Nonmarine Sedimentary Rocks of Tertiary Age in the Lake Mead Region, Southeastern Nevada and Northwestern Arizona

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1259

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By ROBERT G. BOHANNON

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A study of the age, nomenclature, lithology, and tectonic history of Miocene continental deposits in the transition zone between the Great Basin and Sonoran Desert

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1984

UNITED STATES DEPARTMENT OF THE INTERIOR

WILLIAM P. CLARK, *Secretary*

GEOLOGICAL SURVEY

Dallas L. Peck, *Director*

Library of Congress Cataloging in Publication Data
Bohannon, Robert G.
Nonmarine sedimentary rocks of Tertiary age in the Lake Mead region, southeastern Nevada and northwestern Arizona.
(Geological Survey Professional Paper; 1259)
Bibliography: 72 p.
Supt. of Docs. No.: I 19.16:
1. Rocks, Sedimentary. 2. Geology, Stratigraphic—Miocene. 3. Petrology—Mead, Lake, region (Ariz. and Nev.)
I. Title. II. Series.
QE471.B682 552'.5'0979312 81-607893 AACR2

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

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NONMARINE SEDIMENTARY ROCKS OF TERTIARY AGE IN THE LAKE MEAD REGION, SOUTHEASTERN NEVADA AND NORTHWESTERN ARIZONA

By ROBERT G. BOHANNON

ABSTRACT

Tertiary sedimentary rocks form a broad belt north of Lake Mead in eastern Clark County, Nev., and western Mohave County, Ariz., between Las Vegas and the Grand Wash Cliffs. This belt stradles the diffuse boundary between the Great Basin and Sonoran Desert sections of the Basin and Range structural province and is directly adjacent to the Colorado Plateaus province. Detailed study of surface exposures of these rocks has provided information pertinent to their lithology, chronology, and stratigraphy and has resulted in changes in stratigraphic nomenclature and in concepts of the Tertiary tectonic evolution of the Lake Mead region.

Three stratigraphic terms of formational status are endorsed in this report: the Horse Spring, Muddy Creek, and Hualapai. Four mappable stratigraphic units within the Horse Spring Formation are given formal member status; from oldest to youngest these are the Rainbow Gardens, Thumb, Bitter Ridge Limestone, and Lovell Wash Members. Two stratigraphic units unconformably above the Horse Spring at most localities and apparently older than most of the Muddy Creek are left informally designated as the red sandstone unit and the rocks of the Grand Wash trough. The Rainbow Gardens Member encompasses the lower part of the Thumb Formation of Longwell (1963), the lowest Tertiary beds of the Gale Hills Formation of Longwell and others (1965), most of the Horse Spring Formation of Longwell (1928), the Cottonwood Wash Formation of Moore (1972), and the formation at Tassai Ranch of Lucchitta (1966). The Thumb Member comprises the upper part of the Thumb Formation of Longwell (1963), much of the lower Gale Hills Formation of Longwell and others (1965), and the upper part of the Horse Spring Formation of Longwell (1928). The Bitter Ridge Limestone and Lovell Wash Members represent parts of the Gale Hills Formation of Longwell and others (1965), and the lower and middle parts, respectively, of the Horse Spring Formation of Longwell (1963). The red sandstone unit consists of the uppermost beds in both the Gale Hills Formation of Longwell and others (1965) and the Horse Spring Formation of Longwell (1963). Rocks commonly assigned to the Muddy Creek Formation near Grand Wash are called the rocks of the Grand Wash trough herein. The Muddy Creek Formation is also reevaluated to the extent that the term is restricted to rocks demonstrably continuous with those of the type locality. A new principal reference section is defined for the Horse Spring Formation in White Basin and Bitter Spring Valley. The type sections of the Rainbow Gardens, Bitter Ridge Limestone, and Lovell Wash Members are at the localities for which they were named, and the type locality for the Thumb is in Rainbow Gardens.

Twenty-two fission-track age determinations on zircon extracted from basal parts of airfall tuff beds in the Horse Spring Formation and the two informally named rock units are concordant with previously published K-Ar age determinations. These determinations indicate that the Thumb Member ranges from 17.2 to possibly 13.5 m.y. old, the Bitter Ridge Limestone Member from 13.5 to about 13.0 m.y. old, and the Lovell Wash Member from 13.0 to 11.9 m.y. old. The Rainbow Gardens Member has not been directly dated, but is suspected to be no older than about 20 m.y., making the Horse Spring Formation Miocene in age with a possible total age range from about 20 to 11.9 m.y. The red sandstone unit is 11.9 to 10.6 m.y. old, and the rocks of the Grand Wash trough are as old as 11.6 m.y. by fission track ages and as young as 10.9 to 8.44 m.y. by K–Ar determinations. Only two age determinations are available for the Muddy Creek Formation: an 8–m.y. age from interbedded basalt and an age of 5.88 m.y. for the Fortification Basalt Member near the top of the Muddy Creek.

The Rainbow Gardens Member occurs between Frenchman Mountain and Grand Wash, ranges from 50 to 400 m in thickness, and includes clastic rocks ranging from conglomerate to claystone, several types of carbonate rocks, evaporites, and chert. A basal conglomerate occurs, and carbonate lithologies dominate the upper portions of the member, but the middle parts are lithologically diverse. Five lithofacies delineated above the basal conglomerate include the clastic-carbonate, tuff-limestone, gypsiferous, gypsum-limestone, and magnesite facies. All are thought to have been formed in lacustrine and marginal-lacustrine environments developed above a widespread gravel on a pediment surface.

The Thumb Member occurs from Frenchman Mountain to the eastern Virgin Mountains, appears to be as thick as 1300 m or more, and consists of clastic lithologies, ranging from siltstone to breccia, and laminated gypsum. Carbonate lithologies are rare. Fine-grained clastic constituents and gypsum are widespread, forming a lacustrine depositional facies, and coarse-grained clastic lithologies form alluvial lithofacies adjacent to faulted basin margins. The lake is thought to have periodically dried, and the alluvial fans are thought to have formed along high, steep margins.

The Bitter Ridge Limestone Member is distributed between Frenchman Mountain and White Basin, is about 300 to 400 m thick, and at most locations consists of parallel-bedded limestone. Gypsiferous sandstone and conglomerate in Lovell Wash and sandstone, intraformational breccia, and limestone near Lava Butte compose a clastic lithofacies. The stromatolitic limestone is thought to have originated in a lake with very shallow water, while the other facies are thought to be alluvial and to have resulted from syntectonic sedimentation at subaerial sites near lake margins.

The Lovell Wash Member occurs between Frenchman Mountain and White Basin, is about 450 m thick at maximum, and consists of limestone, dolomite, claystone, sedimentary tuff, tuffaceous sandstone, and arenaceous tuff. An isolated lithofacies of sandstone and siltstone occurs near Black Mesa north of Callville Bay, and a conglomerate lithofacies is present in Lovell Wash. A lacustrine environment is favored for most of the member. Tuffaceous rocks either were deposited directly into the lake by airfall or were transported in by fluvial processes. Clastic lithofacies are thought to have originated near active basin-margin faults as alluvial deposits.

The red sandstone unit occurs in White Basin and east of Frenchman Mountain, is as thick as 500 m, and consists of sandstone, gypsiferous sandstone, tuff, and conglomerate. The rocks of the Grand Wash trough occur in the Grand Wash region, are thicker than 500 m, and consist of sandstone, gypsum, conglomerate, tuff, and limestone. The red sandstone unit is thought to be a playa-lake deposit in which sand accumulated by eolian activity, gypsum was deposited in the vadose zone of existing sediment, and conglomerate was shed off active basin-margin fault scarps. The rocks of the Grand Wash trough probably accumulated in a closed basin also.

The Muddy Creek Formation is distributed throughout areas of low elevation in the local part of the Basin and Range province. Its thickness is unknown, and it consists of bedded siltstone, sandstone, gypsum, gypsiferous siltstone, and conglomerate near basin margins. It is thought to have formed during basin- range development in alluvial, fluvial, and lacustrine environments associated with valleys having internal drainage.

The Tertiary sedimentary rocks have been deformed and fragmented by 65 km of left slip along the Lake Mead fault system, 40–60 km of right slip along the Las Vegas Valley shear zone, crustal extension of possibly 100 percent or more in a S. 70° W. direction, and stratal tilting associated with normal faulting. These structural elements are thought to have become active after early stages of sedimentation and to have interacted with one another during sedimentation. A palinspastically restored pre-Rainbow Gardens Member paleogeologic map indicates north-northeast trending, west-dipping thrusts of the Sevier belt west of a topographically featureless autochthon slightly deformed by a large north-trending arch cored by Precambrian crystalline rocks. Between 20 and 17 m.y. ago, the Rainbow Gardens Member was deposited in a broad, shallow sag with low-relief margins developed on the nose and northeastern flank of the arch between the thrusts and the present position of the Colorado Plateau. The Thumb Member was deposited at the same site in a deep fault-bounded trough between 17 and 13.5 m.y. ago, possibly as a result of synchronous initial activity on the Lake Mead fault system and the Las Vegas Valley shear zone. The Bitter Ridge Limestone and Lovell Wash Members occur only northwest of the Lake Mead fault system, and they record major activity on that system and the Las Vegas Valley shear zone about 13 m.y. ago. Crustal extension south of Lake Mead accompanied this activity. The red sandstone unit and the rocks of the Grand Wash trough formed in grabens and on the downthrown sides of tilted mountain blocks, which overprinted earlier structures and may represent early Basin and Range deformation between 12 and 10 m.y. ago. The Muddy Creek Formation filled Basin and Range valleys and overlapped most of the basin-forming structures.

INTRODUCTION

In the Lake Mead region, between Las Vegas, Nev., and the Grand Wash Cliffs in Arizona (fig. 1), are abundant, widespread exposures of nonmarine and probable nonmarine sedimentary rocks of Tertiary age. The oldest of these rocks were deposited upon Mesozoic and Paleozoic rocks which at that time were nearly undeformed except where directly affected by Cretaceous thrust faults. These oldest Tertiary rocks are now highly deformed. They are exposed in mountain ranges and valleys of the Basin and Range structural province, and apparently they predate the development of that province in the Lake Mead region. The youngest of the Tertiary sedimentary rocks, on the other hand, are confined to the valleys of the Basin and Range province, are relatively undeformed, and rest with angular unconformity on all of the older Tertiary and pre-Tertiary rocks. Tertiary deposition was synchronous with the formation of Basin and Range structure, and its style records the historical development of the province. Sedimentation evolved from an early pattern of regional accumulation in a broad downwarp, through a period of deposition in response to strike-slip and associated normal faulting, into final stages of sedimentation in localized Basin and Range valleys. The final stage of basin filling is still active in many parts of the province, but in most of the Lake Mead area, deposition has halted subsequent to downcutting of the Colorado River system, which has initiated a period of dissection and erosion.

The complex Tertiary stratigraphy of the Lake Mead region had not been previously mapped or studied in detail, and its description and interpretation are the chief purposes of this report. Recent detailed geologic mapping in the Valley of Fire (Bohannon, 1977a), in Bitter Spring Valley and White Basin (Bohannon, 1977b), and in the Gale Hills (Bohannon, 1983) provides the basis for the description and the framework for the interpretation. Previously published stratigraphic nomenclature provides no adequate basis for regional mapping and correlation, and it is reevaluated and revised accordingly herein. The early nomenclature evolved over a period of decades, during which time many different geographically restricted stratigraphic names were introduced. There apparently was no understanding of the stratigraphic framework of the region. Ages of the Tertiary rocks were not well understood even in the light of limited K–Ar dating reported by Anderson and others (1972). In the absence of good chronologic and stratigraphic information, it was not possible for previous workers to relate Tertiary rocks regionally, and thus, the described Tertiary geologic history of this part of the Great Basin and the Colorado Plateau was equivocal. This report focuses on revisions and refinements of stratigraphic nomenclature, stratigraphic correlation, rock description, rock age, sedimentary history, and sedimentary and tectonic depositional environments of all of the Tertiary rocks of the Lake Mead region. The evolution of this sedimentary

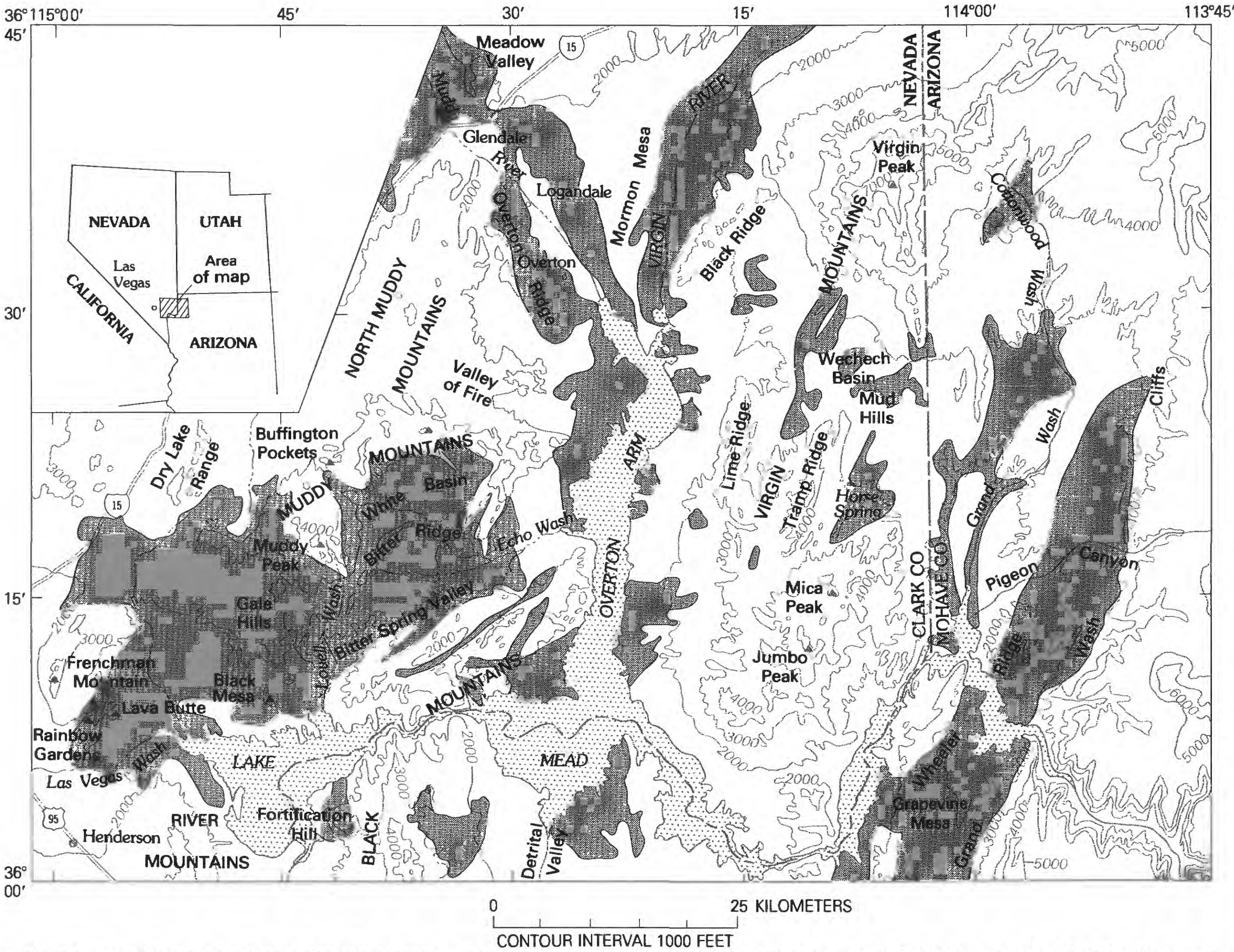


FIGURE 1.—Location map of the Lake Mead region showing the general topography, major physiographic features referred to in the text, and the generalized distribution of Tertiary sedimentary rocks (shaded areas).

sequence is examined in the light of its relation to the development of the Basin and Range province and its differentiation from the Colorado Plateaus province.

ACKNOWLEDGMENTS

The U.S. Geological Survey began studying this area in 1974 as part of a national appraisal of lithium resources, because concentrations of lithium within some of these rocks is abnormally high. Other geologists that contributed to this study in its early phases include J. D. Vine, R. K. Glanzman, and Elizabeth Brenner-Tourtelot. Special thanks are extended to R. E. Anderson, who continuously gave time and attention to the project. Fission-track dates were determined with the aid, instruction, and assistance of Chuck Naeser. National Park Service personnel, especially the rangers at Echo Bay, were extremely helpful and cooperative. Comments resulting from manuscript reviews by R. E. Anderson and T. D. Fouch greatly influenced the report.

STRATIGRAPHIC NOMENCLATURE

HISTORICAL DEVELOPMENT

Two stratigraphic names of formational status, the Muddy Creek and Horse Spring, have been widely accepted in the region, although little attention has been paid to the age and stratigraphic position of the rocks for which the names are commonly used. Stock (1921) named the Muddy Creek Formation for outcrops of nearly undeformed strata in the bluffs of Meadow Valley north of Overton, Nev. Longwell (1921, 1922) named apparently older rocks exposed in a hogback near Horse Spring in the southern part of the Virgin

Mountains the Horse Spring Formation. The type locality of the Horse Spring was not precisely located, and much of the lithologic description was from Overton Ridge 40 km to the northwest (fig. 1).

