several thousand years earlier than 19,500 years ago. Similarly, the three determinations (all from tufa) within 50 feet of the Bonneville shoreline have given ages of 23,150 ± 1000 (sample L-363H) 15,650 ± 300 (sample L-483BB), and 12,500 ± 500 (sample L-672H) years.

After careful evaluation of all available radiocarbon dates from the Lake Bonneville area in terms of the stratigraphic assignments of the samples, Morrison (1965g) concluded that the radiocarbon dates from carbonate samples are erratic, as follows:

Some of these dates, particularly from samples deposited when Lake Bonneville was at levels at and below the Provo shoreline (about 4,800 feet altitude) seem to fit well into the lake-cycle chronology indicated by the "landmark" radiocarbon dates, supplemented by the history of lake oscillations derived from the detailed stratigraphic studies. Dates that "fit" include those from the base, middle, and top of the white marl member of the Bonneville Formation at several widely separated localities (chiefly the southern Promontory Point, Old River Bed and Delta areas). However, the dates that "fit" are only certain, selected ones: other dates from the same stratigraphic horizon and altitude as the dates that "fit", from the same or different localities, commonly differ by 2,000 or more years. A series of dates from a single marl bed near the base of the Alpine Formation near Delta, Utah ranges from "dead" (32,000 years) to about 15,000 years.

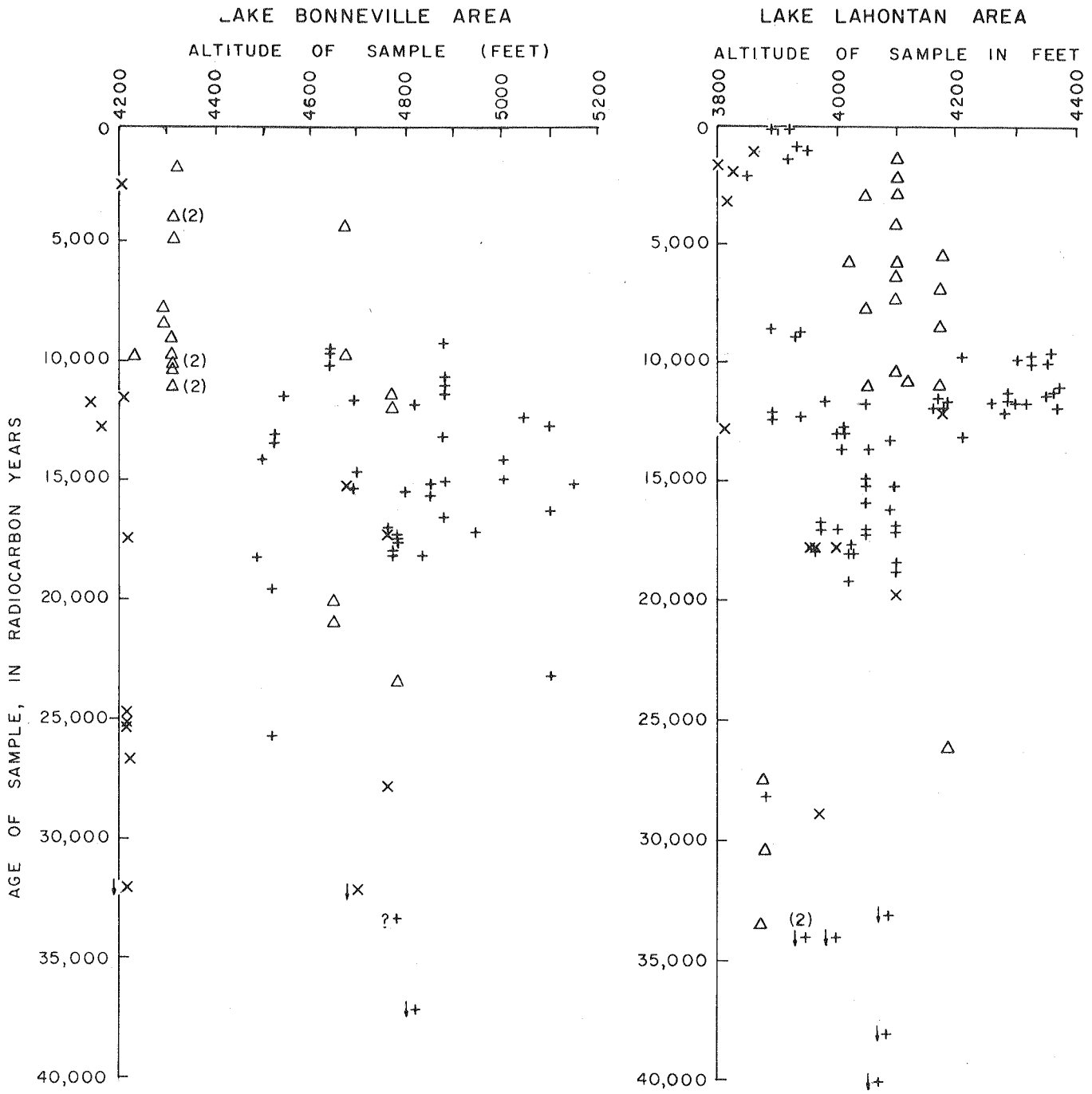


FIGURE 4. Radiocarbon ages of samples from the Lake Lahontan and Lake Bonneville areas, plotted against sample altitude. Samples are classified according to their depositional environment (subaerial, near-shore, and deeper-lacustrine) but their stratigraphic assignments are ignored.

Much has been made of the "internal consistency" of sequences of radiocarbon dates from a few selected stratigraphic localities. Many conflicts between dates become apparent, however, on comparing dates from similar sequences elsewhere. An example of a clear conflict is the sequence of dates from Danger Cave, which, combined with the physical stratigraphic record, would indicate that this cave, whose floor is only a little more than 100 feet above Great Salt Lake, became dry at least 11,500 years ago and was never again inundated by Lake Bonneville. However, a group of five radiocarbon age determinations from marl and lignitic silt near the base of a sequence of lacustrine sediments of the Draper Formation, at about 4,700 feet altitude near Ogden, Utah, range from 9,450 to 10,050 years, averaging about 9,800 years. If we believe that both sets of radiocarbon dates are valid, then we must also believe that about 9,800 years ago Lake Bonneville rose 400 feet above Danger Cave while the cave remained dry.

In view of the numerous dilemmas between the radiocarbon dates and the stratigraphy, we can only affirm the statement made by Eardley and others (1957, p. 1171) concerning the radiocarbon chronology of Lake Bonneville: "The results are inconsistent, and, at present, baffling."

The proposed time-stratigraphic standard for the Great Basin

In a following section entitled "Means of correlation" we conclude that Quaternary correlations are best made on a time-stratigraphic basis, that weathering profiles (geosols) are generally the most effective time-stratigraphic markers for correlating successions in various types of lithogenetic terrains, and that geosols also are not only valid, but probably generally the best, units for defining Quaternary stages and substages. In order to implement this philosophy, we herewith propose a provincial time-stratigraphic standard for the middle and late Quaternary successions of the Great Basin (figs. 6, 7).

Each of the various stages and substages is bounded by a geosol; its upper boundary is the top of a main geosol and it extends downward, through intervening deposits, to the top of the next-lower main geosol. The main (more strongly developed) geosols were formed during main interlacustral-interglacial intervals. Thus a stage includes the interval of time represented by deposits laid down during a main lacustral-glacial interval (such as the time of deposition of the Rye Patch Formation in the Lake Lahontan area) plus the following interval of interlacustral-interglacial deposition and of weathering during which the next-overlying main geosol formed (for example, the Cocoon Soil). The stages are named after the lacustrine formations and geosols of the Lake Lahontan area (which contains the most fully studied and named succession in the Great Basin), using the name of the oldest named formation in the stage followed (after a hyphen) by the name of the next-overlying main geosol (for example, the Rye Patch-Cocoon Stage). This usage is adopted in order both to avoid having to coin and define entirely new names for the stages, and also in order that the rock-stratigraphic and soil-stratigraphic units included within a stage are readily apparent.