In the Virgin Mountain–Grand Wash Cliffs area, stratigraphic nomenclature further evolved with the introduction of three new names and the widespread application of the term Muddy Creek Formation. Longwell (1928, 1936) proposed the name Tassai Wash Group for rocks that unconformably overlie the Permian Kaibab Limestone at the north end of Wheeler Ridge. On lithologic grounds he considered these rocks to be of probable Tertiary age and a possible correlative to the Horse Spring Formation. Lucchitta (1966) tentatively supported that lithologic correlation. Moore (1972) named the Cottonwood Wash Formation for Tertiary rocks unconformably above Cretaceous(?) and Jurassic rocks in Cottonwood Wash. Both the Tassai Wash and Cottonwood Wash are exposed within 25 km of Horse Spring and are lithologically and stratigraphically similar to the Horse Spring Formation in its type locality. These new names appear to have been proposed as a result of a lack of understanding of regional stratigraphy. Slightly deformed to undeformed rocks that unconformably overlie the Horse Spring, the Tassai Wash, and the Cottonwood Wash in the Grand Wash region have been referred to as the Muddy Creek Formation (Longwell, 1928, 1936; Lucchitta, 1966, 1972; Blair, 1978). However, no similarity of detailed lithology, no age correlation, and no direct connection with the Muddy Creek type locality of Stock (1921) was demonstrated for these rocks by the authors. A thick limestone unit overlying the rocks called Muddy Creek in the area of Wheeler Ridge and the Grand Wash Cliffs was named the Hualapai Limestone (Longwell, 1936). Lucchitta (1972) and Blair (1978) consider the Hualapai to be a member of the Muddy Creek Formation, thereby redefining the upper contact of the Muddy Creek and reducing the stratigraphic rank of the Hualapai. These relations are summarized in column *4A* of figure 2, except that the Tassai Wash Group and Cottonwood Wash Formation are not shown in the column owing to lack of space. These two units are equivalent to the lower half of the Horse Spring Formation.

At Overton Ridge near the type locality of the Muddy Creek Formation, Longwell (1921, 1928, 1949) described two formations of Tertiary and possible Tertiary age older than the Muddy Creek—the Horse Spring Formation and the Overton Fanglomerate. Carbonate rocks (largely dolomite and magnesite) of the Horse Spring Formation were described as conformably overlying conglomerate of the Overton Fanglomerate. The Overton Fanglomerate was, in turn, described as unconformably overlying the Cretaceous Baseline Sandstone. However, as a result of detailed geologic mapping, Bohannon (1976, 1977) reduced the rank of the Overton Fanglomerate to the Overton Conglomerate Member of the Baseline Sandstone. Bohannon (1977a) mapped an unconformity, not previously recognized, beneath a thin conglomerate that is conformable with the overlying carbonate rocks that Longwell (1921, 1928, 1949) referred to as Horse Spring Formation. Bohannon (1976, 1977a) includes the thin conglomerate, which was formerly part of the Overton Fanglomerate, with the Horse Spring Formation. The relations described by Longwell (1949) are shown in column *3A*, and those described by Bohannon (1976, 1977a) are shown in the lower left part of column *3B*, both on figure 2.

South of the Muddy Mountains, in the Gale Hills, Bitter Spring Valley, and White Basin, widespread exposures of Tertiary rocks were originally described by Longwell (1921, 1928) as the Horse Spring Formation. Longwell and others (1965) later included rocks thought by them to be the Cretaceous Willow Tank Formation, the Cretaceous Baseline Sandstone, the Cretaceous and Tertiary(?) Overton Fanglomerate, and the Tertiary Horse Spring Formation together as the Cretaceous(?) or Tertiary(?) Gale Hills Formation. By means of detailed geologic mapping, I (Bohannon, 1977b, and unpublished mapping) differentiated the Willow Tank Formation, Baseline Sandstone, and Horse Spring Formation. I did not use the term Gale Hills Formation, and I subdivided the Horse Spring Formation into three informal members (Bohannon, 1977b). The terminology of Longwell and others (1965) as it applies to the rocks of White Basin and Bitter Spring Valley is shown in column *2A* of figure 2. The scheme used by Bohannon (1977b) is not depicted there but is discussed further below.

As part of a reconnaissance study of the geology along part of the Colorado River, Longwell (1963) named the Thumb Formation for exposures of predominantly clastic beds in the vicinity of Rainbow Gardens near Frenchman Mountain. He considered the Thumb Formation to be possibly temporally correlative with the Willow Tank Formation or Baseline Sandstone and on this basis assigned a possible age of Cretaceous or Tertiary to it. Light-colored carbonate beds stratigraphically above the Thumb Formation were correlated with the Horse Spring Formation, and widespread exposures of slightly deformed rocks that unconformably overlie both of these units were mapped as Muddy Creek Formation. The above scheme is diagrammed in column *1A* of figure 2.

For a regional analysis of strike-slip faulting, Bohannon (1979) subdivided many of the above rock units into informal members. These members were based on detailed stratigraphic and lithologic studies as well as age

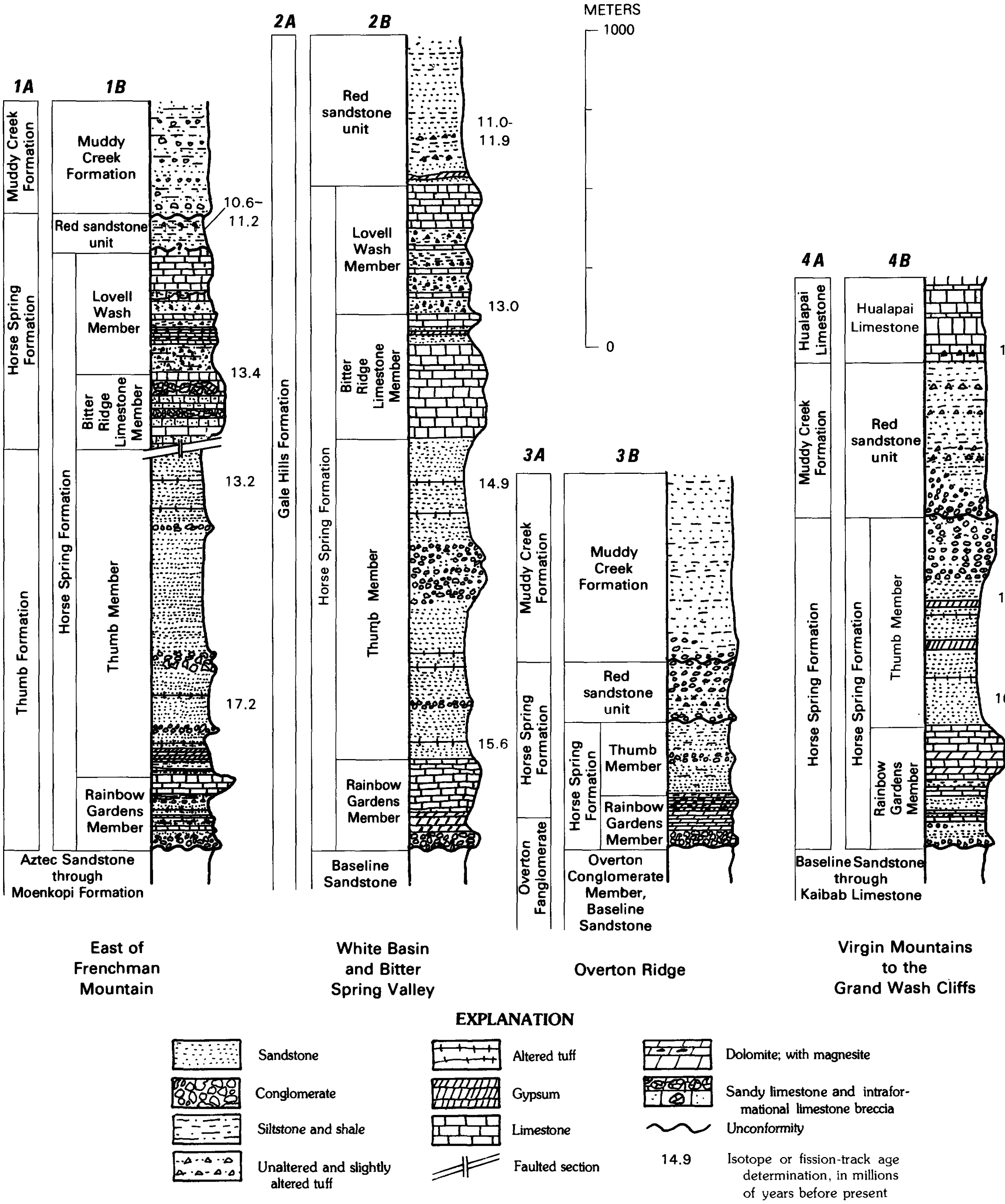


FIGURE 2—General lithology and stratigraphy, previous stratigraphic nomenclature (*A* column), and proposed stratigraphic nomenclature (*B* column) of the Tertiary rocks of the Lake Mead region. Ages of the rocks are generalized from tables 1 and 2.

data, but do not provide a completely adequate regional nomenclature scheme.

The problems inherent with the nomenclature presented above are numerous. Historically, where terms such as Muddy Creek and Horse Spring have been used regionally, it has been without proper attention to stratigraphic details. This problem has been compounded by the large-scale displacement and distortion along the left-slip Lake Mead fault system and the right-slip Las Vegas Valley shear zone and in large areas of crustal extension, all of which were active during sedimentation. These large structures have subsequently fragmented once-continuous rocks, leaving them widely separated geographically (Anderson, 1971, 1973; Bohannon, 1979). Published stratigraphic nomenclature was proposed before this complex depositional and structural history was known, and in the absence of detailed stratigraphic information. Inconsistencies of this nomenclature are discussed below in the light of lithologic data presented in brief descriptions of four composite stratigraphic sections, and age interpretations derived primarily from tuffaceous beds within those sections (fig. 2).

PROPOSED STRATIGRAPHIC NOMENCLATURE

The system of stratigraphic nomenclature proposed in this report retains some of the most widely used geologic names, but reorganizes them slightly. Some names are abandoned, and three new formal names are proposed as a result of detailed geologic mapping. Formal nomenclature is used only where regional geologic, stratigraphic, and structural interpretations substantiate its use. Informal nomenclature is employed where regional relations are uncertain and stratigraphic continuity cannot be demonstrated. Because a basic understanding of stratigraphic and lithologic character of the units is necessary to make the new nomenclature meaningful, brief descriptions, which are keyed to figure 2, are provided below for the area east of Frenchman Mountain, the White Basin–Bitter Spring Valley area, Overton Ridge, and the Virgin Mountains–Grand Wash Cliffs area. More complete presentations of lithologic and age data follow in other sections of this report.

East of Frenchman Mountain, in Rainbow Gardens, the type section of the Thumb Formation of Longwell (1963) contains two distinct mappable units totaling 1,200 m in thickness, and it unconformably overlies Mesozoic formations ranging from the Jurassic and Triassic(?) Aztec Sandstone through the Middle(?) and Lower Triassic Moenkopi Formation. The lower mappable unit includes 30 m of conglomerate overlain by interbedded red to pink sandstone and gray limestone under a resistant, poorly bedded, light-colored limestone. The lower unit is wedge shaped and varies from more than 300 m thick near Las Vegas Wash to less than 30 m thick northwest of Lava Butte. The upper mappable unit, which is almost 1,000 m thick, is primarily red and brown sandstone, but also contains gypsum, conglomerate, breccia, altered green sedimentary tuff beds, partially altered gray tuffaceous beds, and some lava flows. Radiometric ages suggest that the upper unit ranges from possibly older than 17.2 m.y. to possibly as young as 13 m.y.

Overlying Longwell's (1963) Thumb Formation, 700 m of carbonate rock, tuff, and red sandstone that he called Horse Spring Formation can be subdivided into three distinct mappable units. A resistant lower unit, nearly 200 m thick, is pale brown and buff, arenaceous, thick-bedded limestone and intraformational limestone breccia and conglomerate. Above that is a lithologically complex unit of white limestone, white and gray tuff, tuffaceous sandstone, gray and white clay beds, and brown chert. An age from interbedded volcanic rocks in the vicinity of the contact between the two units suggests that they are about 13 m.y. old. A thin unit of red sandstone with gray and white air-fall tuff beds is the highest mappable unit, although the nature of its basal contact is uncertain. Age interpretations from the red sandstone section indicate that it ranges from 11.2 to 10.6 m.y. old.

Brown conglomerate, pink siltstone and sandstone, and white gypsum are conformably higher than all of the rocks described above. No dates have been determined for these rocks in the Frenchman Mountain area. They have been mapped as the Muddy Creek Formation (Longwell, 1963; Longwell and others, 1965).

In White Basin and Bitter Spring Valley, the Tertiary part of the Gale Hills Formation (Horse Spring Formation of Bohannon, 1977b) is similar in lithology and age to the combined Thumb and Horse Spring Formations (Longwell, 1963) east of Frenchman Mountain. At most localities in White Basin and Bitter Spring Valley, these Tertiary rocks unconformably overlie the Baseline Sandstone. In Echo Wash, though, they overlie the Aztec Sandstone.

In Bitter Spring Valley, the Gale Hills, and Echo Wash, the lower part of the Tertiary section contains two mappable units like those of the Thumb Formation of Longwell (1963) at Frenchman Mountain. The lowest unit consists of a thin (10- to 50-m-thick), continuous basal conglomerate overlain by poorly bedded white gypsum. In Echo Wash this gypsum is, in turn, succeeded by a thick lenticular body of wavy-bedded yellow limestone, which is also included in the lowest unit. The upper mappable unit, which is about 1,100 m thick, consists of brown parallel-bedded sandstone, conglomerate and lenticular bodies, and beds of thinly laminated white gypsum. Continuous altered green tuff beds are common in both mappable units. Fission-track and K–Ar dates suggest that these units, whose total thickness is 1,300 to 1,400 m, range in age from 15.6 to 14.9 m.y. Bohannon (1977b) mapped these rocks as the lower member of the Horse Spring Formation and correlated them on a lithologic basis with the Thumb Formation east of Frenchman Mountain.

In White Basin, the upper part of the Tertiary section consists of three different units, which are like those of the Horse Spring Formation of Longwell (1963) east of Frenchman Mountain. About 300 to 400 m of light-buff, pale-yellow, and tan, wavy- and parallel-bedded limestone exposed at Bitter Ridge makes up the lowest of the three. This lowest unit is overlain by a lithologically complex middle unit of white limestone, white and gray tuff and tuffaceous sandstone, gray and white clay beds, and brown chert. The youngest unit, 400 m thick, consists of red sandstone with abundant gray and white sedimentary tuff beds and sparse, discontinuous gypsum lenses. The three units total 1,200 m in thickness. One date from the middle unit suggests that it is about 13 m.y. old. Further age data suggest that the youngest unit may range from as old as 11.9 m.y. to as young as 11.0 m.y. Bohannon (1977b) abandoned the use of the term Gale Hills Formation, mapped the lowest unit of this sequence as the middle member of the Horse Spring Formation, and combined the two uppermost units as the upper member.

At Overton Ridge, the Horse Spring Formation, as mapped by Bohannon (1976, 1977a), is in a stratigraphic position similar to that of the lowest mappable unit in the Thumb Formation of Longwell (1963) east of Frenchman Mountain and the lowest Tertiary unit in Bitter Spring Valley. Here a continuous basal conglomerate 50 m thick is overlain by pink dolomite and magnesite. These rocks, which unconformably overlie the Baseline Sandstone, are in turn overlain by 200 m of brown bedded siltstone and poorly bedded conglomerate. At one location, a thin unit of red sandstone with gray and white tuff beds overlies the latter beds and has an apparent age of 12.5 to 15.6 m.y. An unknown thickness of pink siltstone, pink sandstone, and brown conglomerate unconformably overlies all of the above rocks and constitutes the type locality of the Muddy Creek Formation (Stock, 1921).

In the Virgin Mountains at Wechech Basin and at Horse Spring, the type Horse Spring Formation contains two mappable units, the upper of which is the same age as the upper unit in the Thumb Formation of Longwell (1963) in Rainbow Gardens. Bohannon (1979) described the lithologic similarities between basal units in the two areas. The similarities include the overall wedge shape of the two units and their stratigraphy, which consists, from base to top, of a basal conglomerate above Mesozoic rocks, red sandstone with calcite filled "tubelets," and resistant, poorly bedded, "fragmental" limestone. The upper unit in the Virgin Mountains, which consists of 1,200 m of brown, parallel-bedded sandstone, white laminated gypsum, conglomerate, and altered, green tuff beds, is lithologically similar to the upper unit of the Thumb Formation at Rainbow Gardens and much of the lower member of the Horse Spring Formation of Bohannon (1977b) in Bitter Spring Valley. Age data from Wechech Basin suggest that the upper unit ranges from 16.3 to 15.9 m.y. old and that the two units correlate with those of the Thumb in Rainbow Gardens and the lower member of the Horse Spring in Bitter Spring Valley. However, no rocks known to occur in the type section of the Horse Spring Formation at Horse Spring or in Wechech Basin have the correct lithology, stratigraphic position, or age to correlate with the rocks mapped as Horse Spring Formation near Rainbow Gardens by Longwell (1963).

At Cottonwood Wash, at Grand Wash, and between Wheeler Ridge and the Grand Wash Cliffs, a sequence of red sandstone, gray and white tuff beds, conglomerate, gypsum, and limestone, which is commonly called the Muddy Creek Formation (Longwell, 1928, 1936; Lucchitta, 1972, 1979; Blair, 1978), unconformably overlies beds thought to be equivalent to the lower unit described above in Wechech Basin. At the above-named places the red sandstone is lithologically similiar to the stratigraphically highest unit in White Basin and to rocks that occur unconformably beneath the Muddy Creek Formation east of Frenchman Mountain. The interpreted age range of 11.6 to 8.4 m.y. for this red sandstone unit suggests that it correlates temporally both with the latter units and possibly with the lower part of the Muddy Creek at its type locality. The unit commonly called the Hualapai Limestone is apparently part of the Muddy Creek Formation in Detrital Valley and is also gradational above the red sandstone described above in Grand Wash, but lies on Precambrian rocks between the two valleys.

The nomenclature of the rocks of the Lake Mead region is redefined below.

The Horse Spring Formation as herein redefined has its principal reference area, designated in this report, in Bitter Spring Valley and White Basin. This area contains the thickest, best exposed, and most lithologically complete section of these rocks known. As redefined herein, the Horse Spring Formation includes all the Tertiary rocks below the Muddy Creek Formation of Stock (1921), with the exception of the informal unit of red sandstone with gray and white tuff beds which occurs east of Frenchman Mountain and in White Basin. Although the principal reference area is remote from Horse Spring, the name is retained because of its time-honored acceptance and use. A principal reference section 2,100 m thick is defined between longitudes 114°36′ and 114°37′ W. and latitudes 36°15′45″ and 36°19′30″ N. (Muddy Peak 15-minute quadrangle).

This part of Bitter Spring Valley, Bitter Ridge, and White Basin contains a complete north- to northwest-dipping section, which includes the base and top of the Horse Spring Formation and representative strata of four mappable units herein designated as members. The base of the Horse Spring Formation is defined at the regionwide unconformity above Mesozoic formations, upper Paleozoic formations, and the Cretaceous and Tertiary(?) Baseline Sandstone. The top of the Horse Spring Formation is defined at the well-developed contact between the white limestone, white and gray tuffaceous rocks and light-gray claystone of the uppermost Horse Spring, and the overlying unit of red sandstone (fig. 2).

Type sections for the four formal members of the Horse Spring Formation have been chosen in areas where the best exposures and most representative lithologies of each member are present. These locations do not necessarily correspond to the location of the Horse Spring principal reference section defined above.

The oldest member of the Horse Spring Formation is herein named the Rainbow Gardens Member for exposures in Rainbow Gardens. The type section, which is about 300 m thick, is designated at latitude 36°08′30″ N. and longitude 114°57′30″ W. in the Henderson, Nev., and Frenchman Mountain, Nev., 7½-minute quadrangles. This member includes the oldest mappable unit within Longwell's (1963) Thumb Formation east of Frenchman Mountain, the oldest Tertiary mappable unit in the Bitter Spring Valley area, most of the Horse Spring at Overton Ridge, and the lowest unit in the Horse Spring Formation of Longwell (1921, 1922) in the Virgin Mountains area. At its type section, the base of the Rainbow Gardens Member corresponds to the base of the Horse Spring Formation where it unconformably rests on the Moenkopi Formation. The type section dips to the southeast, and its top is defined at the top of the resistant limestone that forms a well-developed hogback throughout Rainbow Gardens. Complete location-by-location lithologic descriptions, detailed stratigraphic sections of the Rainbow Gardens Member, and more exact definitions of member boundaries can be found below in the section "Description of Rock Units."

The Thumb Member of the Horse Spring Formation is redefined here as the rocks stratigraphically above the Rainbow Gardens Member and below the carbonate rocks of the Bitter Ridge Limestone Member. The principal reference section of the Thumb Member, which is as much as 1,000 m thick, is defined in the Rainbow Gardens area at about 36°07′30″ N. latitude and 114°56′45″ W. longitude in the Henderson, Nev., and Frenchman Mountain, Nev., 7½-minute quadrangles. Here, the Thumb rests conformably on the upper limestone of the Rainbow Gardens Member. This member includes the upper mappable unit of Longwell's (1963) Thumb Formation east of Frenchman Mountain. Although the name Thumb Valley no longer appears on local topographic maps, the name "Thumb" is retained for the Thumb Member because of its time-honored acceptance and use. Complete location-by-location descriptions accompanied by measured stratigraphic sections can be found below in the section "Description of Rock Units."

The limestone that composes the hogback of Bitter Ridge between Bitter Spring Valley and White Basin is herein defined as the Bitter Ridge Limestone Member of the Horse Spring Formation.[1] The base of the Bitter Ridge Limestone Member is defined at the top of the stratigraphically highest sandstone bed of the Thumb Member, and the top of the Bitter Ridge is defined at the top of the uppermost resistant limestone bed, which is overlain by less resistant gray and white tuffaceous beds. The type section, which is about 300–400 m thick, is at Bitter Ridge at latitude 36°18′30″ N. and longitude 114°35′00″ W. in the Muddy Peak, Nev., 15-minute quadrangle. In this area, the member dips to the north. Complete lithologic descriptions are included in a subsequent section of this report.

The youngest member of the Horse Spring Formation is herein called the Lovell Wash Member and is named for rocks stratigraphically above the Bitter Ridge Limestone Member in Lovell Wash. The type section in Lovell Wash is defined at latitude 36°12′45″ N. and longitude 114°42′30″ W. in the Hoover Dam, Nev., 15-minute quadrangle, where about 300 m of the member is exposed in a syncline.

The unit of red sandstone and siltstone that contains gray and white tuff beds and discontinuous gypsum lenses in White Basin and the area east of Frenchman Mountain is not included with the Horse Spring Formation, because it possibly is unconformable with the Horse Spring. There is also a lithologically and chronologically similar unit in Grand Wash and between Wheeler Ridge and the Grand Wash Cliffs. These two units apparently have distributions and sedimentary-tectonic histories different from those of the Horse Spring Formation. In the Grand Wash area, the red sandstone is commonly referred to as Muddy Creek Formation (Longwell, 1936; Lucchitta 1966, 1979), but is confined within local basins (Lucchitta, 1966) that are not continuous with the basin in which the principal reference section of the Muddy Creek was deposited. Furthermore the red sandstone in the Grand Wash area is older than the Muddy Creek Formation at its principal reference section. For the above reasons,

[1]There are two ridges locally called Bitter Ridge. The other is in the Virgin Mountains and is not composed of Bitter Ridge Limestone Member.

these units are left informally designated as the red sandstone unit in White Basin and east of Frenchman Mountain, and as the rocks of the Grand Wash trough in the Grand Wash area, throughout this report.

The Hualapai Limestone presents a special nomenclature problem because it is commonly called a formal member of the Muddy Creek Formation in recent literature (Blair, 1978; Blair and Armstrong, 1979; and Lucchitta, 1972, 1979). Its member status is chiefly based upon the fact that limestone is interbedded with red sandstone at the base of the main body of Hualapai Limestone at Grapevine Mesa, and the red sandstone has traditionally been termed Muddy Creek. In this report, however, the red sandstone that is interbedded with the limestone of the Hualapai is considered to be part of the rocks of the Grand Wash trough rather than part of the Muddy Creek. On this basis, it is better to refer to the Hualapai as part of the rocks of the Grand Wash trough rather than as a member of the Muddy Creek. However, the Hualapai extends to the west of Grapevine Mesa beyond the western limits of the underlying red sandstone, where it rests directly on Precambrian crystalline rocks. It ultimately extends into Detrital Valley, where it rests on rocks called Muddy Creek Formation. Because the stratigraphic relations of the Hualapai with the Muddy Creek in Detrital Valley are incompletely understood owing to a paucity of published maps and accurate descriptions there, and because the Hualapai interfingers with informally named rocks in the Grand Wash trough, it is left unassociated with either the rocks of the Grand Wash trough or the Muddy Creek; it is restored here to its original formational rank (Longwell, 1936) and referred to simply as the Hualapai Limestone.

The Muddy Creek Formation of Stock (1921) is slightly reevaluated in this report in that the use of that term is restricted somewhat. Only rocks that can be demonstrated to have been stratigraphically continuous with those of the Muddy Creek type locality are called Muddy Creek Formation.

AGE OF THE TERTIARY ROCKS

The precise age of the Tertiary nonmarine sedimentary rocks in the Lake Mead region has been poorly documented largely because fossils are rare to nonexistent, and because some important unconformities were not detected. Although Anderson and others (1972) report 24 K-Ar determinations from igneous rocks associated with the nonmarine sedimentary rocks, the authors did not agree among themselves (Anderson and others, 1972, p. 283) that the age determinations were representative of the age of the sedimentary rocks. The disagreement focused upon whether the ages were determined from lava flows interbedded with the sedimentary rocks or from younger shallow intrusive rocks, and on whether or not the dates from demonstrated extrusive rocks were reset by thermal effects from nearby intrusive rocks. Several additional factors must be considered concerning the dates presented by Anderson and others (1972). The lower part of the section was never dated by them, even in Rainbow Gardens, and they still considered it to be possibly Cretaceous in age. Also, saline minerals present throughout the Horse Spring Formation suggest that the associated ground water was capable of altering volcanic rocks[2] and of subsequently chemically adjusting the apparent K-Ar ages. In addition, the ages reported by Anderson and others (1972) were grouped and referred to in terms of the confusing system of stratigraphic nomenclature in existence at the time and they, therefore, must be reevaluated in the light of newly documented stratigraphic relations.

Twenty-five fission-track age determinations were made on zircon extracted from basal tuff beds interpreted to be of air-fall origin interbedded with the other Tertiary sedimentary rocks. The fission-track dating method was chosen for several reasons: zircon is present, is not susceptible to alteration, and has a high resistance to track annealing upon heating. Also, fission-track dating of zircon, which is rich in uranium, works especially well in Tertiary rocks. The age-determination procedure follows that of Naeser (1976), and lab work was done in Naeser's lab under his guidance.

Two important assumptions must be made when evaluating fission-track age determinations as primary ages. It must be assumed that the dated rock has not endured a heating event later than its original formation, or that it has not undergone a prolonged cooling history. Also, it must be assumed that the dated grains are not detrital and have had the same thermal history as the encompassing rock. The inferred air-fall origin and the limited stratigraphic thickness of the dated tuffs suggest that they have not undergone a slow cooling history, and their mineralogy indicates that they have not been postdepositionally heated beyond the annealing temperature of zircon. Naeser (written communication, 1978) has demonstrated that the approximate annealing temperature of zircon through geologic time is about 175°-200°C. The presence of both heulandite[3] and analcime in the dated tuffs suggests that

[2]Many of the dated rocks are highly altered.

[3]Both clinoptilolite and heulandite are present in these tuffs. Ordinarily, when X-ray diffraction techniques are used, heulandite is masked by clinoptilolite. By means of heating experiments outlined by Mumpton (1960), Harry Starkey (written communication, 1978) demonstrated the presence of heulandite in the dated tuffs.

they have not been subjected to temperatures above about 150°-175°C for long time periods (Coombs, 1971; p. 324, fig. 3). In most cases, the presence of glass or zeolite adhering to the dated grains after grinding and mineral separation attests to the nondetrital nature of the grains. An individual example (sample 40 from Overton Ridge) in which detrital contamination may present a serious problem is discussed separately below.

The relevant K-Ar dates presented by Anderson and others (1972) are shown in table 1, the 19 new fission-track dates are given in table 2, and the supporting data are summarized in table 3. The most important dated samples are located on three regional diagrams of the Muddy Mountains area, the Virgin Mountains-Grand Wash Cliffs area, and the Frenchman Mountain area (fig. 3).

East of Frenchman Mountain, six fission-track and K-Ar samples date the Thumb Member of the Horse Spring Formation. The Rainbow Gardens Member has not been dated owing to a paucity of datable rocks. Fission-track samples 20, 21, 22, and 34 date the Thumb Member and suggest a range from 16.2 to 13.2 m.y. Sample 34 is the youngest of the samples from the Thumb Member at 13.2 m.y.; it is probably anomalously young because its age overlaps with those of stratigraphically higher samples. Two samples from the Thumb Member have K-Ar ages reported by Anderson and others (1972) that appear to fall within the above fission-track range (samples 12 and 13; 17.2±3 and 15.6±3 m.y. respectively). These samples are from unaltered core rock of a pyroxene-olivine andesite that can be demonstrated to be a lava flow interstratified with the sedimentary rocks (R. E. Anderson, written commun., 1978). Algally laminated carbonate incrustations and domes deposited on the upper surface of this andesite testify to its origin as a lava flow.

Several of the K-Ar samples reported by Anderson and others (1972) from the Thumb are much younger than the above age range (samples 7, 8, and 9). Although these samples are possibly from extrusive igneous rocks interstratified with the Thumb Member, later chemical analyses indicate that the sampled rocks are altered and contain as much as 8 percent K_2O. This excess potassium explains their anomalously young K-Ar ages; these samples should be disregarded (R. E. Anderson, written communication, 1978).

TABLE 1.—*Selected previously published K-Ar ages for Tertiary rock samples from the Lake Mead region, Nevada and Arizona*

[Ages are taken from Anderson and others (1972, table 1) except as noted. Data have not been recalculated to new constants]

Sample No. This rept.	Sample No. Orig.[1]	Rock type	North latitude	West longitude	General locality	Rock unit	K-Ar age (m.y.)
1	1	Ash-flow tuff--------	36°38′20″	114°31′30″	Northern Muddy Mts., near Glendale.	Possibly Hiko, Racer Canyon or Harmony Hills Tuff.	21.3 ±0.4
2	2	--------do--------	36°38′20″	114°31′40″	----------do----------	-------------do------------	19.6 ±0.8
3	3	--------do--------	[2]36°30′	114°36′	SE. of Muddy Mts.-------	Thumb Member --------------	15.3 ±0.7
4	4	Tuff?--------------	36°13′	114°48′	SW. of Muddy Mts.------	-------------do------------	14.9 ±0.5
5	5	--------do--------	36°14′	114°45′30″	----------do----------	-------------do------------	15.1 ±0.5
6	6	Basaltic lahar-------	36°09′	114°46′	S. of Black Mesa---------	Uncertain -------------------	13.2 ±0.5
7	7	Mafic alkalic igneous rock.	36°06′20″	114°57′22″	Rainbow Gardens--------	Thumb Member--------------	10.9 ±1.1
8	8	Biotite-hornblende rhyodacite.	36°07′50″	114°56′25″	Rainbow Gardens, NE. of Red Needle.	Igneous rocks of Lava Butte ----	13.4 ±0.7
9	9	--------do--------	36°07′50″	114°56′25″	----------do----------	-------------do------------	11.7 ±2.0
10	10	Mafic alkalic igneous rock.	36°07′15″	114°58′35″	Rainbow Gardens--------	Thumb Member--------------	11.8 ±1.0
11	11	--------do--------	36°07′15″	114°58′35″	----------do----------	-------------do------------	11.8 ±0.7
12	12	Pyroxene-olivene andesite lava.	36°07′27″	114°56′38″	Rainbow Gardens, SE. of Red Needle.	-------------do------------	17.2 ±3
13	13	--------do--------	36°07′27″	114°56′38″	----------do----------	-------------do------------	15.6 ±3
14	15	Basalt lava---------	35°56′39″	114°39′25″	SE. of Hoover Dam------	Fortification Basalt Member, Muddy Creek Formation.	4.9 ±0.4
15	21	--------do--------	35°49′40″	114°38′20″	Malpais Flattop Mesa ----	-------------do------------	5.8 ±1.0
16	22	--------do--------	36°10′10″	114°41′20″	Callville Wash----------	-------------do------------	11.3 ±0.3
[3]17	23	--------do--------	36°02′45″	114°39′35″	Fortification Hill--------	-------------do------------	10.6 ±1.1
18	24	--------do--------	36°09′55″	114°46′	Black Mesa-------------	-------------do------------	11.1 ±0.5
19	([4])	--------do--------	36°02′48″	114°39′36″	Fortification Hill--------	-------------do------------	5.88±0.18

[1]Sample numbers shown by Anderson and others (1972, table 1).

[2]Probably an incorrect coordinate, as Anderson and others (1972, table 1), describe this location as "near Bitter Spring" and show it at about 36°15′ N. on their map.

[3]Now superseded by sample no. 19.

[4]Unnumbered sample from Damon and others (1978).