Subdivision into substages is not feasible at the present time, except within late Wisconsinan and Recent time. The substage units are bounded by geosols (which mark their upper boundaries, except in the case of the late substage of the Fallon Stage), and they are named on the same basis as the stages. The two earlier substages are named after lacustrine formations and soils of the Lake Bonneville area (e.g., the Bonneville-Graniteville substage); the two substages of the Fallon Stage are named informally.

Using geosols to define the boundaries of all the stages and substages is believed to be pragmatically the most feasible manner of provincial time-stratigraphic classification in this region, because the geosols are para-time-parallel, and also are the most ubiquitous and commonly the best stratigraphic markers (Morrison, 1965h).

The rock-stratigraphic and soil-stratigraphic units that comprise each of the proposed stages and substages in the successions of the Lake Lahontan and Lake Bonneville areas, are shown in figure 6. The type area for both the Lovelock-Humboldt Valley Stage and the Rye Patch-Cocoon Stage is the bluffs along the Humboldt River near Rye Patch Dam (fig. 1). The type area for both the Eetza-Churchill Stage and the Sehoo-Toyeh Stage is the bluffs along the Truckee River north of Wadsworth. For the two substages within the latter stage, the type area of the Bonneville-Graniteville substage is the large gravel pits on southern Promontory Point, Utah (fig. 4); and the type area for the Draper-Midvale substage is eastern Jordan Valley, south of Salt Lake City, Utah. The type area for the Fallon Stage, as well as the early and late substages of this stage, is the lowlands of the southern Carson Desert near Fallon, Nevada (fig. 1).

Glacial stratigraphy of the Rocky Mountains (Wasatch Range) and correlations with the Lake Bonneville succession

The most comprehensive studies of the Quaternary glacial geology of the Rocky Mountain region by modern stratigraphic methods including soil stratigraphy, have been by Richmond (1960, 1962, 1964a, 1965b). The Wasatch Range of central Utah is a representative part of this region. An area of several square miles at the western front of this range, below the mouths of Little Cottonwood and Bells Canyons (fig. 3), is of unique importance because it is probably the only place in the world where tills deposited by mountain glaciers actually intertongue with pluvial lake sediments, and where these stratigraphic relations are sufficiently well exposed unequivocably to demonstrate direct correlations between some of the glacial and lake maxima. Little Cottonwood and Bells Canyons were the most intensely glaciated of any in the entire 115-mile-long Wasatch Range, and their glacial geology is typical of that of the Rocky Mountain region. Richmond (1964a) and Morrison (1965a) jointly studied the glacial geology of these canyons and the relations of the glacial deposits to the deposits of Lake Bonneville. Tiny remnants of till and of possible till from either one or two pre-Wisconsinan (pre-Bull Lake) glaciations, were identified, extensive till and outwash units were correlated with the Bull Lake (earlier) and Pinedale Glaciations of Wisconsinan age, and cirque-basin deposits were correlated with the Neoglaciation. Periods of complete deglaciation probably intervened between each glaciation. The till and outwash of the Bull Lake Glaciation were divided into lower and upper units that locally are separated by a diastem that presumably records marked glacial recession. The deposits of the Pinedale Glaciation were divided into three units (lower, middle, and upper) that presumably record separate stades of this glaciation, although there is no conclusive evidence of marked recession and readvance of the glaciers between these units. The deposits of the Neoglaciation are divided into those of two stades (Temple Lake and Historic), that appear to have been separated by complete deglaciation in this area.

Originally Richmond (1961, 1964a) and Morrison (1961b, 1965a) concluded that the last rise of Lake Bonneville to the Bonneville shoreline occurred in late Bull Lake (= late Alpine) time. Subsequently both men (Richmond, 1964a, p. D37; Morrison, 1965b, 1965c, 1965d) revised this interpretation, on the basis of evidence from exposures that

were not available during the earlier investigation, and now conclude that the final lakerise to the Bonneville shoreline took place in post-Bull Lake (= post-Alpine) time. The relations are best demonstrated in two exposures along Little Cottonwood Creek west of Wasatch Boulevard, studied in detail by Morrison (described in Morrison 1965d, stop 1). In this area, three separate, successive tills of Bull Lake age can be identified. The lowermost till locally overlies the Dimple Dell Soil. The lower, middle, and upper tills of this glaciation extend down to minimum altitudes of about 5,015, 5,070, and 5,100 feet respectively, reaching from 1 to 1 1/4 miles beyond the canyon mouth. Each of these tills (and coeval outwash gravel) is underlain by lake sediments of the Alpine Formation, in relationships that demonstrate clear, direct correlation between the deposits of the Bull Lake Glaciation and the Alpine Formation. Moreover, the upper and middle tills show evidence of having been deposited in standing water --demonstrating synchroneity of the glacial and lake maxima they record. Thus, the last Alpine lake maximum is correlated with the late Bull Lake glacial maximum, and the second-from-last Alpine lake maximum with the middle Bull Lake glacial maximum; presumably the third-from-last Alpine lake maximum also can be correlated with the early Bull Lake maximum.

Overlying all the deposits of the Bull Lake Glaciation is a strongly developed weathering profile which is correlated both with the Promontory Soil and with the post-Bull Lake soil of Richmond (1964a). This geosol is not found on younger glacial deposits, but it is locally preserved below the Bonneville shoreline, although in most places it has been completely eroded by subsequent wave-action. The upper till (and where present, the Promontory Soil) are successively overlain by: (1) gravel, sand, and silt of the white marl member of the Bonneville Formation, including the distinctive white marl bed; (2) a diastem; (3) sand and gravel of the upper member of the Bonneville Formation; and (4) the typical Graniteville Soil. The white marl member has been traced to within 20 feet of the Bonneville shoreline, and the upper member extends up to and underlies this shoreline.

End moraines of post-Bull Lake age are far above the Bonneville shoreline in both Little Cottonwood and Bells Canyons, and the intervening remnants of outwash gravels and stream terraces are too discontinuous to permit reliable direct correlation of the younger glacial and lacustrine sequences. These sequences have been correlated indirectly, however, by soil stratigraphy and by comparison of similar climatic-depositional cycles. On this basis, the white marl and upper members of the Bonneville Formation are correlated with the early and middle stades, respectively, of the Pinedale Glaciation. In Little Cottonwood Canyon and its tributaries the end moraines of the early stade of the Pinedale glaciation are at about 6,600 feet altitude, moraines of the middle stade of this glaciation are at altitudes of 6,870 to 8,400 feet and end moraines of the late stade at altitudes of 8,650 to 9,750 feet. The deposits of the early and middle stades of this glaciation bear the Graniteville (+Midvale) Soil, but those of the late stade bear only the Midvale Soil.

Till of the Neoglaciation occurs in the higher cirque basins, generally above 9,200 feet altitude. The end moraines of the Temple Lake Stade of this glaciation bear the early Recent soil, but those of the Historic Stade are devoid of soil development.