TABLE 2.—*Zircon fission-track ages of samples from Tertiary rocks of the Lake Mead region, Nevada and Arizona*

[Analytical data are given in table 3]

Sample No.	Rock type	North latitude	West longitude	Locality description	Stratigraphic unit	Fission-track age (m.y.)
20	Green air-fall tuff ----	36°11′10″	114°54′45″	5 km NE. of Lava Butte --	Thumb Member--------------	14.8±1.4
21	Silver-gray air-fall tuff	36°11′10″	114°55′00″	----------do----------	-------------do------------	16.1±1.5
22	--------do--------	36°10′47″	114°54′15″	----------do----------	-------------do------------	16.2±0.8
23	Green air-fall tuff ----	36°17′27″	114°34′05″	Bitter Spring Valley------	-------------do------------	15.4±0.8
24	--------do--------	36°18′15″	114°36′12″	----------do----------	-------------do------------	15.6±1.0
25	White air-fall tuff ----	36°19′34″	114°38′10″	White Basin------------	Red sandstone unit------------	11.9±0.9
26	Silver-gray-air-fall tuff	36°19′34″	114°38′10″	----------do----------	-------------do------------	11.7±1.3
27	--------do--------	36°19′55″	114°39′05″	----------do----------	-------------do------------	11.2±1.1
28	Gray air-fall tuff -----	36°12′37″	114°42′15″	Lovell Wash------------	Lovell Wash Member----------	13.0±0.8
29	Silver-gray air-fall tuff	36°20′45″	114°40′28″	White Basin------------	Red sandstone unit------------	11.0±0.9
30	--------do--------	36°30′55″	114°28′55″	Overton Ridge----------	-------------do------------	15.6±0.9
31	Ash-flow tuff--------	36°39′10″	114°31′52″	Northern Muddy Mtns. near Glendale.	Unknown (possibly equivalent to Hiko, Racer Canyon, or Harmony Hills Tuff).	20.7±1.2
32	Silver-white air-fall tuff.	36°08′25″	114°55′10″	SE. of Lava Butte -------	Red sandstone unit------------	10.6±0.9
33	White air-fall tuff ----	36°09′20″	114°54′15″	East of Lava Butte-------	-------------do------------	11.2±1.2
34	Green air-fall tuff ----	36°08′20″	114°56′30″	1.5 km SW. of Lava Butte.	Thumb Member--------------	13.2±0.9
35	--------do--------	36°29′13″	114°09′40″	Wechech Basin----------	-------------do------------	15.9±1.0
36	--------do--------	36°29′25″	114°09′14″	----------do----------	-------------do------------	16.3±1.9
37	White air-fall tuff ----	36°20′20″	114°07′58″	Horse Spring area--------	Rainbow Gardens Member.-----	15.1±0.8
38	Green air-fall tuff ----	36°17′45″	114°29′45″	Echo Wash-------------	Thumb Member--------------	15.3±2.0
39	Silver-gray air-fall tuff	36°30′55″	114°28′55″	Overton Ridge----------	-------------do------------	15.0±0.8
40	--------do--------	36°30′55″	114°28′55″	----------do----------	-------------do------------	12.5±0.9
41	Gray air-fall tuff -----	36°07′37″	114°01′35″	Pierce Ferry area--------	Rocks of Grand Wash trough (below level of Hualapai Ls.).	10.8±0.8
42	Gray air-fall tuff -----	36°07′37″	114°01′35″	----------do----------	Rocks of Grand Wash (several meters below sample 41).	11.6±1.2
43	--------do--------	36°07′37″	114°01′35″	----------do----------	Rocks of Grand Wash trough (same level as sample 41).	11.1±1.3

Five fission-track ages and three K–Ar age determinations from tuffs of an interpreted air-fall origin from the Thumb Member south of the Muddy Mountains and in the Virgin Mountains fall in the range of ages derived from that member near Frenchman Mountain. One fission-track sample[4] from the Rainbow Gardens Member near Horse Spring gave an age of 15.1±0.8 m.y., but this seems young because nearby samples from the overlying Thumb are slightly older. These older samples (samples 35 and 36) indicate that the Thumb Member in Wechech Basin is about 15.9 to 16.3 m.y old. A similar age range of 15.6–13.3 m.y. is indicated for the Thumb Member by fission-track dates of samples from Bitter Spring Valley and Echo Wash south of the Muddy Mountains (samples 23, 24, and 38). Anderson and others (1972) report three K–Ar ages for samples from tuffs within the Thumb Member in the Gale Hills and in Bitter Spring Valley. These samples (samples 3, 4, and 5) are from rocks grouped by Anderson and others (1972) as Horse Spring Formation, range from 15.3 to 14.9 m.y., and have ages concordant with other ages from the Thumb Member of that formation.

The Thumb Member exposed at Overton Ridge is dated by samples 30, 39, and 40 and ranges in age between 15.6 and 12.5 m.y. Samples 30 and 39 are concordant, whereas sample 40 is discordant. The dated tuffs are separated by no more than a few meters stratigraphically. There is no apparent reason for the age discrepancy, but it is possible that detrital zircons are present in the older samples. This explanation, however, is not considered likely as the two older determinations are the concordant ones.

The ages of the Bitter Ridge Limestone and Lovell Wash Members of the Horse Spring Formation are interpreted from two K-Ar dates, from one fission-track date, and from abundant bracketing dates from stratigraphically higher and lower units. The two K-Ar determinations, 13.4±0.7 and 11.7±2.0 m.y. (samples 8 and 9; Anderson and others, 1972), are both for the rhyodacite of Lava Butte, which occurs stratigraphically between the Thumb Member and the base of the

[4]Sample 37, obtained from and located by Richard Glanzman (written commun., 1978); dated by the author.

TABLE 3.—*Analytical data for zircon fission-track age determinations shown in table 2*

[Samples analyzed using the external detector method described by Naeser (1976). Determinations made in the laboratory of C. W. Naeser. Decay constant for spontaneous fission, $\lambda_f=7.03\times10^{-17}yr^{-1}$; total decay constant for ^{238}U, $\lambda_d=1.551\times10^{-10}yr^{-1}$; atomic ratio $^{235}U/^{238}U$, $I=7.252\times10^{-3}$; thermal neutron fission cross section for ^{235}U, $\alpha=580\times10^{24}$ cm^2]

Sample No.	Field No.	Lab No.	Fossil-track density[1] (λ_s) (10^6 tracks/cm^2)		Induced-track density[1] (λ_i) (10^6 tracks/cm^2)		Neutron flux (ϕ) (10^{15} n/cm^2)	Number of grains	Correlation coefficient of total counts (r)	U content (ppm)
20	1-121-1	2,044	1.15	(211)	4.69	(862)	1.01	8	0.811	134
21	1-121-2	2,045	1.03	(224)	3.87	(842)	1.01	8	.792	110
22	1-121-3	2,046	2.87	(450)	10.7	(1,682)	1.01	6	.981	305
23	1-67-270	2,047	2.73	(714)	10.7	(2,798)	1.01	10	.900	305
24	1-67-271	2,048	1.80	(253)	6.89	(968)	1.00	6	.958	198
25	1-67-272A	2,049	3.38	(370)	17.0	(1,856)	1.00	6	.802	490
26	1-67-272B	2,050	.938	(181)	4.79	(924)	1.00	8	.740	138
27	1-67-273	2,051	1.04	(205)	5.55	(1,094)	.998	8	.808	198
28	1-96-174	2,052	2.20	(381)	10.3	(1,748)	.996	8	.938	298
29	2-131-73	2,053	1.80	(321)	9.70	(1,728)	.994	8	.775	281
30	1-28-63	2,054	1.84	(375)	6.90	(1,278)	.992	6	.979	203
31	174-94-1	2,055	2.69	(239)	7.68	(894)	.990	6	.918	223
32	1-13-2	2,056	.701	(140)	3.90	(780)	.988	7	.980	114
33	1-13-1	2,057	.821	(133)	4.33	(702)	.986	6	.844	126
34	1-13-3	2,058	2.41	(391)	10.8	(1,746)	.984	8	.834	316
35	1-23-1	2,059	1.98	(321)	7.31	(1,184)	.982	6	.922	214
36	1-23-2	2,060	2.83	(595)	10.2	(2,138)	.980	8	.118	300
37	GP-5	2,061	2.50	(536)	9.64	(2,070)	.978	8	.947	284
38	1-69-165	2,062	.896	(121)	3.41	(460)	.976	6	.718	101
39	1-28-X1	3,171	3.28	(633)	13.75	(2,656)	1.05	8	.961	377
40	1-28-X2	3,172	1.51	(331)	7.62	(1,666)	1.05	8	.894	209
41	2-80-1a	3,173	1.55	(248)	9.03	(1,658)	1.05	6	.943	248
42	2-80-1b	3,174	.91	(232)	4.96	(1,260)	1.05	8	.698	136
43	2-80-2	3,175	1.03	(215)	5.85	(1,216)	1.05	8	.577	160

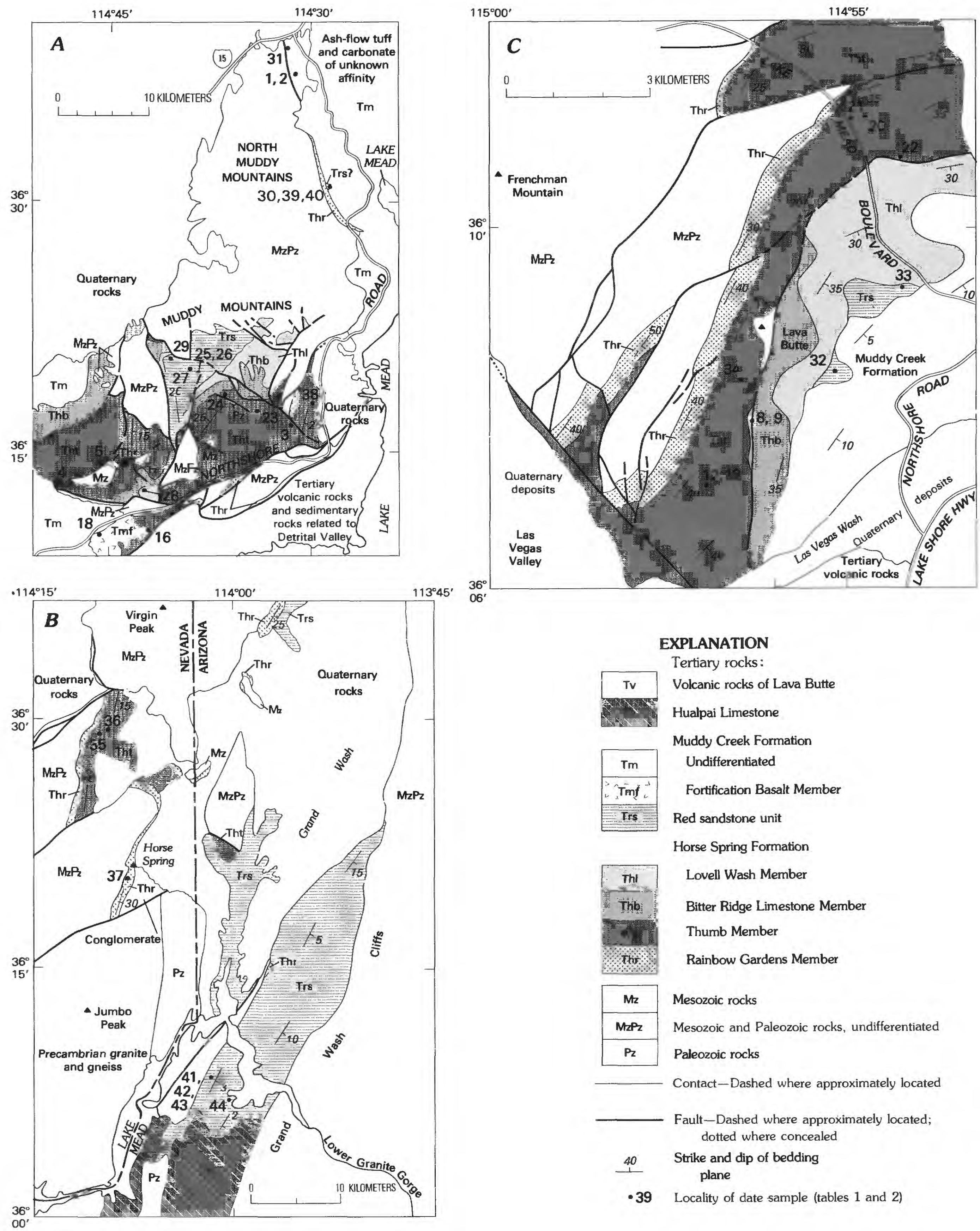
[1]Numbers in parentheses show total number of tracks counted in each sample.

Bitter Ridge Limestone Member. The rhyodacite has some features that indicate it is intrusive and others that suggest it is extrusive, and many of its contacts are fault-bounded. Nonetheless, a conglomerate composed of clasts of rhyodacite similar to that of Lava Butte lies stratigraphically within the Bitter Ridge Limestone Member near Lava Butte. This conglomerate probably indicates either the rhyodacite of Lava Butte was subaerially exposed, eroded, and transported into the Bitter Ridge Limestone or that it domed through and erupted into that member. It is inferred then that the age of the rhyodacite of Lava Butte dates either the lower beds of the Bitter Ridge Limestone Member or the contact between that member and the Thumb Member. A fission-track age of 13.0±0.8 m.y. was obtained from the Lovell Wash Member in Lovell Wash.

Unwelded ash-flow tuffs and overlying carbonate rocks are exposed near Glendale, Nev. Two K–Ar ages from the volcanic rocks have been reported by Anderson and others (1972), one K–Ar age has been reported by Shafiqullah and others (1980), and one fission-track age was derived in the present study. The K–Ar ages of 21.3±0.4 and 19.6±0.8 m.y. reported by Anderson and others (1972, samples 1 and 2), the date of 20.0±0.8 m.y. reported by Shafiqullah and others (1980, sample 91, p. 252), and the fission-track age of 20.7±1.2 m.y. (sample 31) are concordant. These rocks have traditionally been referred to as Horse Spring Formation (Anderson and others, 1972; Longwell, 1921, 1949; and Longwell and others, 1965), but they are older than the rest of the Horse Spring Formation, and no other ash-flow tuffs are known from that formation. Thus, their age range should not be used to define the age of deposition of the Horse Spring. Ekren and others (1977) describe several synchronous or nearly synchronous ash-flow deposits from Lincoln County, Nev., including the Hiko, Racer Canyon, and Harmony Hills Tuffs, that may temporally correlate with the ash flows near Glendale. Additional geologic mapping and stratigraphic studies may clarify the relation between these ash flows and the Horse Spring Formation.

Available data indicate that the Horse Spring Formation is Miocene in age and ranges from older than 17.2 m.y. to possibly 11.9 m.y. old. Although undated at

FIGURE 3 (facing page).—Tertiary geology and important sample sites in the Muddy Mountains area (*A*), Virgin Mountains–Grand Wash Cliffs area (*B*), and Frenchman Mountain area (*C*).


A
114°45′
114°30′
0 10 KILOMETERS
Ash-flow tuff and carbonate of unknown affinity
31
1, 2
Tm
NORTH MUDDY MOUNTAINS
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Trs?
30,39,40
Thr
36° 30′
MzPz
Quaternary rocks
ROAD
MUDDY MOUNTAINS
29
25,26
27
Thb
Thl
38
24
23
Quaternary rocks
36° 15′
Tm
Thb
5
Mz
NORTHSHORE
28
Tertiary volcanic rocks and sedimentary rocks related to Detrital Valley
Tm 18
Tmf
16
LAKE
B
114°15′
114°00′
113°45′
Virgin Peak
NEVADA
ARIZONA
Thr
Trs
Quaternary rocks
36° 30′
36
35
Thl
Mz
MzPz
Wash
Grand
Horse Spring
37
Thr
Conglomerate
36° 15′
Pz
Trs
Cliffs
Jumbo Peak
Precambrian granite and gneiss
41, 42, 43
44
LAKE MEAD
Grand
Lower Granite Gorge
36° 00′
0 10 KILOMETERS
Wash
C
115°00′
114°55′
0 3 KILOMETERS
Thr
Frenchman Mountain
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Thl
BOULEVARD
33
Trs
Lava Butte
32
Muddy Creek Formation
ROAD
NORTHSHORE
8, 9
Thb
Quaternary deposits
Las Vegas Valley
Las Vegas Wash
Quaternary
Tertiary volcanic rocks
LAKE SHORE HWY
deposits
36° 06′
EXPLANATION
Tertiary rocks:
Tv Volcanic rocks of Lava Butte
Hualpai Limestone
Muddy Creek Formation
Tm Undifferentiated
Tmf Fortification Basalt Member
Trs Red sandstone unit
Horse Spring Formation
Thl Lovell Wash Member
Thb Bitter Ridge Limestone Member
Thumb Member
Thr Rainbow Gardens Member
Mz Mesozoic rocks
MzPz Mesozoic and Paleozoic rocks, undifferentiated
Pz Paleozoic rocks
Contact—Dashed where approximately located
Fault—Dashed where approximately located; dotted where concealed
40 Strike and dip of bedding plane
•39 Locality of date sample (tables 1 and 2)

the present time, the Rainbow Gardens Member is not considered to be much older than about 20 m.y. The overlying Thumb Member appears to range from about 17.2 m.y. to possibly 13.5 m.y. old. The Bitter Ridge Limestone Member is apparently as old as 13.4 m.y. or slightly older, and the Lovell Wash Member is probably no younger than 11.9 m.y., which is the oldest age determined for the overlying red sandstone unit.

The age of the red sandstone unit that overlies the Horse Spring Formation is indicated by fission-track ages of two samples from near Frenchman Mountain and four samples from White Basin. Four fission-track age determinations provide the basis for the age interpretation of the rocks of the Grand Wash trough, which underlie the Hualapai Limestone between Wheeler Ridge and the Grand Wash Cliffs. Two K–Ar determinations reported by Blair (1978) date the Hualapai Limestone in Detrital Valley. Near Frenchman Mountain, samples 32 and 33 from the red sandstone unit are 10.6 and 11.2 m.y. old, respectively, whereas samples 25, 26, 27, and 29 from White Basin indicate that this unit ranges from 11.9 to 11.0 m.y. old. West of the Grand Wash Cliffs, the stratigraphically and structurally lowest dated beds of the rocks of the Grand Wash trough range from 10.8 to 11.6 m.y. old (samples 41, 42, 43, and 44). Blair (1978) reports a K–Ar age of 10.9± 1.1 m.y. from a basalt "intercalated with the * * * lower part of the Muddy Creek Formation." The basalt of the Muddy Creek Formation sampled by Blair (1978) is in Detrital Valley. Blair (1978) also reports an 8.44±2.2 m.y. age from a tuff within the Hualapai Limestone. A basalt flow that overlies the rocks of the Grand Wash trough has been dated by Damon and others (1978) at 3.80±0.11 m.y. and 3.79±0.46 m.y. old. It appears that in the Muddy Mountain–Frenchman Mountain area the red sandstone unit is Miocene in age with a possible range from about 11.9 to 10.6 m.y or younger. In the Grand Wash Cliffs area, the rocks of the Grand Wash trough and the Hualapai Limestone are, respectively, older than 11.6 m.y. and possibly as young as about 4 m.y.