On the basis of stratigraphic data obtained from below the mouth of Little Cottonwood Canyon, as well as at Promontory Point and the Delta-Oak City areas and elsewhere (fig. 3), it is evident that in Alpine (-Bull Lake) time Lake Bonneville rose at least three times to within 100 feet of the Bonneville shoreline; once (probably the last

time) during this period it rose to somewhat above this shoreline, causing a short-lived but catastrophic overflow at Red Rock Pass. The two later lake maxima of Alpine age were essentially synchronous with the last two main glacial maxima of Bull Lake age. In inter-Alpine-Bonneville time, when the Promontory Soil was formed, Lake Bonneville became nearly or completely dry. In Bonneville Formation time Lake Bonneville had its last two high rises, the first to within 20 feet of the Bonneville shoreline, and the second to this shoreline, causing a second overflow at Red Rock Pass. Inasmuch as the Bonneville Formation is correlated with the early and middle stades of the Pinedale Glaciation, and the second overflow was during the lake cycle that is recorded by the upper member of the Bonneville Formation, the second overflow presumably took place during the middle Pinedale glacial maximum.

The Midwest and Southern Great Plains

The pertinent stratigraphic descriptions for the Illinois-Wisconsin and Southern Great Plains regions have been published or are in press and will not be repeated here. The presently-used stratigraphic terminology, indicated glacial pulsations, and inferred climatic history are summarized in figures 2 and 6.

The types of useable evidence, and the climatic expression, is strongly contrasted in these latter two regions. The Southern Great Plains are most comparable to the Great Basin, because they also contain deposits that are predominantly alluvial, with minor amounts of eolian deposits and lacustrine deposits in small basins. The morphology of the major geosols in the plains is similar to the pedocal facies in the Great Basin. Although there is a paucity of radiocarbon dates, abundant molluscan faunas of this plains area contribute important evidence for correlation. Recent literature (Frye and Leonard, 1952; 1957a; 1957b; 1963; 1964; 1965, in press) has been used extensively in the presentation of stratigraphic units for the Southern Plains on figure 6.

The Illinois-Wisconsin region is dominated by glacial tills, with loess deposits in an important secondary position. The stratigraphic framework was based on data from both the tills and the loesses, and particularly on those areas where the two are interlayered. In this region the geosols display little if any of the pedocal facies, but are instead pedalfer and intrazonal soils. Although the pedalfer soils of the Midwest have considerable similarity to the pedalfer facies of the western regions, the intrazonal soils (accretion-gleys etc.) are prominently represented only in the Midwest among the regions considered here. Of particular utility to regional correlations are the abundant radiocarbon dates from this area. More than 100 useable radiocarbon dates are currently available from Illinois, Wisconsin, and immediately adjacent areas. Although there exists an unusually large body of literature dealing with the glacial deposits and loesses of Illinois, for use in this study and for inclusion on figures 2 and 6 we have drawn largely from recent studies and their contained stratigraphic framework (Frye and Willman, 1960; 1963a; 1963b; Frye, Glass, and Willman, 1962; Frye, Willman, and Glass, 1960; 1964; Frye, Willman, and Black, 1965 in press; Willman, Glass, and Frye, 1963; Leonard and Frye, 1960).

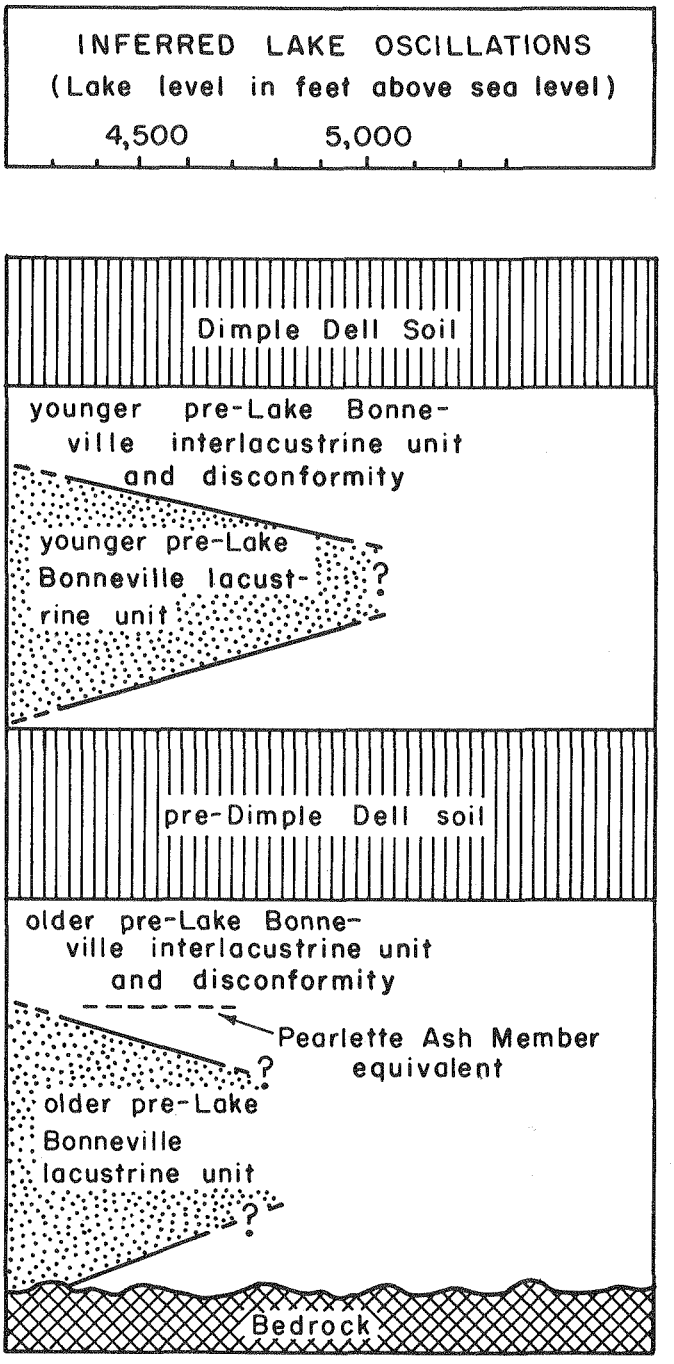
IN BEHALF OF THE MIDWESTERN TIME-STRATIGRAPHIC CLASSIFICATION

The Midwestern standard classification of glacial and interglacial stages, originally proposed by Chamberlin (1895) and Leverett (1899), and progressively modified through the years, has been and still is widely accepted by most Pleistocene geologists. Unfortunately, since about 1961 this classification has been abandoned by the U. S. Geological Survey. This has resulted from a serious misinterpretation of the new Stratigraphic Code (Amer. Comm. on Stratigraphic Nomenclature, 1961). The U. S. Geological Survey has chosen to regard the classic Midwestern glacial and interglacial stages as merely geologic-climate units, and the new Code specifically forbids "climatic subdivisions" being called stages and substages (reversing the authorization of such usage by the 1933 Code). However, the new Stratigraphic Code also states (p. 659) that "stage" and "substage" should be used for Quaternary rocks as for other parts of the column; thus, time-stratigraphic terminology is not prohibited for the Quaternary, provided that the units are properly defined and meet the requirements of time-stratigraphic units. Ideally, the boundaries of time-stratigraphic units are isochronous surfaces. This is exactly as they have been defined in the revised Midwestern time-stratigraphic classification (Frye and Leonard, 1952; Frye and Willman, 1960, 1963) used in this paper.

The fundamental framework for the differentiation of the stages in the Midwest is provided by the interglacial geosols, the Sangamon, Yarmouth, and Afton Soils. These geosols themselve are used as the basis for definition of the interglacial stages. The deposits of the intervening glacial stages include not only the glacial till units from which they were named (and which are their most distinctive deposits) but also outwash, alluvium, loess, and colluvium. The tops and bottoms of the glacial stages are defined by the interglacial geosols between which they are intercalated. Therefore, as we explain in the next chapter, these boundaries are essentially time-parallel, and neither neither the interglacial nor the glacial stages are time-transgressive geologic-climate units.

It is our opinion that the Midwestern stages of the Quaternary, as well as provincial stages properly defined in other areas such as the Great Basin, are entirely valid time-stratigraphic units. As pointed out above, we prefer to establish an interregional correlation on the basis of time-stratigraphic units (stages and substages), insofar as possible, instead of geologic-climate and rock-stratigraphic units.

One little-understood aspect of the non-parallelism between Quaternary stages and glaciation-interglaciation units is illustrated by the Great Basin pluvial lake records, and in some respects, by the Rocky Mountain and Midwestern successions. These indicate that commonly some deposition occurred during the early part of an interglaciation before the start of the weathering interval of this interglacial. Thus the lower boundaries of interglaciation units commonly do not coincide with (are older than) the lower boundaries of the interglacial stages (fig. 5).



TENTATIVE CORRELATIONS	
ROCKY MOUNTAIN GEOLOGIC-CLIMACTIC STANDARD[1]	MID-CONTINENT TIME-STRATIGRAPHIC STANDARD[2]
Sacagawea Ridge-Bull Lake Interglaciation	Sangamonian Stage
Sacagawea Ridge Glaciation	Illinoian Stage
Cedar Ridge Sacagawea Ridge Interglaciation	Yarmouthian Stage
Cedar Ridge Glaciation	Kansan Stage

1. After Richmond (1964a and b)
2. After Frye and Leonard (1952)

FIGURE 5. Illustration of the non-coincident lower boundaries of interglaciation geologic-climatic units and the Midwestern interglacial stages, based on the stratigraphic record at southern Promontory Point, Utah (after Morrison, 1965c).

PROPOSED CORRELATIONS

Means of correlation

GENERAL PROBLEMS IN QUATERNARY TIME-STRATIGRAPHY

The term correlation has many connotations in stratigraphy, but its most common stratigraphic meaning is the relationship of the time (or age) of the formation of rocks, or determinable geologic events, from one place to another. Correlations are traditionally made by the physical tracing of strata or by the matching of assemblages of fossils. These techniques are clearly not useable for the establishment of contemporaneity between isolated, widely separated depositional provinces where the deposits do not contain similar assemblages of diagnostic fossils, and moreover they may not establish time-equivalence.

In the past it has proved very difficult to maintain consistent time-stratigraphic correlation across great distances between such varied lithogenetic terrains as continental-glacial, mountain-glacial, alluvial-terrace, and pluvial-lake terrains, particularly for the stage and smaller subdivisions. Paleontology is of little assistance, both on account of the scantiness of faunal and floral remains in many deposits, and, more importantly, because the finer time-stratigraphic subdivisions (stage and smaller) of the Quaternary span time intervals that were too short for appreciable evolutionary change in species. Thus, the fossil record, even where present, is not diagnostic for fine age placement and correlation across the distances considered here. Fossil assemblages of mollusks and pollen locally have been used successfully for fine subdivision of Quaternary sequences, but such subdivision has been based on ecological implications, (the biozones are controlled primarily by environment instead of evolution). Used on this basis the fossil record affords merely rock-stratigraphic or geologic-climate subdivision, and across great distances such units are likely to be time-transgressive.

Widespread volcanic-ash beds, although time-parallel, unfortunately are rare. Isotopic and other geochemical and geophysical means of dating are not themselves a basis for time-stratigraphic classification, although they may be valid for determing time-equivalence of units, provided the the dates can be independently verifed.

The traditional means of correlating Quaternary successions is by matching depositional sequences interpreted as indicative of similar successions of cycles of climatic change. Climatic change was probably the most distinguishing characteristic of the Quaternary. Periodic climatic fluctuations of varying amplitude and duration caused changes in rate and type of various surficial erosional and depositional processes, and these variations are identifiable in the geologic record to a degree that makes the Quaternary record unique in post-Paleozoic time. The basic climatic oscillations are judged to have been worldwide and probably essentially synchronous, although their local manifestations were influenced by latitude, altitude, continentality, storm tracks, and other factors. The effects of the climatic oscillations upon the depositional-erosional record are most marked at middle and high latitudes (and at high altitudes at low latitudes). The climatic-depositional cycles are manifest by fluctuations in surficial processes such as advances and retreats of glaciers, rises and falls of pluvial lakes, eustatic shifts in sea level, aggradation and degradation along streams, soil development, and other phenomena.

Generally, the amplitude and relative duration of the climatic-depositional cycles can be estimated from the distribution, thickness, and lithologic character of the deposits

that record them. A category of stratigraphic units designed to reflect climatic-depositional fluctuations has recently been described and named geologic-climate units (Amer. Comm. Stratigraphic Nomenclature, 1961, p. 660). By matching the successions of these units in separate areas, the sequences of deposits that record them can be correlated on a geologic-climate basis.

Inadequacy of geologic-climate units as a basis for long-range correlation

Various uncertainties, however, confound attempts at long-distance correlation solely by this means. Correlation may be hampered by the complexity of the record in one area and its meagreness in another; by its distortion by non-climatic variables such as diastrophism, and by omissions due to erosion, nondeposition, or lack of exposure. Commonly in such cases one cannot be certain that he has correctly identified the same depositional cycle (or geologic-climate unit) in the sequences in different areas.

The main defects of the geologic-climate means of correlation lie in the inherent non-time-parallelism of geologic-climate units, and in the fact that the various types of depositional cycles that may result from a given climatic cycle may be of different duration and also may be out of phase with each other. For example: till deposited during the Woodfordian substage of the Wisconsinan stage spans many more thousands of years in southern Ontario than it does at the Shelbyville end moraines in central Illinois. Pluvial lake cycles cannot be assumed to be exactly synchronous and of the same duration as glacial cycles, even in the same region. In extreme cases, two sets of climatic-depositional cycles (geologic-climate units) may be as much as 100 percent out of phase with each other -- for example, cycles of glaciation compared with eustatic shifts in sea level. In the Rocky Mountains and other mountain systems of the Western United States, strong alluviation and stream aggradation took place during the various glacial maxima. On the Mississippi delta and at seamouths of other rivers, on the other hand, marked down-cutting occurred during the glacial maxima because of eustatic drop in sea level.

ADVANTAGES OF CORRELATION BY SOIL STRATIGRAPHY

Many of the uncertainties inherent in geologic-climatic correlation can be minimized by using soil stratigraphy. This means of correlation uses weathering profiles (geosols) as time-stratigraphic markers. Although this technique was used more than half a century ago as a basis for establishing the major stages of glaciation in the Midwest, its use elsewhere is relatively recent. Modern stratigraphic studies of Quaternary deposits in the temperate and near-temperate regions of the world have shown that the successions usually include sequences of weathering profiles (geosols) that are analogous from region to region, in terms of relative age and development. Sedimentary units between the soils record little or no soil development, although in some cases their deposition may have lasted longer than the times of soil formation. The soil-forming intervals within the range of radiocarbon dating occupied about 1/7 to 1/12 of their respective climatic-depositional cycles (Morrison, 1964b), or probably only about 10 to 15 percent of the total duration of the Wisconsinan stage. Thus, except for the three major pre-Wisconsinan interglacial intervals, soil-forming intervals were comparatively brief, distinctly separated, and occupied only a small part of total Quaternary time. This interpretation clearly indicates that the rate of soil development (weathering) at these latitudes varied exponentially, probably through several orders of magnitude, attaining its greatest intensity during the strong-

er soil-forming intervals. Evidently, therefore, the soils observed in the stratigraphic sequences were formed in response to special combinations of climatic factors that produced relative erosional stability and accelerated chemical weathering. Soil-forming intervals were periodically repeated parts of climatic cycles that are manifest in Quaternary sequences of each area.