Although the age range of the Muddy Creek Formation has not been determined in the Lake Mead region, Anderson and others (1972) and Damon and others (1978) report several K–Ar ages from the Fortification Basalt, which they refer to as a member of the Muddy Creek Formation. The Fortification Member apparently was extruded into the basin of the Muddy Creek Formation during the late stages of Muddy Creek deposition. The ages derived for the Fortification Basalt Member are summarized in table 1. The age I consider the most reliable for the Fortification is that reported by Damon and others (1978) of 5.88±0.18 m.y., because it was derived using new techniques limiting the effects of abundant $CaCO_3$ in the dated sample. Also, the latter date is concordant with the earlier ages for Fortification samples from south of Lake Mead, where not as much $CaCO_3$ is present in the basalt. Eberly and Stanley (1978, sample 124, p. 928) report an age of 8 m.y. derived from a basalt flow interstratified with the Muddy Creek Formation near the Overton Arm of Lake Mead. No age range is given for this sample, and examination of the outcrop from which it was taken indicates zeolitization and alteration of plagioclase. Although the Muddy Creek Formation is the most poorly dated of the Tertiary rocks, it appears to be no older than about 10.6 m.y. near Frenchman Mountain, where it overlies the dated red sandstone unit, and at Fortification Hill it may be no younger than about 6 m.y.

DESCRIPTION OF ROCK UNITS

Throughout the descriptive part of this report, terms will be used that might have ambiguous meanings. Thus, definitions of potentially ambiguous terms are included in this section.

Bedding terminology used is that of Reineck and Singh (1975, figs. 135 and 136, p. 82 and 83), which is modified from Campbell (1967), and from McKee and Weir (1953). Using this terminology, bedding relations are described as parallel or nonparallel and as continuous or discontinuous. The terms even, wavy, and curved are used to describe surfaces of beds. Beds of equal thickness are referred to as uniform beds. Terms such as tabular, lenticular, and wedge shaped are self-explanatory; they describe the shapes of individual beds, bedsets (see below), or mappable units.

Bed thickness is commonly given in metric units. However, in some instances bedding is simply described as thin or thick following the definitions of those terms in Reineck and Singh (1975, fig. 136, p. 83). The term bedset is used in this report to describe groups of two or more beds of the same character. Bedsets can be simple (one lithology) or composite (more than one lithology).

On a larger scale, formations and members are subdivided using the terms unit and facies. A unit is a group of beds and (or) bedsets lithologically distinct from other units. The term facies is simply used to describe the aspect or character of the sediment within beds of one and the same age (Pettijohn, 1975). Two types of facies are discussed: lithofacies (such as carbonate-sandstone) and depositional facies (such as lacustrine).

HORSE SPRING FORMATION

RAINBOW GARDENS MEMBER

DISTRIBUTION AND THICKNESS

The thickness of the Rainbow Gardens Member varies considerably, as is illustrated by figure 4, which shows the regional distribution of 11 surface stratigraphic sections. In Rainbow Gardens (sec. *A*, fig. 4), the Rainbow Gardens Member is wedge shaped. Southwest of section *A*, along strike, the member is thicker than 300 m, but northeast of section *A* the upper parts of the member undergo an abrupt lithofacies change into lithologies of the Thumb Member. Consequently, the Rainbow Gardens Member thins to less than 50 m in this direction. A similar northward thinning occurs in the Virgin Mountains, where the member is also wedge shaped. Here sections *K* and *F* (fig. 4) indicate that the member is thicker than 300 m in their vicinity, but it thins to less than 100 m at section *D* (fig. 4). The Rainbow Gardens Member is thinnest in the Gale Hills and in Bitter Spring Valley, where it is only about 60 m thick (sec. *G*, fig. 4). In its easternmost exposures near the Grand Wash Cliffs (secs. *E* and *J*), the member may be thicker than 275 m, but because it is unconformably overlain by younger deposits, its original thickness cannot be measured. In general, the thickest section of the Rainbow Gardens Member is about 400 m thick and the thinnest about 50 m thick. The regional distribution and palinspastic restoration of these thickness trends are discussed below.

LITHOLOGY

The lithologically varied Rainbow Gardens Member includes clastic sedimentary rocks ranging in grain size from conglomerate to claystone, several types of carbonate rocks, evaporite beds, and chert. Conglomerate occurs at the base of the member at every known exposure, and, in general, carbonate lithologies dominate its upper parts. The greatest diversification is in the middle and lower middle parts of the member, where sandstone, siltstone, claystone, limestone, dolomite, gypsum, chert, and conglomerate are all interbedded.

Clastic and Siliceous Lithologies

The resistant, blocky-weathering gray, gray-brown, and red-brown basal conglomerate varies considerably in thickness from about 50 m to as little as 1 or 2 m. It has a well-defined, scoured basal contact where it unconformably overlies Mesozoic and upper Paleozoic formations. The upper contact of this basal unit is also well defined and is planar at most locations. However, channel-form beds are exposed in stratigraphic sections *B* (Echo Wash) and *C* (Overton Ridge). In these channels, which are at least 3 m deep, there is limited interfingering of conglomerate with the overlying rocks.

Most clasts in the basal conglomerate are of gray cherty limestone similar in lithology to rocks of the Kaibab and Toroweap Formations of Permian age, and red and red-brown sandstone that resembles sandstone of Mesozoic age. Other clasts include gray limestone and brown quartzite similar in lithology to other local Paleozoic rocks. In southernmost Rainbow Gardens, granitic and gneissic clasts occur. Limestone clasts, which range in relative abundance from 60 to 90 percent, are the dominant clast type, whereas the percentage of sandstone clasts ranges from 10 to 40. The limestone clasts are commonly subangular, and the sandstone clasts are subrounded to round. Clast sorting is moderate. Clasts range in diameter from as little as a few centimeters to as much as 1 m. Clast-supported texture is present. The matrix makes up about 20 percent of the rock and is chiefly gray crystalline limestone or arenaceous limestone, though a red-brown calcareous sandstone occurs locally. The matrix imparts a hard, well-indurated aspect to the rock and produces blocky, resistant outcrops.

Bedding character varies within the basal conglomerate. Locally the conglomerate is unbedded; but more commonly the bedding is poorly defined, is both even and curved, and is discontinuous. In some outcrops, the bedding appears parallel from a distance but is lenticular in detail. In many cases it is defined only by clast trains and clast size changes. Internal low-angle trough crossbeds occur at many locations and range in amplitude from a few centimeters to 1 m.

Conglomeratic beds occur in the middle and lower middle parts of the exposed sections at Rainbow Gardens, the Echo Hills, Wechech Basin, and Cottonwood Wash (secs. *A*, *I*, *D*, and *E*, respectively, fig. 4). In general, these beds consist of thin, discontinuous zones of conglomerate in sandstone or of short, stubby lenses at the base of sandstone beds. The clasts are small, rarely exceeding a few centimeters in diameter, and they are composed chiefly of subangular to subround resistant limestone and cherty limestone that resembles limestone of the Kaibab and Toroweap Formations. In Wechech Basin, some of the clasts are well-rounded, hard, small (less than 10 cm in diameter), pieces of quartzite that closely resemble clasts of the locally exposed Upper Triassic Shinarump Member of the Chinle Formation.

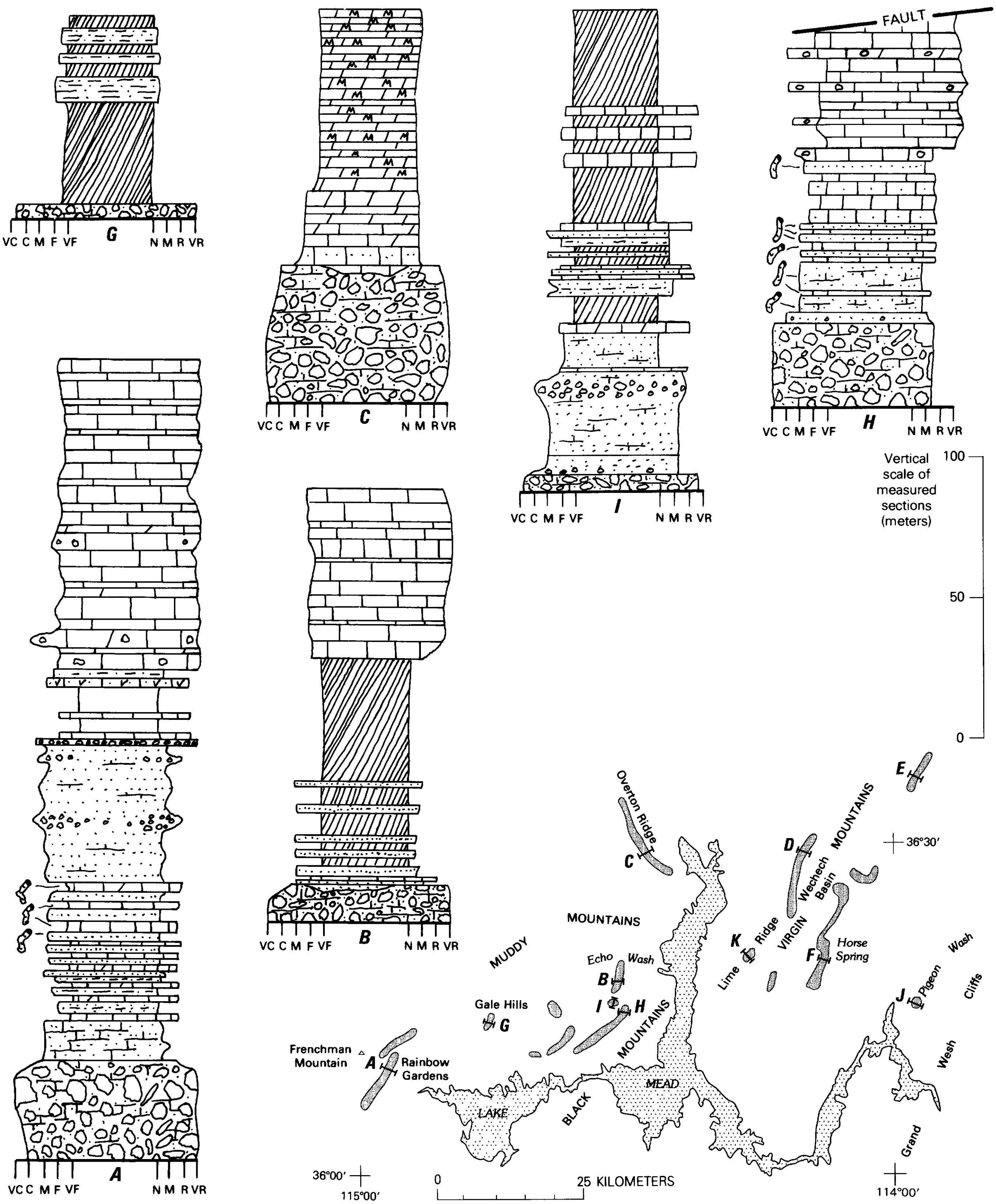
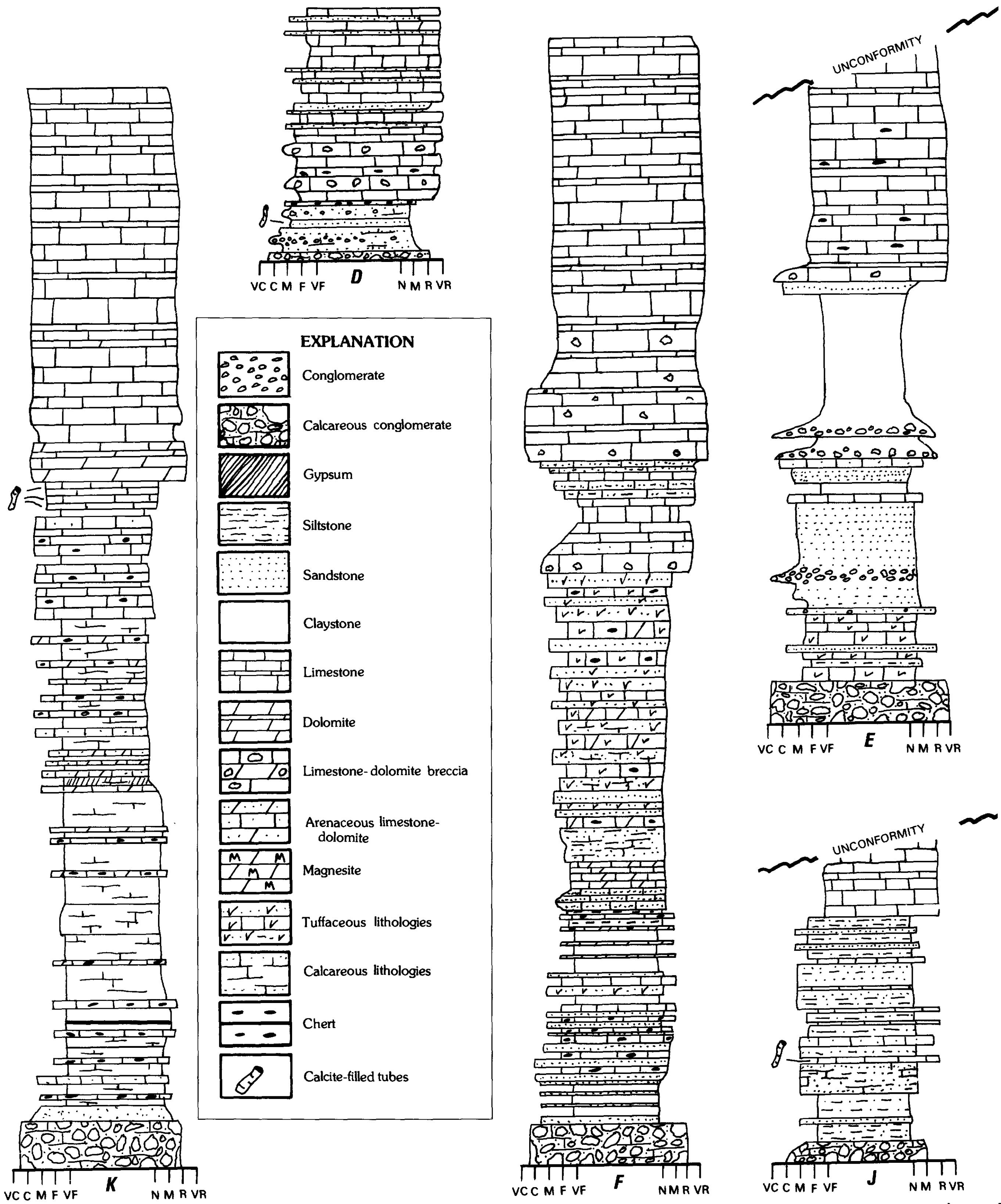


FIGURE 4.—Measured stratigraphic sections of the Rainbow Gardens member of the Horse Spring Formation with inset showing geographic distribution of outcrops. The Member overlies Mesozoic and upper Paleozoic beds unconformably at all sections, and it is overlain conformably by the Thumb Member at all sections except *E*, *H*, and *J*. The left side of each column depicts bulk grain size: VC, very coarse; C,



coarse; M, medium; F, fine; V, very fine. The right side of each column depicts relative resistance to weathering: N, nonresistant; M, moderately resistant; R, resistant; VR, very resistant.

Red, red-brown, and brown sandstone with grain-supported texture is a major component of the middle and lower middle parts of the stratigraphic sections at Rainbow Gardens, Wechech Basin, Cottonwood Wash, the northern Black Mountains, Echo Hills, and Pigeon Wash (secs. *A, D, E, H, I,* and *J* respectively, fig. 4). The sand grains are composed chiefly of medium-grained, rounded quartz, but in rare cases coarse-grained sandstone, grit,[5] and siltstone are interbedded with the medium-grained sandstone. The coarser grained types are composed of subangular grains of carbonate rocks. Silt- and clay-size matrix is rare to absent. Sand grains are cemented by calcareous cement. Bedding is parallel, wavy, and continuous overall, but some beds have small-scale internal cross-laminations. It is apparent that Mesozoic clastic rocks, especially the Aztec Sandstone, were the source for the sandstone beds because of the similarity in sand grains, but the direction of transport is uncertain.

Red-brown and brown siltstone is present within the sandstone, and within gypsiferous sandstone (mentioned below), but it is minor in volume. Its color and its association with the sandstone suggests that it too may have been locally derived from Mesozoic clastic rocks.

White and light-gray, nonresistant, calcareous claystone beds are abundant in the Lime Ridge and Cottonwood Wash sections and are present in the section at Horse Spring (secs. *K, E,* and *F* repectively, fig. 4). Similar beds also occur at Rainbow Gardens (sec. *A*, fig. 4). These claystone beds are in the middle and lower middle parts of the Rainbow Gardens Member and are associated with clayey carbonate rocks and tuffaceous rocks. The claystone beds are as thick as 1 m and are continuous over lateral distances as great as 1 km, but internal bedding, laminations, or structures were not observed owing to insufficient exposure. X-ray data suggest that the clay includes species with 0.7–, 1.0–, and 1.5–nm peaks (R. K. Glanzman, written communication, 1979). These claystone beds are inferred to have formed as the byproduct of alteration of tuffaceous minerals. This inference is based on relict texture in which clay occurs mixed with micrite in the shape of pumice lapilli and fine-grained pumice fragments.