The only possible weathering factor that could have caused these periodic intervals of accelerated weathering is marked increase in temperature (Morrison, 1964b and in press). Increase in precipitation alone, assumed by most soil scientists to be the dominant soil-forming factor, cannot adequately explain the weathering optima. An array of geologic evidence supports this interpretation -- notably the evidence that the stronger geosols formed during interglacial intervals, instead of during the wetter and colder glacial intervals. The most strongly developed soils formed during the three major interglacial (and pluvial-lake interlacustral) intervals; weaker soils formed during some of the shorter and warmer recession intervals; and soil development at other times was inappreciable.

Climatologists suggest that secular temperature variations were worldwide and synchronous, based on evidence that they result primarily from changes in solar energy (Bell, 1953; Brooks, 1949; Butzer, 1957a, 1957b, 1961; Flohn, 1950, 1952; Schwarzback, 1961; Wexler, 1953; Willett, 1949, 1951, 1953; Wolback, 1953. Also see additional references appended to last page of Reference List.); changes in precipitation tend to be less ubiquitous and synchronous. Moreover, the climatic changes have been proportionately much greater at middle and high latitudes than in the tropics. These conclusions, coupled with the inferred comparative brevity of the soil-forming intervals, suggests that geosols formed essentially synchronously throughout middle and high latitudes, in other words, they are para-time-parallel. Probably slight non-time-parallelism occurs in soils due to variations in latitude and altitude (and possibly other local climatic influences), but these differences appear to be relatively small, again because of the synchronous, worldwide character of the relatively brief maxima of solar energy that induced the soil-forming intervals. Thus, geosols in middle and high latitudes are judged to be more nearly time-parallel than any of the common sedimentary units in Quaternary successions -- much more s so than glacial, lacustrine, or fluvial deposits.

In this respect we dissent from the majority opinion of the Pleistocene subcommittee of the American Commission on Stratigraphic Nomenclature (Richmond, 1959, p. 669). That subcommittee concluded that soils may be no more time-parallel than their glacial and pluvial counterparts, and should not define time-stratigraphic (stage) or geologic-time (age) units. We propose, on the contrary, that geosols are at least para-time-parallel throughout temperate latitudes, and that, because they combine the desirable qualities of being essentially time-parallel, distinctive, and relatively ubiquitous, they generally are the best key beds for both defining and correlating stages and substages of the Quaternary, not only on a provincial basis but also interregionally in middle and high latitudes.

Geosols have been used for nearly 70 years in the Midwest as the units comprising the interglacial stages -- the Sangamon, Yarmouth, and Afton Soils respectively for the Sangamonian, Yarmouthian, and Aftonian Stages. We believe that this usage is pragmatically more sound for purposes of local and interregional correlation than recent attempts (e.g., by the U. S. Geological Survey) to demote these stages to second-class status, namely, to geologic-climate units.

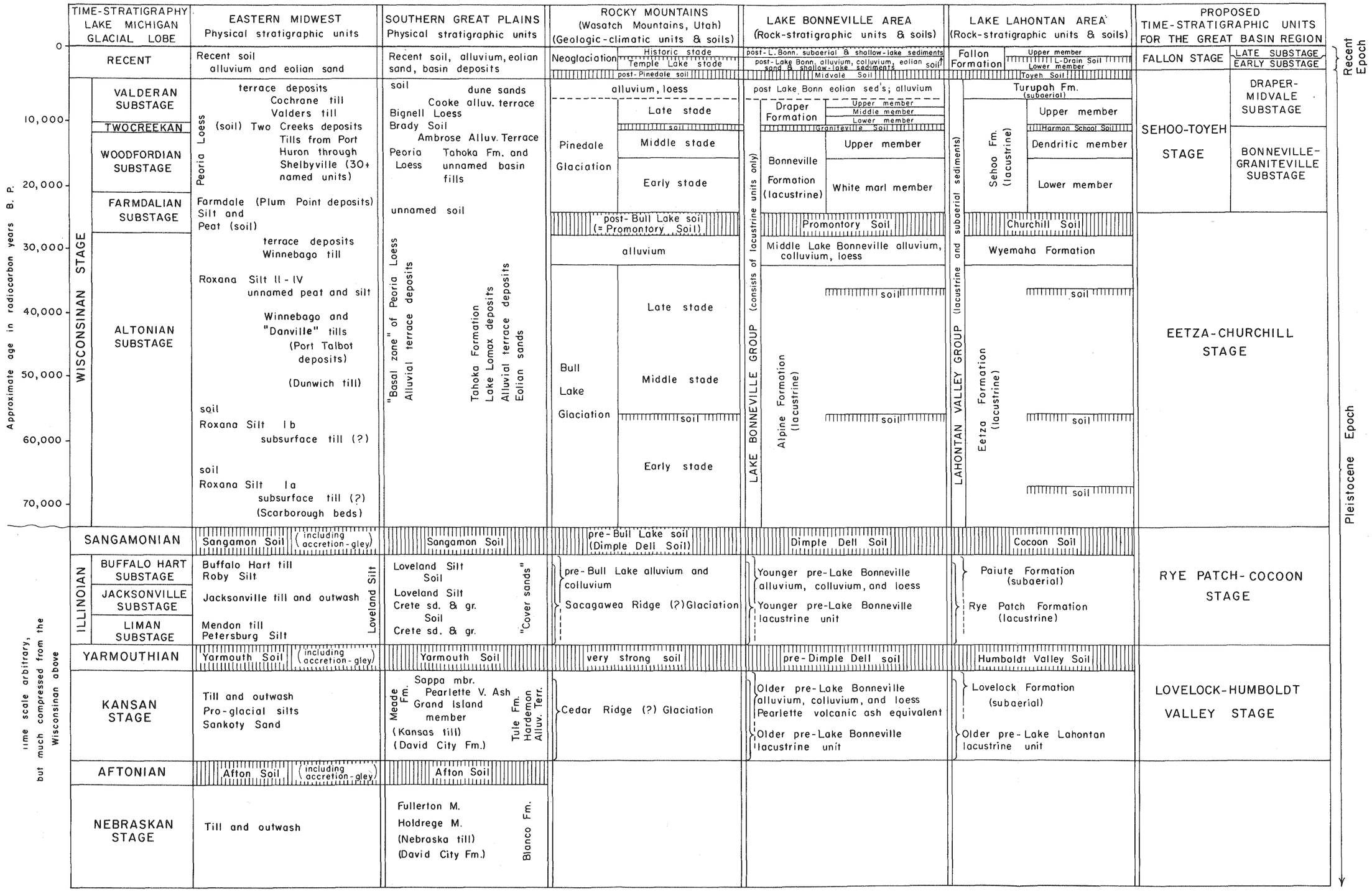


FIGURE 6. Correlation chart for units of middle and late Quaternary age in the Eastern Midwest, Southern Great Plains, Rocky Mountains, Lake Bonneville, and Lake Lahontan areas, including the proposed provincial time-stratigraphic standard for the Great Basin region.

In making time-stratigraphic correlations by use of geosols, the total Quaternary sequence (rock-stratigraphic units and soil-stratigraphic units) of each area should be known as fully as possible, particularly noting the relative position (age) and relative degree of development of the geosols in each area. The basic framework for correlation is provided by matching the most strongly developed geosols of the areas under consideration, as closely as possible in terms of their relative ages and relative degrees of development. The strongly developed geosols are generally the most readily recognized in the successions of each area, and also are the most readily evaluated in terms of their relative development within a given soil succession.

After the prominent geosols are correlated with each other, the rock-stratigraphic (or geologic-climatic) units and weaker geosols that are intermediate in age between them are then correlated by matching those units that record depositional cycles (or parts of cycles) of similar relative age, magnitude, and climatic genesis. Thus, units that represent early lake cycles are correlated with each other and with units that represent early glacial cycles; likewise, lake recessional units are correlated with glacial-recessional units. It should be recognized that such correlations are influenced by the completeness of detail and accuracy of the stratigraphic records of the areas being correlated. Weakly developed geosols are less useful than thick mature profiles as time-stratigraphic markers because they are less easily identified.

AUXILIARY MEANS OF CORRELATION: RADIOCARBON CHRONOLOGY AND DATA ON CLIMATIC FLUCTUATIONS

In arriving at the tentative correlations proposed for these widely distributed regions in figures 2 and 6 all available lines of evidence were examined.

Radiocarbon dates have been utilized as a subsidiary, rather than the primary means of correlation. This is prompted by difficulties in the detailed reconciliation of certain groups of radiocarbon dates with one another and with the geologic correlations, particularly in the Lake Bonneville and Lake Lahontan areas. However, in spite of certain possibly anomalous dates in the western basins, the wealth of radiocarbon dates from the basins and from the Midwest are of great utility within the range of the method. Further, they serve to check or confirm the basic correlations in the mid-to-late Wisconsinan, that were determined by soil-stratigraphic methods and by the matching of semi-repetitive sequences.

Climatic fluctuations in the various areas are evidenced by changes in environmental conditions that are manifest in the physical sedimentary successions, soils, fauna and flora, and landforms of each area. For the Lake Lahontan area additional information on fluctuations in temperature and precipitation have been obtained from analysis of lake area-evaporation relations during the various lake maxima and soil-forming maxima; these are graphed in figure 2. Somewhat less quantitative climatic information is available for the Lake Bonneville, Wasatch Range, and Lake Michigan lobe areas.

In conclusion, the correlation presented herein is believed to be reasonably valid on a time-stratigraphic basis, because of its close control not only be geosols, which are believed to be nearly time-parallel in the latitude range of the areas under consideration, but also by the numerous radiocarbon age determinations from each of the areas, supplemented by other evidence on climatic fluctuations.

Suggested correlations

Applying the soil-stratigraphic method of correlation, the basic framework of the correlation scheme is established by correlating geosols of similar relative degree of development. We first correlate the youngest very strongly developed geosol in each succession. Thus, the Cocoon and Dimple Dell Soils of the Great Basin are considered equivalent to the Sangamon Soil of the Great Plains and Midwest.[2/] From this foundation, we next correlate the next-older very strongly developed geosols; hence the Humboldt Valley and pre-Dimple Dell soils are correlated with the Yarmouth Soil of the Great Plains-Midwest. Next to be correlated are the strongly developed geosols that are next-younger than the Sangamon Soil and its correlatives. In other words, the Churchill and Promontory Soils of the Great Basin are considered to be equivalents of the soil of Farmdalian age in the Midwest. This correlation is supported by the radiocarbon chronology of these respective areas.

Finally, we correlate the various younger moderately to weakly developed geosols, in their relative order, between the various successions: The weakly developed Harmon School Soil of the Lake Lahontan area is correlated with the more strongly developed Graniteville Soil of the Lake Bonneville area and with the Brady Soil of the eastern Great Plains and the well-dated Two Creeks peats and soil of Wisconsin. The Toyeh and Midvale Soils are probably equivalent to an unnamed terrace soil (of thermal maximum age) in the central Great Plains and to the relict soil on the Cooke alluvial terrace in the Red River Valley of Texas. A geosol of equivalent age has not as yet been recognized in Illinois. The L Drain Soil of the Lake Lahontan area is considered to be equivalent to the early Recent soil of the Lake Bonneville-Wasatch Range area. All these correlations likewise are supported by radiocarbon dates.

The deposits intermediate in age between these main geosols are correlated as follows: The Eetza Formation of Lake Lahontan is correlated with the Alpine Formation of Lake Bonneville, with drift of the Bull Lake Glaciation in the Wasatch and Rocky Mountains, and with the Altonian drifts in Illinois. The Sehoo Formation of Lake Lahontan likewise is correlated with the Promontory Point and Draper Spit Formations of Lake Bonneville, with drift of the Pinedale Glaciation in the Wasatch and Rocky Mountains, and with the Woodfordian and Valderan drifts in the Eastern Midwest.

The establishment of approximate contemporaneity of the Farmdalian interval among the several regions is of particular importance. It should be noted that the Farmdale peats of Illinois have been determined by extensive radiocarbon dating to be about 27,000 to 22,500 radiocarbon years old, and that the top of the immediately older Roxana Silt is commonly leached to depths of 10 feet or more. Further continent-wide consistency is suggested by the fact that the Farmdale peats and silts locally show several minor pulses of deposition separated by peat accumulation, that perhaps are counterparts of the local compound occurrences of the Churchill and Promontory Soils. It also should be noted here that the Altonian deposits of Illinois contain two well-defined soils below the Farmdale peat, and soil at the top and above the Sangamon Soil.

[2/] The range in degree of development and in morphology of the Cocoon and Dimple Dell Soils is completely contained within the range displayed by the Sangamon Soil of the central and southern Great Plains and the Midwest. The principal difference is that in the interior plains region these changes in soil profile characteristics occur across distances of hundreds of miles, whereas in the Great Basin they are more closely associated geographically, mainly because of the considerable changes in altitude (and hence the orographic control on precipitation and temperature) within a few miles.

In connection with the 7,000-year gap in radiocarbon age determinations from the deposits of early Sehoo age, and the somewhat smaller gap from these of early Bonneville age, it is interesting to note that in the Midwest many radiocarbon dates from this time interval have been determined, from the peat and wood in the upper part of the Farmdale and from the overlying Morton Loess (lowermost Woodfordian).

Figure 7 summarizes the gross time-stratigraphic correlations between the Great Basin and the Eastern Midwest.

The proposed provincial time-stratigraphic standard for the Great Basin differs in several respects from that proposed for the eastern Midwest (Frye and Willman, 1960, 1963; Frye, Willman, and Black, 1965):

(1) In the Midwest, for the Sangamonian and older stages, the three interglacial geosols (Sangamon, Yarmouth, and Afton Soils) each define and fully comprise a stage. The intervening stages, represented most distinctively (but not entirely) by glacial deposits, are named separately (as the Illinoian, Kansan, and Nebraskan Stages), after the names of their respective till units. The stages that we propose for the Great Basin, however, extend through a complete lacustral-interlacustral (glacial-interglacial) cycle. This is done (instead of having separate stages for the lacustral and interlacustral intervals) because it would be difficult or impossible to find sufficiently ubiquitous and time-parallel markers that would enable lacustral-glacial stages to be differentiated consistently from interlacustral-interglacial stages, particularly on the basis needed for precise stratigraphic studies (e.g., where the interlacustral geosols are compounded).

(2) The Wisconsinan Stage of the Midwest is broken into two stages in the Great Basin. This follows traditional usage in the West, which probably is because the main interlacustral-interglacial interval within Wisconsinan time (the Farmdalian substage) has been more generally recognized in the West than in the Midwest, and also because the existence of extensive and repetitive continental glaciation older than the type Farmdale and younger than Sangamonian, has become established in the Midwestern region only during the past half-dozen years.