Dark-green, black, and white chert is interbedded with limestone, claystone, and tuff. This chert occurs in thin, continuous beds that have well-defined bases and tops; in small, irregular lenses; and in lenticular beds a few centimeters thick. The continuous chert beds are generally black or green and are interbedded with claystone and carbonate beds, whereas the lighter-colored chert is more lenticular and occurs in carbonate beds. Chert is most common in the middle of the member in the southern Virgin Mountains, but it also occurs in sparse amounts in the upper carbonate unit of the northern Virgin Mountains.

[5]Super coarse grained sandstone or very fine grained conglomerate.

Carbonate and Sulfate Lithologies

White, light-buff, light-gray, and brown limestone and dolomite, and arenaceous limestone and dolomite are the dominant lithologies above the basal conglomerate in the Rainbow Gardens Member. Eight of the eleven stratigraphic sections have a thick unit of resistant carbonate rocks, commonly limestone, in their upper part. Most of the middle parts of the stratigraphic sections contain many limestone and dolomite beds that are interbedded with other rock types.

The thick, resistant upper limestone units (fig. 5) form hogbacks and consist of 25-cm- to 1-m-thick uneven, wavy beds that are parallel to one another and relatively continuous. Bedding is defined primarily by erosional differences and is obvious from a distance but is commonly difficult to detect on close inspection. Fine-grained limestone with wavy internal laminations (evident in hand specimen) is common. However, many other bedsets and beds have a tufa-like appearance: they are porous, do not appear to be internally bedded or laminated, and have irregular and indistinct bedding contacts. In addition to these tufa-like beds, intraformational limestone breccia occurs in the lower parts of some resistant limestone units. Breccia clasts are about 5 cm in diameter and are similar in lithology both to the matrix that surrounds them and to other nearby limestone beds. All the limestone probably contains siliceous detritus, and some beds contain enough sand to be called arenaceous limestone, but sand content is gradational. The arenaceous detritus is medium-grained quartz sand that is moderately well rounded.

In the middle parts of the studied stratigraphic sections, many individual limestone, dolomite, and arenaceous limestone beds range in thickness from a few centimeters to a meter. These beds are continuous, have well-defined bedding surfaces, are a little more resistant than the surrounding rocks, and are composed of medium- to fine-grained crystalline carbonate, which may represent some degree of recrystallization. In hand specimen, many exhibit wavy internal laminations. Dolomite is more prevalent in the fine grained beds (R. K. Glanzman, written communication, 1979). There is a gradation from relatively pure limestone beds into calcareous sandstone beds, and all the beds probably have some siliceous clastic material in them.

At Overton Ridge, the Rainbow Gardens Member contains bright white, extremely fine grained sedimen-

FIGURE 5.—Resistant limestone unit in the upper part of the Rainbow Gardens Member near Rainbow Gardens. View to the north-northeast.

tary magnesite and dolomite (fig. 6). Bedding is parallel, even, continuous, and fairly uniform, ranging in thickness from a few centimeters to 40 cm. This magnesite-bearing unit is underlain by pink limestone and dolomite that is calcite rich at its base and dolomite rich at its top. Above the limestone and dolomite, at the base of the magnesite-bearing unit, dolomite is the dominant mineral and calcite is absent. Dolomite and magnesite vary in proportion to each other throughout the magnesite-bearing unit. Trioctohedral smectite, rich in lithium (probably hectorite), is a common associate of the magnesite and dolomite and makes up as much as 30 percent of the rock. A less abundant associate of the magnesite is celestite, which occurs disseminated throughout the rock and in a 1-cm-thick bed or bedding-parallel vein.

White, light-gray, and pink gypsum is the dominant lithology directly above the basal conglomerate in studied stratigraphic sections *B*, *G*, and *I* (fig. 4) and throughout Bitter Spring Valley and the Gale Hills. The gypsum forms thick units, some relatively pure, that are interrupted only by thin, brown, red-brown, and pink, fine-grained sandstone and siltstone beds and rare gray limestone beds. Silt and possibly clay are disseminated in some of the gypsum and apparently cause its pink color. Bedding is obvious from a distance because of color changes, and it appears to be irregular, uneven, and discontinuous, but close inspection reveals that it is indistinct and that veins are common. The gypsum may be recrystallized, and it may have been bedded or laminated when it was deposited.

SEDIMENTARY STRUCTURES

One sedimentary structure, not described above, which occurs in the middle parts of several of the studied stratigraphic sections of the Rainbow Gardens

FIGURE 6.—Magnesite-bearing Rainbow Gardens Member at Overton Ridge. The uniform, parallel, even bedding is apparent in the white magnesite. The lower limestone- and dolomite-bearing unit beneath the magnesite is less obvious. The high ridge is composed of the basal conglomerate. View to the north.

Member, is a system of branching, mostly vertically oriented calcite-filled tubes (fig. 4). These tubes are found in beds of limestone and dolomite, arenaceous limestone and dolomite, and calcareous sandstone. They are about a centimeter or less in diameter, and some are as long as 1 m. Several different origins are possible for these tubes. They could be root or burrow casts, but it is more likely that they represent filled escape pipes formed by fluid expulsion related to sediment dewatering during compaction. This inorganic origin is favored because no signs of organic activity are recognized in the rocks. The mineralogy of associated strata (such as gypsum) suggests salinities that were not compatible with indigenous biologic activity, except perhaps that of algae.

FACIES AND THEIR DISTRIBUTION

The Rainbow Gardens Member is readily subdivisible on a lithologic basis. One obvious lithologic subdivision consists of the basal conglomerate, but this unit does not qualify as a lithofacies because it cannot be demonstrated to be laterally equivalent to any other lithology in the member. However, lateral lithologic (facies) variation is recognized above the basal conglomerate. Five lithofacies are recognized: (1) A lithofacies of interbedded sandstone, siltstone, conglomerate, claystone, limestone, and dolomite, which is overlain by a resistant unit of limestone, is called the clastic-carbonate facies. (2) A similar lithofacies of tuffaceous carbonate rocks, sandstone, and claystone, which is also overlain by limestone is called the tuff-limestone facies. (3) A gypsiferous lithofacies occurs and is referred to herein by that name. (4) A lithofacies of gypsum overlain by limestone and a lithofacies of interbedded gypsum and limestone are grouped, forming the gypsum-limestone facies. (5) A lithofacies of magnesite and dolomite is called the magnesite facies.

The present distribution of the five facies is controlled, to a large extent, by Tertiary faults, especially the Lake Mead fault system of Anderson (1973) and Bohannon (1979). The paleogeographic significance of the facies cannot be evaluated without palinspastic restoration of the lateral slip on these faults. Such a restoration is attempted in the section entitled "Paleogeologic and paleotectonic evolution." For now, the facies are described in their present configuration relative to major geographic features and important fault traces (fig. 7).

The clastic-carbonate facies is exposed north of the Lake Mead fault system in Rainbow Gardens, between branches of the fault system 30–40 km northeast of Rainbow Gardens in the northern Black Mountains, and southeast of the main branches of the fault system in Wechech Basin 65 km northeast of Rainbow Gardens. An isolated exposure of this facies is at the north end of Wheeler Ridge in Pigeon Wash, about 25 km southeast of Wechech Basin. In Rainbow Gardens, the clastic-carbonate facies thins to the north and becomes sandier in a zone that is transitional to the gypsiferous facies. In

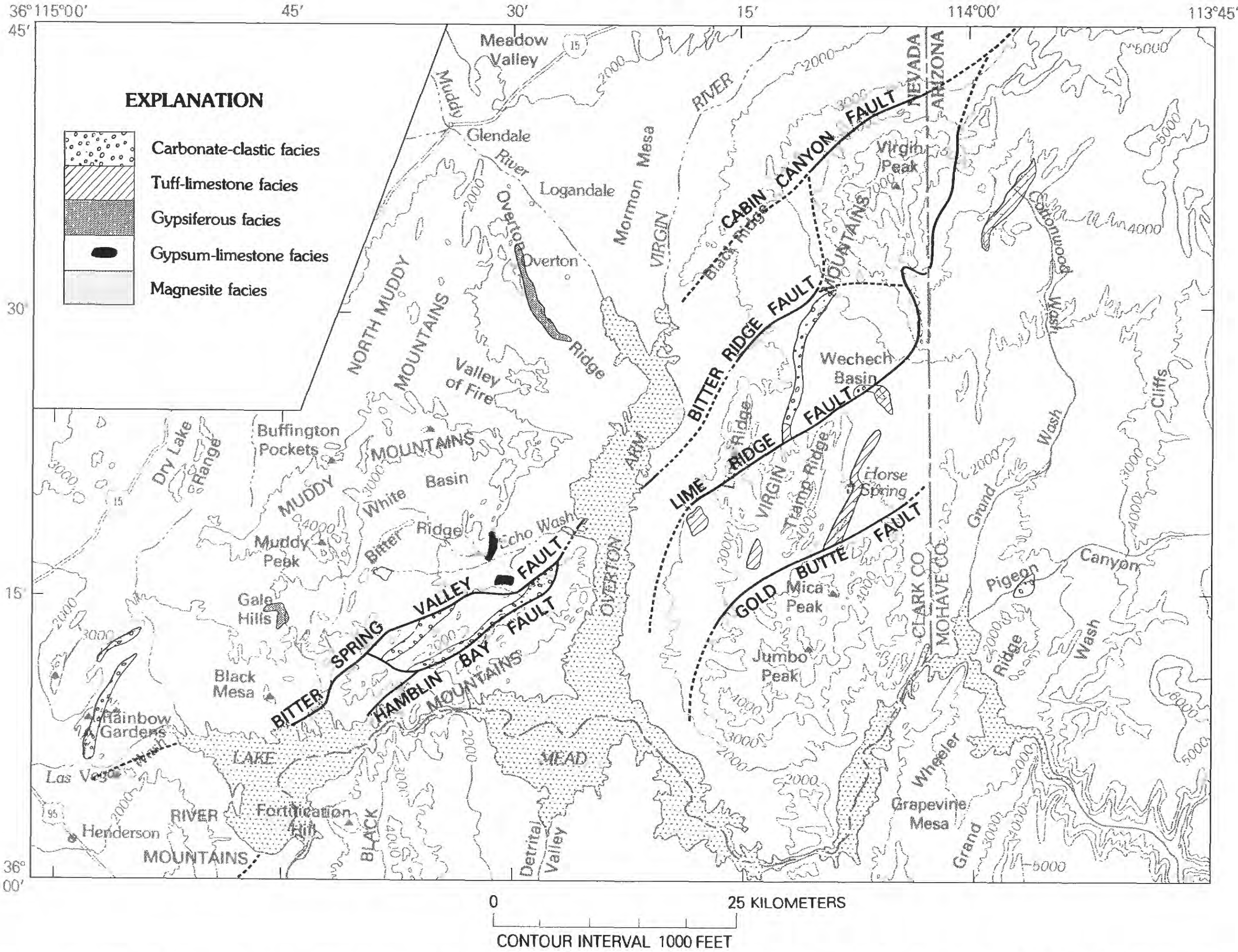


FIGURE 7.—Distributions of the five lithofacies of the Rainbow Gardens Member, and locations of related prominent faults of the Lake Mead fault system of Anderson (1973) and Bohannon (1979).

the Black Mountains, the clastic-carbonate facies is fault bounded and cannot be demonstrated to grade into other facies. However, in Wechech Basin, excellent exposures indicate a gradual transition of this facies into the tuff-limestone facies to the south toward Horse Spring. This transition is also exposed in Cottonwood Wash. The isolated exposure of the clastic-carbonate facies in Pigeon Wash is southeast of the transition described above, beyond the area where the tuff-limestone facies is exposed.

The tuff-limestone facies, the thickest of the five facies, is confined to the Virgin Mountains region and is widespread. It is best exposed between the Lime Ridge and Gold Butte faults, two left-separation faults that are associated with the Lake Mead fault system (Bohannon, 1979), but the northern transition of this facies with the clastic-carbonate facies is exposed on both sides of the Lime Ridge fault. The southern transition of this facies with the Pigeon Wash exposure is covered.

The gypsiferous facies occurs north of the Lake Mead fault system in the Gale Hills and Bitter Spring Valley. Although it is the thinnest of the five lithofacies, it is exposed over a wide area. North of Rainbow Gardens, it is gradational into the clastic-carbonate facies. To the east, the gypsiferous facies grades into the gypsum-limestone facies, which is distinguished from it by (1) a thick unit of wavy-bedded limestone stratigraphically above the gypsum in the area north of Echo Wash and (2) limestone interbedded with the gypsum on the north flank of the Echo Hills. The latter exposure is within 1 km of the clastic-carbonate facies in the northern Black Mountains. Although the gypsum-limestone facies of the Echo Hills and the clastic-carbonate facies of the Black Mountains are different in composition and no gradation can be observed between them, their close proximity can be explained by the intervening Bitter Spring Valley fault, a major branch of the Lake Mead fault system. The Bitter Sping Valley fault bounds the gypsiferous and gypsum-limestone facies to the south, but to the north, they may once have intergraded with the magnesite facies.

The magnesite facies occurs only at Overton Ridge and is isolated from the other facies across faults and large covered areas. Based upon present distribution, it is assumed to be most closely related to the gypsum-limestone facies. However, the closest exposures of these two facies are 25 km apart.

ENVIRONMENTS OF DEPOSITION

The basal conglomerate probably was deposited as a gravel veneer on a widespread pediment surface developed on Mesozoic and upper Paleozoic rocks. The tabular, sheetlike deposit is no thicker than 50 m and thins in places to as little as 1 m, but it is present in all exposures of the member. Despite its thinness, it apparently once covered a large geographic area.[6] The conglomerate has a well-defined upper contact, which shows evidence of erosion in the form of channels and scours, and there is little or no evidence of any interfingering of the upper part of the conglomerate with the overlying rocks, except in those channels. In most places it has indistinct, discontinuous bedding typical of alluvial or stream deposits. However, some parts of it are unbedded, and these might be the result of mass flow. The cement and matrix are chiefly crystalline carbonate minerals, a composition which suggests vadose-zone crystallization. A major unanswered question about this unit is the degree to which it is diachronous. Most alluvial conglomerates are diachronous to some extent, and they commonly grade laterally into time-equivalent finer grained rocks. However, no such gradation has been observed for this conglomerate, so it is interpreted to have been deposited prior to the other facies of the member. Therefore, if the conglomerate is at all diachronous, its older parts must have been subaerially exposed prior to deposition of the overlying beds. Such a history is compatible with a pediment gravel model.

The rocks overlying the basal conglomerate probably were deposited in a complex system of lake, lakeshore, marginal lake, playa, spring, and alluvial environments that developed upon the pediment gravel deposit. Although detailed bed-by-bed discrimination of these environments has not been attempted, a general evaluation of the most likely environments for these strata is undertaken here.

A thick, resistant limestone unit composes the upper third of both the clastic-carbonate and tuff-carbonate facies, and its lithology is essentially the same in both, indicating little environmental difference during its deposition. Beneath that limestone unit, however, contrasting lithologies indicate significant environmental differences between the two facies. Both facies may have been deposited near the margins of a large lake or playa system. The facies include clastic rocks that appear to have been locally derived and that were probably transported by fluvial processes. The bedding, however, is parallel, indicating a flat depositional surface. The tuff-carbonate facies could be a stream deposit, but its source must have been nearby coeval volcanic deposits rather than local bedrock. Many features of the upper limestone unit, such as its wedge shape, its "tufa-like" appearance, and its irregular bedding, suggest that it may have been deposited near springs that fed into the basin.

The gypsum-limestone and gypsiferous lithofacies probably represent lacustrine deposits. Because the gypsum is recrystallized, it is not possible to tell whether standing water existed during its deposition, or whether it was deposited in the vadose zone of existing sediments, but the coexistence of gypsum and limestone suggests evaporative concentration in a permanent lake with evaporite crystal growth both in the lake and in the bounding sediments. Because the available exposures are few and the study of them was limited, it is not known whether deposition occurred in one or more lakes.

In the magnesite lithofacies, magnesite occurs with dolomite and smectite clay in extremely fine grained, parallel, even, continuous, uniform beds that contain ripple marks and plant fragments. These features collectively suggest a lacustrine sedimentary origin for the magnesite facies, and the uniform increase in the Mg–Ca ratio through time suggests an orderly chemical evolution of lake water during deposition. In the lower beds of this deposit, calcite is dominant, dolomite is present, and magnesite is absent; but higher in the section, dolomite increases in abundance relative to calcite. In the upper part of the section, magnesite is present where calcite is absent. The carbonate minerals may have evolved from high-calcium to high-magnesium mineral species simply by using up the available calcium in the lake waters through time. Deposition in a nearly closed drainage system seems likely.

[6]After palinspastic reconstruction it appears that this deposit covered nearly 3,000 km^2.

THUMB MEMBER

DISTRIBUTION AND THICKNESS

The Thumb Member has a distribution similar to that of the Rainbow Gardens Member (fig. 8), but it does not occur at Pigeon or Cottonwood Wash. It is thicker than the Rainbow Gardens Member, although its thickness is variable and is difficult to determine because of faulting. In unfaulted, complete stratigraphic sections, such as those in the Gale Hills and in Bitter Spring Valley, the Thumb Member is as thick as 1300 m.