(3) The boundary between the Pleistocene (Wisconsinan) and Recent is placed arbitrarily at 5,000 years in the Midwestern standard (Frye and Willman, 1960, 1963), which approximately marks the warmest part of the thermal maximum. The arbitrary placement was made because no buried soil that could be used as a basis for this boundary has been identified in the upper Mississippi Valley region. In the Great Basin, however, the proposed boundary is placed at the top of the Toyeh Soil and its equivalents (Morrison, 1961c, 1965f), because those geosols form the most widely identifiable and traceable stratigraphic marker unit, and also the most nearly time-parallel unit, in all the late Quaternary lithogenetic terrains (glacial, lacustrine, alluvial, eolian, and colluvial) of this region. This geosol formed during the late part of the altithermal interval, and ceased to form about 4,000 or possibly 3,800 years ago. Thus the proposed Pleistocene-Recent boundary is about 1,000 years younger in the Great Basin than the arbitrary radiocarbon age assigned to it in the Midwest -- but this seeming difference is more apparent than real.

(4) No counterpart of the Fallon Stage of the Great Basin, coincident with the Recent Epoch, has yet been defined in the Midwest. Designation of a stage in this stratigraphic position is merited in the Great Basin because of the superb Recent stratigraphic record, both geologic and archaeologic, in this region. This record is particularly complete and detailed in the terminal basins, as illustrated by its detailed study in the southern Carson Desert, Nevada (Morrison, 1964a).

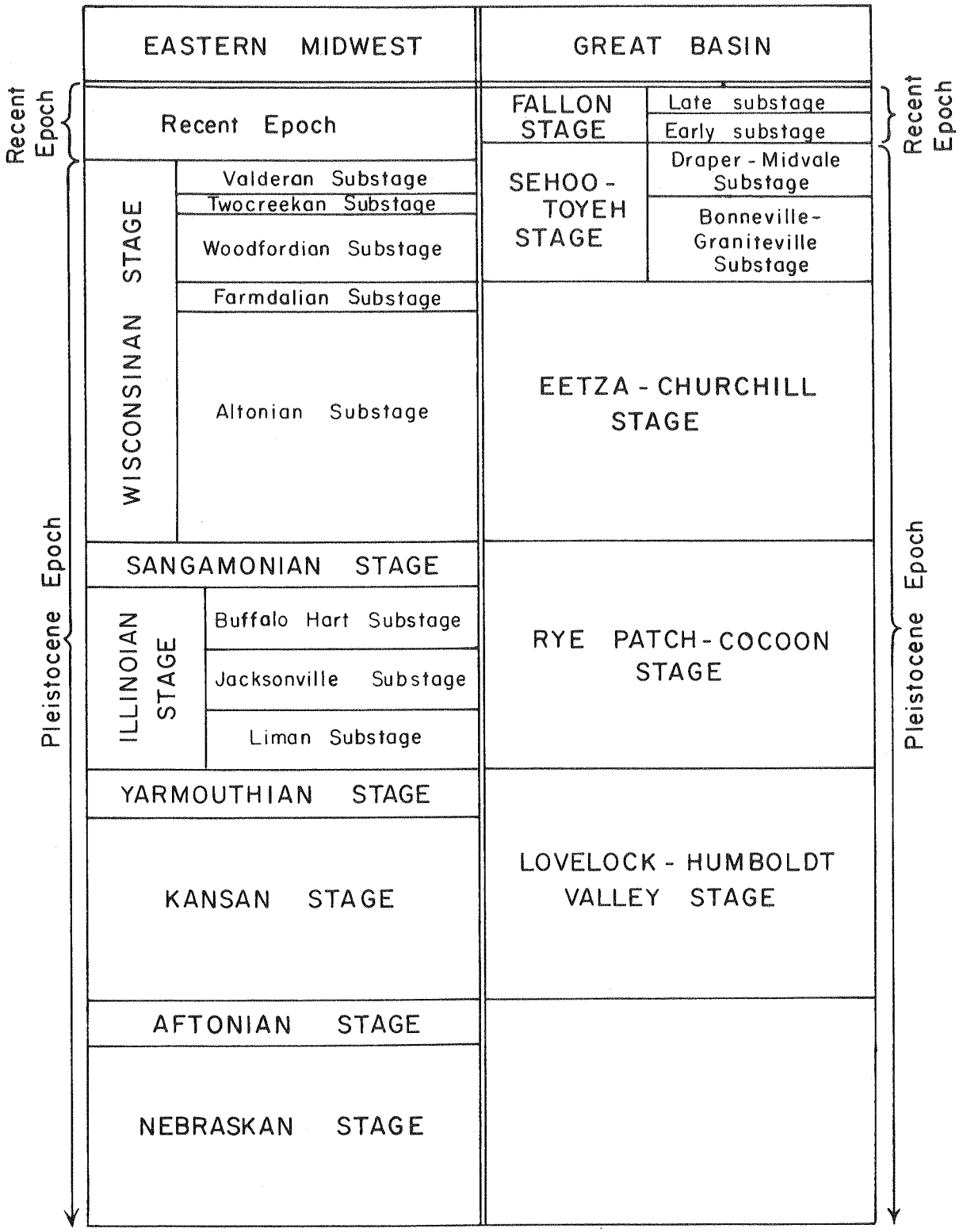


FIGURE 7. Correlation of Quaternary time-stratigraphic units in the Eastern Midwest and Great Basin.

Some implications of the correlations; problems needing further investigation

One of the objectives of this attempt at a detailed interregional correlation is to point out a few of the controversial sectors of the correlation scheme, and their possible implications. The uncertainties arise mainly within the smaller time-stratigraphic subdivisions; from the evidence available, the correlations seem to be reasonably certain between the time-stratigraphic divisions of stage rank. Considerable certainty also holds for the correlation of the Eetza-Churchill Stage with the Altonian and Farmdalian substages of the Wisconsinan Stage, and also for the correlation of the Sehoo-Toyeh Stage with the Woodfordian, Twocreekan, and Valderan substages.

The uncertainties in correlations between the smaller time-stratigraphic (and, of course, the smaller geologic-climatic and rock-stratigraphic) units may result from several factors:

(1) Imperfection of the preserved stratigraphic record in given areas because of non-deposition and/or erosion of certain elements. As pointed out by Wheeler (1959, 1964), lacunae (missing intervals of the stratigraphic record, including both degradational vacuities and non-depositional-erosional hiatuses) are integral parts of time-stratigraphy.

(2) Incomplete knowledge of the stratigraphic record, generally because of inadequate study.

(3) Local complications of the record because of non-climatic variables, such as deformation, volcanism, and drainage-route changes.

(4) Differences in the duration and/or climate character of the smaller climatic cycles, or in the depositional-erosional records of these climatic cycles, between the various regions.

The first three factors are encountered commonly in other parts of the geologic column, but the last factor is almost unique to Quaternary time-stratigraphy. That it is a valid factor will be shown below; its affirmation is most positive in the younger successions that can be compared on the basis of a reasonably consistent isotopically determined chronology, as among the units with well established radiocarbon dates in the Lake Lahontan, Lake Bonneville, and Midwestern areas. Among the more interesting inferences of the correlation scheme are indications that some climatic-depositional cycles varied in degree of change in temperature and/or precipitation and perhaps even in duration, from region to region.

A few of the implications and evident problems will be considered first within the Great Basin-Cordilleran region, and then between the Great Basin and Midwest.

RELATIONS BETWEEN LAKES LAHONTAN AND BONNEVILLE AND THE GLACIAL SUCCESSIONS OF THE SIERRA NEVADA AND ROCKY MOUNTAINS

From the earlier studies of Lakes Lahontan and Bonneville, and correlation of their deposits with the then rather imperfectly known glacial succession of the Sierra Nevada (Morrison, 1961d, 1964a) it was concluded that the fluctuations of the two pluvial lakes were similar and synchronous, and that the lake fluctuations paralleled the oscillations of the mountain glaciers. On the basis of more advanced subsequent stratigrapic studies

that have doubled the number of lake cycles recognized from the successions of Lakes Lahontan and Bonneville (with no assurance that the lake history has yet been fully determined), the parallelism and synchroneity of lake and glacial cycles now appears to be less perfect. The main lacustral and glacial intervals still appear to be essentially synchronous and similar in magnitude. However, for the smaller fluctuations some interesting differences are becoming evident:

(1) For Lake Lahontan, four lake cycles have been identified from deposits between the Churchill and Harmon School Soils, whereas in the Lake Bonneville succession only two lake cycles have been identified between the Promontory and Graniteville Soils. Likewise, only two correlative stades of the Pinedale Glaciation are known in the Wasatch Range and elsewhere in the Rocky Mountain region.

(2) The moderately strong Graniteville Soil appears to be the same age as the weak Harmon School Soil (furthermore, no soil as strong as the Graniteville has so far been observed between the Toyeh and Churchill Soils in the Lake Lahontan area). This seems especially interesting because these two areas are now so similar in climate.

(3) Three lake maxima are recognized for Lake Bonneville between the times of formation of the Graniteville and Midvale Soils, and the first of these was a comparatively high rise. In contrast, only two comparatively low maxima are known for Lake Lahontan between the Harmon School and Toyeh Soils.

(4) The three highest lake maxima of Alpine time quite possibly (but not certainly) correlate with the three highest lake maxima of Eetza time; likewise, the last, intermediate-level lake cycles in both areas probably are correlative. Correlations between the other intermediate and low-level Alpine and Eetza lake cycles are very uncertain, expecially the earlier ones.

Diversion of the Bear River (fig. 3) into the Lake Bonneville drainage area in late Alpine time (discussed in Morrison, 1965b) may explain certain anomalies in relative heights of the later lake cycles, but probably cannot account entirely for all differences in magnitude or number of lake cycles.

Because of problems such as these, the deficiencies of correlations based on matching sequences of the smaller climatic-depositional cycles, either lacustrine or glacial, are increasingly obvious. For instance, at this time, it seems unwise to attempt more than rough correlations between the various lake cycles recorded by the Sehoo Formation and those recorded by the Bonneville and Draper Formations. Correlations between the various lake cycles of Alpine and of Eetza age are even more uncertain.

SOME DEDUCTIONS FROM AND PROBLEMS CONCERNING THE CORRELATIONS BETWEEN THE GREAT BASIN AND THE MIDWEST

Among the deductions that can be made from (and problems concerning) the correlations between the Great Basin and Midwestern successions are the following:

(1) Pre-Sangamonian Quaternary stratigraphy is better exposed and also better known in the Midwest than in the Great Basin. Details of correlation within any of the Midwestern glacial stages and the lacustral-interval portions of the Great Basin stages are obscure -- for example, between substages of the Illinoian Stage (the Buffalo Hart, Jacksonville, and Liman substages) and parts of the Rye Patch Formation and of the younger pre-Lake Bonneville lacustrine unit.

(2) In the Cordilleran region of the western U. S., two glaciations of Wisconsinan age are generally recognized, and the earlier of these was the greater throughout this region. It is generally recognized, in the Sierra Nevada for example, that the Tahoe (earlier) was more extensive and probably longer-lasting than the Tioga Glaciation; in the Rocky Mountains the Bull Lake Glaciation likewise surpassed the Pinedale Glaciation. The same relations hold for Lakes Lahontan and Bonneville: The Eetza and Alpine lacustrals rose somewhat higher and were considerably longer-lasting than the Sehoo and Bonneville-Draper lacustral intervals. In the Midwest, however, there is a widespread opinion that the early Wisconsinan (Altonian) glacial advances were not as extensive as those of late Wisconsin (Woodfordian) age. Wright (1964), for example, considers that the main glaciation of Wisconsinan time is represented by the Woodfordian and Valderan substages. This generally-held opinion derives from the fact that extensive glacial deposits of Altonian age have been documented only during the past decade, and that the presently available evidence indicates that the several episodes of Altonian glaciation attained major proportions only in the Lake Michigan lobe and lobes advancing farther east; so far, continental glacial deposits of Altonian age have not been recognized with certainty west of the Mississippi River. Furthermore, much of the drift of Altonian age was scoured away by the Woodfordian ice advances in northern Wisconsin, although late Altonian drift is widespread in southern Wisconsin. The impression that the Shelbyville end moraines (marking the Woodfordian glacial maximum) extended farther than any of the early Wisconsinan glacial maxima is correct only locally. In Illinois, Altonian glaciers lacked only a few tens of miles of attaining the southern limit of the Shelbyville, and in Indiana, Ohio, and Pennsylvania (White and Totten, 1965) the early Wisconsinan maxima locally extended beyond the Woodfordian maximum.

(3) Turning to more detailed correlations within the Wisconsinan Stage, many of the same uncertainties pertain that exist between Lakes Lahontan and Bonneville. For example, four certainly, and probably five ice advances as far south as Illinois are recognized within Altonian time, but beyond the simple fact of relative sequence and the position of soils and peats, correlations with either the three known stades of the Bull Lake Glaciation in the Rockies, or with the various Alpine and Eetza lake cycles, are as yet tenuous. Correlations between Woodfordian units and the western successions also present some uncertainties. Three major groupings within the Woodfordian tills (marked by the fronts of the Bloomington and the Valparaiso morainic systems) are perhaps to be correlated with the early and middle stades of the Pinedale Glaciation, with the white marl and upper members of the Bonneville Formation, and with the lower and dendritic members of the Sehoo Formation.

(4) The Churchill-Wyemaha and the Promontory intervals were major interlacustrals, marked by strong weathering (soil formation) in the Great Basin. The correlative Tahoe-Tioga and Bull Lake-Pinedale Interglaciations were similarly well marked in the western Cordillera. Complete deglaciation and development of the strong weathering profiles indicates that this period was considerably warmer than now throughout the West. In the eastern Midwest, the correlative Farmdalian interval, although clearly marked by major ice recession (to a positon north of the United States), may not have been one of complete continental deglaciation (Frye, Willman, and Black, 1965). The peat and organic-rich silts, and lacustrine and colluvial deposits characteristic of the Farmdale Silt, and its

fauna, indicate cool moist conditions. Permafrost and buried glacial ice may have survived through the substage in northern Wisconsin. In the loess successions, however, the Farmdalian is represented by more than 10 feet of leached loess --obviously recording considerable chemical weathering. The Farmdale weathering profile generally lacks a textural B-horizon because it is represented by accretion deposits and organic-rich silts in poorly drained situations, now commonly preserved below younger tills, and was subject to an episode of marked erosion in the areas of thick loess along the major valleys. Hogan and Beatty (1963) have described remnants of buried paleosols of this age in southern Wisconsin with A and possibly B-horizons.

Many of the problems presented above probably will be resolved by future detailed stratigraphic studies, both within the areas discussed and in intervening areas, assuming improvements in the methods of obtaining geochemically-determined chronologies from the successions. Nevertheless, some non-parallelism and even non-synchroneity probably will persist between the fluctuations recorded in the various areas. Any indications of non-synchroneity between climatic-depositional cycles of various regions should be thoroughly explored, because knowledge of the degree of variation of this factor is highly significant to all stratigraphic means of correlation of Quaternary deposits.

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