At Rainbow Gardens (studied stratigraphic section *A*, fig. 8) the principal reference section of the Thumb Member is at least 850 m thick, but its top is faulted. Near Lava Butte, north of stratigraphic section A, the Bitter Ridge Limestone Member conformably overlies the Thumb Member, but a large fault in the Thumb makes section measurements there uncertain. The Thumb Member dips to the east at Rainbow Gardens and probably is present in the subsurface between there and the Gale Hills. Surface exposures of the Thumb also occur north, northwest, and south of Frenchman Mountain, and it is likely that the Thumb Member occurs in the subsurface west of Frenchman Mountain.

The Thumb Member is widespread in the Gale Hills, where a complete and relatively unfaulted stratigraphic section (*B* on fig. 8) indicates that it is about 1,200 m thick. Between the Muddy Mountains and locality *B*, the member appears to be thicker than 1,200 m, but it is repeated by faults and neither its top nor its base is exposed. Surface exposures of the Thumb are bounded to the south by a zone of faults. However, it is thought that the member occurs in the subsurface south of that fault zone. There are no outcrops of the Thumb north of the Gale Hills in the Muddy Mountains or in California Wash, and facies and provenance information described below suggest that it was never deposited there.

Relatively unfaulted stratigraphic sections in Bitter Spring Valley and Echo Wash (sections *C* and *D* respectively, fig. 8) indicate the member's maximum thickness of 1,300 m. Surface exposures in Bitter Spring Valley are bounded to the south by the Bitter Spring Valley fault. Only thin, discontinuous remnants of the member occur in the northern Black Mountains between the Bitter Spring Valley and Hamblin Bay faults. At the north end of Bitter Spring Valley, the Thumb dips to the north under the Bitter Ridge Limestone Member. It underlies at least the southern part of White Basin but probably does not underlie the northern part. Instead, the Thumb apparently abuts against a steep subsurface buttress unconformity under the southern part of the basin. In Echo Wash, the Thumb is unconformably overlain by younger deposits. Isolated outcrops near the west shore of the Overton Arm of Lake Mead suggest that the Thumb is present in the subsurface throughout the Overton Arm area north of the eastward-projected trace of the Bitter Spring Valley fault.

In the Virgin Mountains, surface exposures of the Thumb Member occur from Wechech Basin, where studied stratigraphic section *E* (fig. 8) attains a minimum thickness of 1,150 m, to the Gold Butte fault. The exposures near Horse Spring (fig. 8) are isolated from all others and are atypical, being composed entirely of unbedded breccia. East of Wechech Basin only isolated, small exposures occur and the eastern depositional extent of the Thumb is not known.

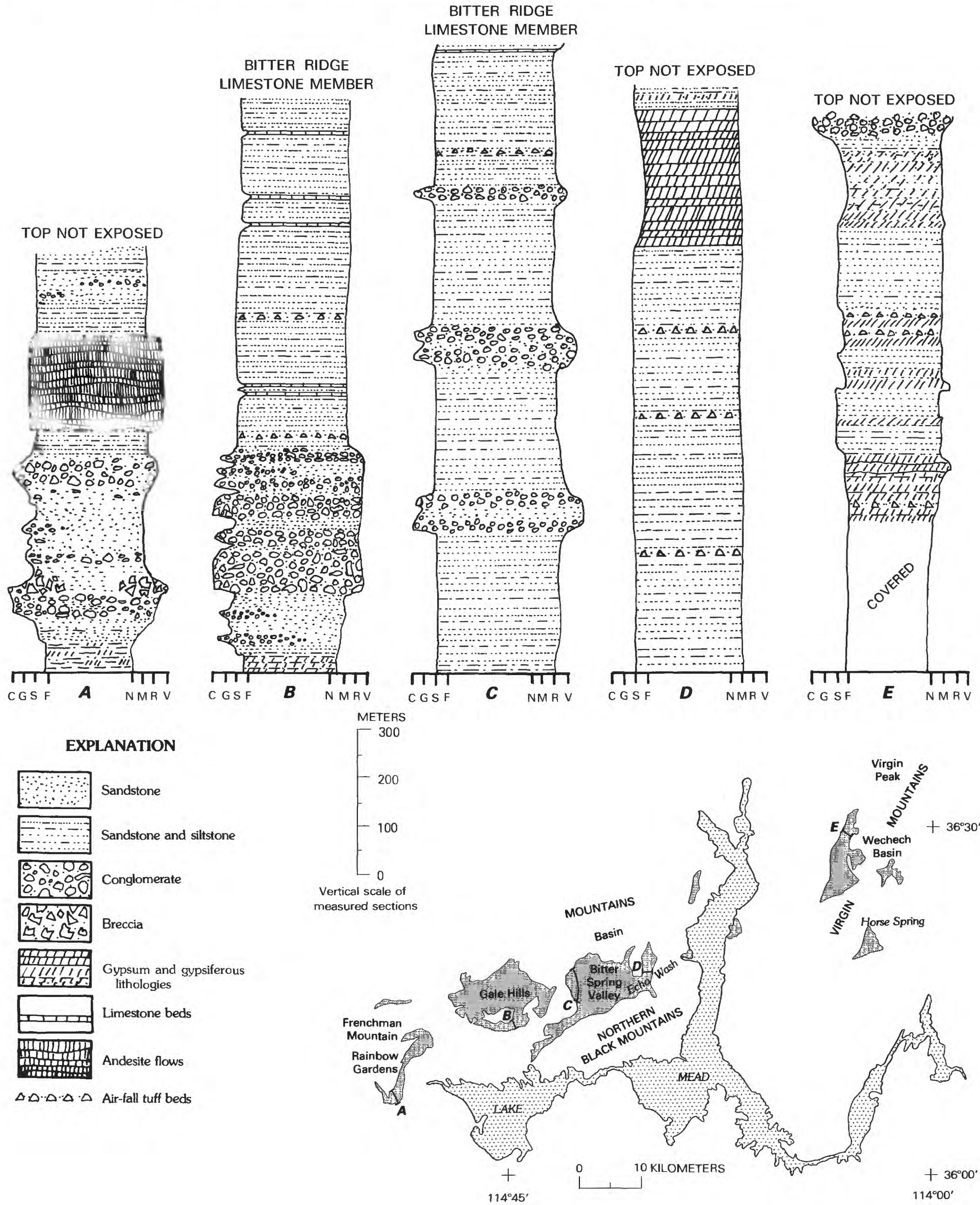
Although limited in thickness and extent, the exposures of probable Thumb Member at Overton Ridge (not measured and not depicted on fig. 8) are the most northerly known for that member. These exposures, which dip to the east, indicate that the Thumb is present in the subsurface in the Muddy and Virgin River valleys, but its extent is uncertain.

LITHOLOGY

The Thumb Member is chiefly clastic, consisting of sandstone, siltstone, conglomerate, and breccia, but gypsum occurs at many localities in thick, pure units. Carbonate, predominately limestone, is present locally. Sandstone is the most widespread rock type, but conglomerate also occurs at all locations except Echo Wash.

Clastic Rock Types

The conglomerate-sandstone ratio varies abruptly with geographic locality. In the southern part of Rainbow Gardens, conglomerate makes up about 50 percent of the member, sandstone constitutes about 30 percent, and other rock types the remainder. North of Rainbow Gardens, the sandstone content of the member increases to more than 90 percent. In the Gale Hills, sandstone makes up about 75 percent and conglomerate 20 percent of measured section *B* (fig. 8). North of the measured section near the Muddy Mountains, conglomerate is dominant. In southern Bitter Spring Valley, sandstone is the most abundant rock type except in the conglomeratic southwest part of the valley. In northern Bitter Spring Valley, the lower and upper parts of studied stratigraphic section *C* (fig. 8) are dominated by sandstone, but the middle part, especially in the north-central part of the valley, is conglomeratic. The clastic


BITTER RIDGE LIMESTONE MEMBER
BITTER RIDGE LIMESTONE MEMBER
TOP NOT EXPOSED
TOP NOT EXPOSED
TOP NOT EXPOSED
COVERED
C G S F A N M R V
C G S F B N M R V
C G S F C N M R V
C G S F D N M R V
C G S F E N M R V
METERS
300
200
100
0
Vertical scale of measured sections
EXPLANATION
Sandstone
Sandstone and siltstone
Conglomerate
Breccia
Gypsum and gypsiferous lithologies
Limestone beds
Andesite flows
Air-fall tuff beds
Virgin Peak
VIRGIN MOUNTAINS
36°30′
E
Wechech Basin
Horse Spring
MOUNTAINS
Basin
Bitter Spring Valley
D
Echo Wash
C
Gale Hills
B
NORTHERN BLACK MOUNTAINS
Frenchman Mountain
Rainbow Gardens
A
LAKE
MEAD
0
10 KILOMETERS
114°45′
114°00′
36°00′

rocks in the stratigraphic section in Echo Wash (section *D*, fig. 8) are nearly all sandstone, but a thin lens of conglomerate is exposed at one locality about 1,000 m from the base of the section. The stratigrahic section in Wechech Basin (section *E*, fig. 8) is chiefly sandstone and gypsiferous sandstone, but about 20 m of conglomerate is exposed stratigraphically high in the member. South of Horse Spring, breccia and conglomerate are the only rock types present.

Most of the sandstone is fine grained, brown, and parallel bedded, but some is lenticularly bedded, fine to coarse grained, and red brown. The brown, parallel-bedded type occurs in Rainbow Gardens near Lava Butte and in nearly all of the Gale Hills, Bitter Spring Valley, Echo Wash, and Wechech Basin. The red-brown, lenticularly bedded type occurs only in parts of Rainbow Gardens and interbedded with conglomerate in other areas. At Rainbow Gardens, the coarse-grained sandstone composes much of the member north of Lava Butte and in the vicinity of stratigraphic section *A* (fig. 8).

Brown, fine-grained sandstone occurs in parallel, continuous beds of uniform thickness. Some bedding surfaces are even, but others are undulatory (fig. 9). Although regionally these beds vary from as thin as 1 cm to as thick as 50 cm, in any one exposure bedding thickness commonly does not vary by much more than 15 cm. The most common bed thickness is between 8 and 15 cm. Many individual beds and most definable bedsets are continuous, though accurate measurements of lateral continuity are not possible because of colluvial cover and offsets on abundant small faults. Some thin beds are laterally discontinuous, but these are generally part of continuous bedsets. Only rare thick beds are lenticular, and these commonly consist of the coarser grained rocks. Most individual bedding surfaces are defined by abrupt changes in grain size.

Most of the sandstone ranges from medium grained to very fine grained, but coarse-grained sandstone and siltstone also occur. Most grains are composed of quartz and carbonate minerals with minor amounts of feldspar, lithic fragments (chiefly of carbonate rocks), and micas. Point counts of 100 grains indicate carbonate grain abundances from 50 to as much as 70 percent, and quartz abundances of 25 to 45 percent. Other constituents occur in amounts ranging from a trace to as great as 5 percent. In most samples, matrix and cement minerals compose 20 to as much as 40 percent of the rock. Both carbonate-clay and gypsum cements occur. The carbonate-clay mineral cement is composed chiefly of fine-grained crystalline to amorphous carbonate minerals that fill pores between grains. The brown color of the cement indicates contamination of the carbonate with clay minerals. Large gypsum crystals surround many of the sand grains, giving some samples of the sandstone a texture that resembles poikilitic texture in igneous rocks. Because neither type of cement leaves many pores, the porosity and permeability are low. It is not uncommon to find both types of cement in one sample.

Conglomerate of the Thumb Member has bedding, clast types, clast percentages, and clast-matrix percentages that vary geographically. The following discussion of clast types and percentages is keyed to figure 10, which depicts the results of pebble counts and the geographic distribution of sandstone versus conglomerate.

In the southern part of Rainbow Gardens (locality 7, fig. 10), most of the conglomerate is interbedded with sandstone in nonparallel, discontinuous, uneven, nonuniform beds that range in thickness from a few centimeters to 2 m. Bedding is defined by grain-size changes between sandstone and conglomerate, and trough cross-bedding, defined by clast trains, is common. The rock has a clast-supported texture, and the clasts are moderately sorted and moderately rounded. The largest clast is 70 cm in diameter, but most average about 25 cm. Some continuous conglomerate beds have well-defined, parallel bases and tops. Clasts in these beds are supported by mud, silt, and sand; are only 2 to 5 cm in diameter; occupy about 25 percent of the rock; and exhibit inverse grading near the base of the bed. All the conglomerate at Rainbow Gardens grades into sandstone to the north. This lithofacies change is especially well displayed by one thick, well-defined hogback forming a unit that thins considerably to the north and that grades entirely into sandstone in the vicinity of Lava Butte.

In the northern part of the Gale Hills and Bitter Spring Valley (localities 1, 2, and 4 on fig. 10) the conglomerate is coarse-grained, thick-bedded, and abundant. Continuous, well-defined, but poorly sorted and unbedded conglomerate is common near the resistant

FIGURE 8 (facing page).—Generalized stratigraphic sections of the Thumb Member of the Horse Spring Formation with map showing geographic distribution of outcrops. All five stratigraphic sections are conformably underlain by Rainbow Gardens Member. Sections *A*, *B*, *D*, and *E* on this figure overlie, respectively, sections *A*, *G*, *B*, and *D* on figure 4. Section *C* on this figure has no counterpart on figure 4, but Rainbow Gardens Member does occur beneath it. The left side of each section depicts bulk grain size: C, conglomeratic; G, fine-grained conglomerate or grit; S, sandstone; F, finer grained than sandstone. The right side of each section depicts relative resistance to weathering: N, nonresistant; M, moderately resistant; R, resistant; V, very resistant.

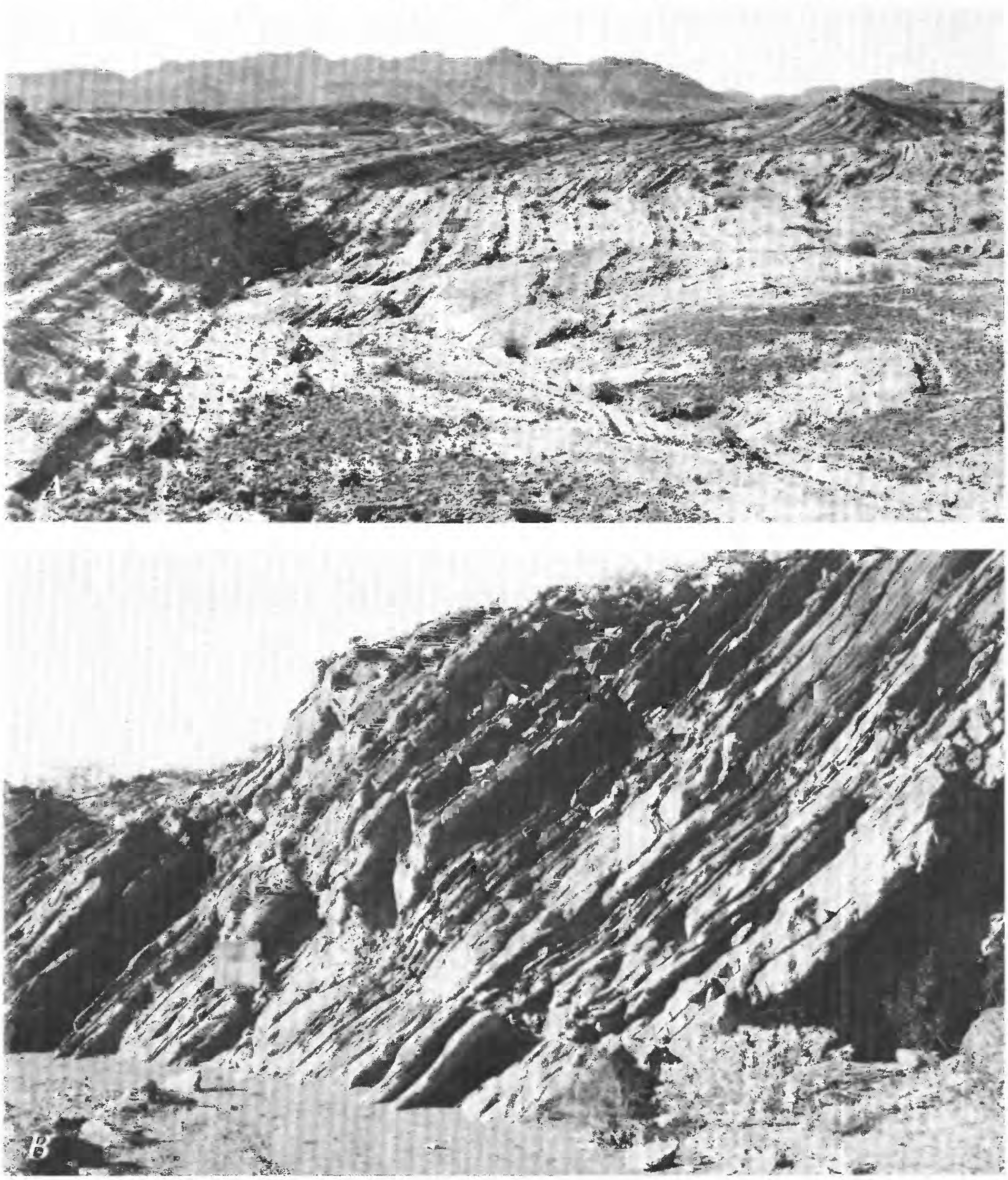


FIGURE 9.—Examples of parallel, continuous bedding within sandstone of the Thumb Member. *A*, View south towards the Black Mountains across Echo Wash (not visible) shows extreme lateral continuity of bedding in a stratigraphic section of sandstone with even bedding surfaces. *B*, An outcrop in Callville Wash, north of Callville Bay, shows undulatory bedding. Photo case on the left is 50 cm square.

Paleozoic carbonate units of the Muddy Mountains. This bedding contrasts with the lenticular, discontinuous, unevenly bedded conglomerate with moderate clast sorting in more southerly exposures (localities 9, 10, 11, 12, and 5 on fig. 10). Most of the conglomerate in the Gale Hills and Bitter Spring Valley has clast-supported texture, but some of the well-defined, unbedded units have matrix-supported clasts. Clast diameters of one meter and greater occur adjacent to outcrops of Paleozoic strata, but clast size decreases to

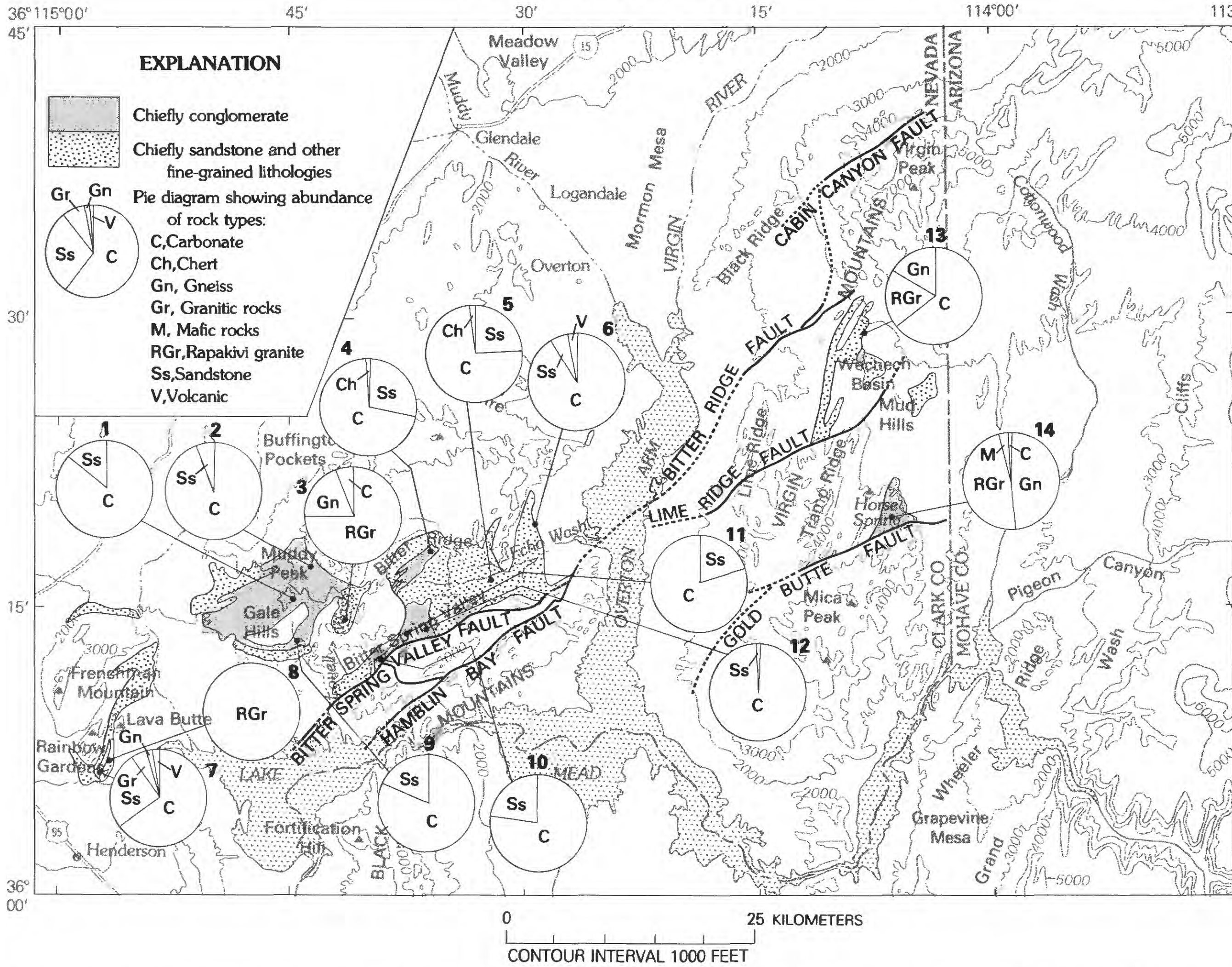


FIGURE 10.—Distributions of the conglomerate facies and the fine-grained facies of the Thumb Member, relative abundances of clast types, and locations of major faults of the Lake Mead fault system.

the south to about a 25-cm average. The unbedded units commonly have well-defined, parallel, inversely graded bases and parallel tops (fig. 11.). Carbonate clasts predominate over sandstone clasts in the conglomerate (fig. 10, localities 1, 2, 4, 5, 6, 9, 10, 11, and 12), and all clasts are moderately rounded. A small percentage of volcanic clasts occur in a conglomerate lens north of Echo Wash (fig. 10, locality 6).

Conglomerate occurs in Wechech Basin, but exposures are limited. Its bedding is discontinuous, nonparallel, and uneven. The clasts, the largest of which is 10 cm, are in grain contact, and the matrix is of well-indurated sandstone. Clasts are a mix of carbonate rock types, granitic types with rapakivi granite, and gneiss (fig. 10, locality 13). Conglomerate is apparently more abundant in the southern part of Wechech Basin.

Large lenses, small discontinuous beds, and widespread exposures of breccia occur within the Thumb Member in Lovell Wash, in Rainbow Gardens, and north of the Gold Butte fault (localities 3, 8, and 14, respectively, fig. 10). In Rainbow Gardens, nearly monolithologic breccia of the Thumb Member occurs in unstratified, unsorted lenses with angular clasts more than 1 m in diameter. Little or no matrix matter is present, and the clasts of rapakivi granite and other granitic rocks are tightly fitted. Brenner-Tourtelot (1979) shows the location of most of the breccia lenses in the Thumb between Rainbow Gardens and Lake Mead Boulevard (see fig. 3*C* for the location of Lake Mead Blvd.), but she also shows some at other localities that occur in younger deposits. In Lovell Wash, clasts of rapakivi granite, other granitic rocks, gneiss, and carbonate rocks occur in thin, discontinuous breccia beds that are interbedded with sandstone. North of the Gold Butte fault, bedding appears to be nonexistent and the clasts, which consist of gneiss, rapakivi granite, other granitic

FIGURE 11.—A continuous, well-defined conglomerate bed within the Thumb Member of the Horse Spring Formation. This particular bed occurs in Bitter Spring Valley and is interbedded with parallel-bedded sandstone. It is not close to outcrops of Paleozoic strata, although conglomerate beds of this type are more prevalent near such outcrops. The well-defined base of the bed is in shadow, and there is a thin zone of inverse clast grading near its base. The texture is generally matrix-supported.

rocks, carbonate rocks, and mafic igneous rocks, are as large as several meters in diameter.

CARBONATE AND SULFATE ROCKS

The best exposure of gypsum, a primary constituent of the Thumb Member, occurs in the steep sides of Echo Wash, where thick, pure units as much as 20 m thick occur in the upper part of stratigraphic section *D* (fig. 8). Strata average about 15 cm thick in the blocky-weathering gypsum and are parallel, wavy, continuous, and uniform. Internal laminations, defined by changes in shade from white to dark gray, are wavy, continuous, parallel, and a few millimeters thick. At other locations in some recrystallized units of gypsum, the parallel laminations are not visible. Some of this recrystallization is a near-surface weathering phenomenon; the fine internal structure is only visible in outcrops in deeply incised drainages where rapid erosion is taking place. Possibly all the gypsum had finely laminated primary texture. In places, the gypsum contains sandstone, siltstone, and clay.

Limestone of the Thumb Member occurs in the southern part of the Gale Hills, in Bitter Spring Valley and north of Echo Wash. In nearly all places, it is dense, very hard, fine-grained, yellow and gray lithographic limestone and is resistant to weathering. It occurs in thin (2- to 10-cm-thick), even, well-defined, parallel beds that are interbedded with sandstone. In Bitter Spring Valley the lithographic limestone is beneath the Bitter Ridge Limestone Member. North of Echo Wash, limestone near the Rogers Spring fault grades south into sandstone.

TUFFACEOUS ROCKS AND VOLCANIC FLOWS

Pale green hornblende-biotite tuff beds, bedsets, and units (fig. 12) occur interbedded with all of the of the Thumb Member except the conglomerate. These tuff units also occur in the Rainbow Gardens Member, the Bitter Ridge Limestone Member, and the lower part of the Lovell Wash Member, but they are most common in the Thumb. The tuffs range in thickness from 15 cm to 10 m and have uniform, even, discontinuous internal

FIGURE 12.—One of the green tuff units (light-colored bed in center of photo) interbedded with sandstone of the Thumb Member in the Gale Hills. This particular unit is about 2 m thick. Units such as this provide zircons for fission-track age determinations.

crossbedding and parallel bedding. The thickest units commonly contain unbedded basal layers as thick as 20 cm, which are possibly original, unreworked ash falls. Throughout the tuffs, euhedral andesine, sanidine, biotite, and hornblende phenocrysts are set in a matrix of green clinoptilolite and heulandite altered from the original glass and glass shards. Quartz is present in minor amounts but is rarely euhedral.

The lava flows of the Thumb Member in Rainbow Gardens were not studied in detail and are not reported on herein.

Sedimentary Structures

Environmentally significant textural features of many conglomerate beds include their matrix support, their basal inverse clast grading, and their well-defined bases and tops. The lack of internal structures in some of the beds is also environmentally significant. These nearly structureless beds differ from other conglomerate units, in which internal trough crossbeds are well defined, clasts are supported by a sandy matrix, and the boundaries between conglomerate and sandstone units are poorly defined. Flat bedding contacts are present at the base of many conglomerate beds. These flat contacts may indicate deposition on a low-relief surface without large initial dips. Another simple, but significant, sedimentary structure occurs within many gypsum units in the form of thin, parallel laminations in thicker parallel beds.

Perhaps the most interesting sedimentary structures within the Thumb occur in its widespread parallel-bedded sandstones. To evaluate the structures in these beds, a detailed microsection was measured in Echo Wash, where they are well exposed. Figure 13 is a diagram of the microsection and figure 14 is a photograph of the rocks. The parallel-bedded sandstone shown in figure 14 is typical of much of the Thumb, and the structures associated with those beds are probably representative of structures throughout a wide area. One coarse-grained sandstone bed that was measured contains abundant small-scale cross-laminations, but its upper and lower 2 cm are not laminated. Several upward-fining sandstone and siltstone beds are exposed, and many of these have small-scale cross-laminations in their lower parts, whereas others are not laminated. One inversely graded bed grades upward from nonlaminated and parallel-laminated siltstone into cross-laminated sandstone. Shale chips occur in one of the beds, and another contains large-scale trough cross-laminations. Many irregular and wavy bedding surfaces occur, suggesting possible scour. In general, parallel laminations and structureless bedding appear to be associated with siltstone beds, whereas most sandstone

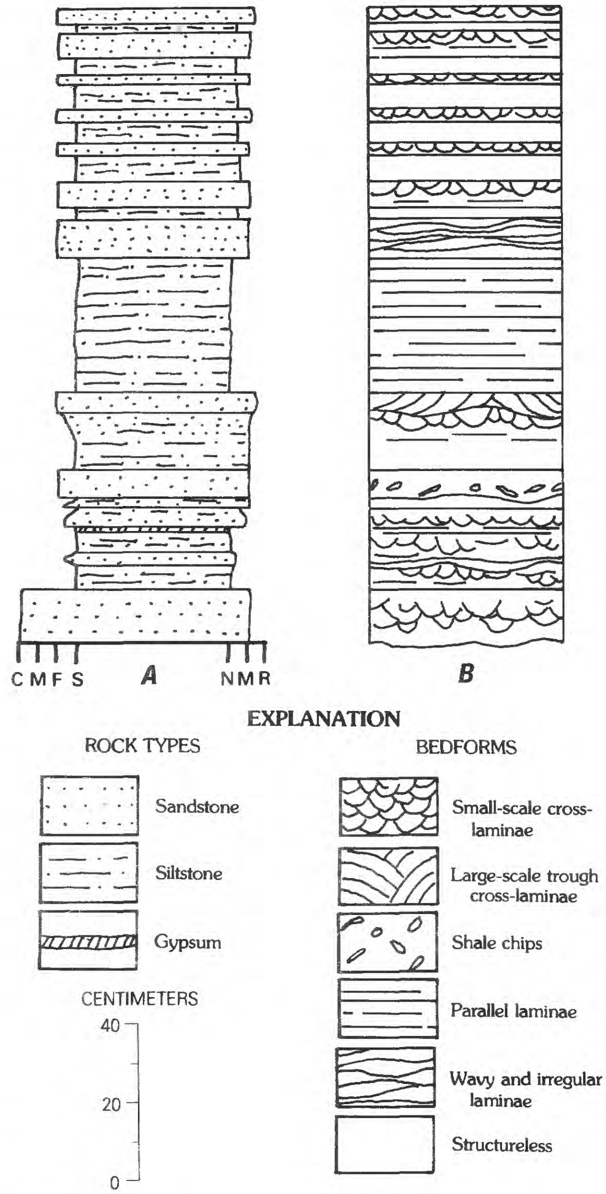


FIGURE 13.—Lithology (*A*) and bedforms (*B*) of a microsection in the Echo Wash area. (See photo, fig. 14.) The left side of the lithologic column (*A*) depicts grain size: C, coarse-grained sandstone; M, medium-grained sandstone: F, fine-grained sandstone: S, siltstone. The right side depicts relative resistance to weathering: N, nonresistant; M, moderately resistant; R, resistant.

beds appear to contain small-scale cross-laminations or wavy irregular laminations. Where bedding surfaces are exposed, oscillation ripple marks can be observed. No mud cracks were observed.

Depositional Environments

The parallel and continuous bedding in most of the Thumb Member may indicate deposition on a flat, even surface such as a lake bottom. Such a setting seems

FIGURE 14.—Rocks measured for the Echo Wash microsection (fig. 13). Distance showing along measuring rod at edge of photo is 1.4 m.

reasonable for the origin of gypsum and limestone, and it is also a likely environment of deposition for the parallel-bedded sandstone. Some of the conglomerate beds that have continuous, even bases parallel to underlying bedding were probably also deposited in a lacustrine environment. Standing water was probably always present during the deposition of the laminated gypsum and the dense, hard limestone beds, but it may only have been sporadically present during the deposition of the parallel-bedded sandstone and siltstone. It seems prudent to interpret the parallel, thin laminations in gypsum as structures that formed by precipitation in standing water. The water depth is uncertain, but the fact that the thin laminations were preserved suggests that it was moderately deep and that bioturbation was rare. The presence of limestone and gypsum suggests saline, alkaline water.

Much of the conglomerate and associated sandstone has discontinuous, lenticular, uneven, nonuniform, poorly defined bedding suggestive of fluvial deposition. These thick deposits, which probably represent alluvial fan accumulations, interfinger with the parallel-bedded sandstone thought to be lacustrine in origin. Also, debris-flow beds of nearly unstructured conglomerate with well-defined, flat bases, matrix-supported clasts, and inverse basal clast grading are interbedded with both the alluvial lenticularly bedded fanglomerate and the lacustrine parallel-bedded sandstone.

Analysis of the microsection depicted on figure 13 indicates standing water was present during deposition of some of these beds. Oscillation ripple marks, the even, unscoured bedding surfaces, and abundant small-scale cross-laminations are consistent with deposition in a permanent lake with slow-moving currents. Some bedding surfaces are uneven and irregular, and may be scoured or may have been deposited during times of high flow. Small- and large-scale cross-stratification indicates rapid deposition in a fluid medium and suggests possible storm activity accompanied by deposition of a large sediment load. The lowest bed in the microsection is coarse-grained sandstone, which occurs above an irregular scoured base and has small-scale cross-stratification. This bed is similar to subaqueous flows, such as distal turbidites. The sequence suggests that sediment-charged water entered the lake during a storm and resulted in deposition of the lowest coarse-grained bed. Rapid subaqueous deposition probably continued to form the overlying siltstone and sandstone beds with small-scale cross-laminations and irregular bedding. The thin gypsum layer was probably deposited in the aftermath of rapid storm deposition, after the water had cleared. Two graded beds of fine-grained sandstone and siltstone containing small-scale cross-laminae deposited above the gypsum indicate further clastic influx. The bedding surface at the top of the upper graded bed is wavy and uneven, suggesting lacustrine wave action or subaerial eolian scour. Above the wavy surface, a structureless bed of sandstone with shale chips at its base indicates rapid deposition accompanied by erosion and incorporation of the underlying bed. The bed overlying the structureless sandstone coarsens upward from unstructured to parallel-laminated siltstone into cross-laminated sandstone, as if formed in a small delta prograding into the lake. At the top of the coarsening-upward bed is an irregular bedding surface that could have been caused by scour or wave reworking. A sandstone bed with trough cross-laminations above the wavy surface suggests rapid deposition. The cross-laminated bed is succeeded by laminated siltstone and several interbedded cross-laminated sandstone and unlaminated siltstone beds without evidence of exposure or scour.

The above scenario is speculative, and it illustrates only a likely sequence of events occuring during deposition of the lacustrine sandstone. Certainly, there are other areas where the relative abundances of the described structures are different and where such things as uneven bedding surfaces are more common than they are at the location of the microsection. Also, ratios of coarse-grained to fine-grained detritus obviously must have varied considerably at different geographic localities during deposition, but only numerous closely spaced sections could document the nature of such changes.

FACIES AND PROVENANCE

The Thumb Member, as described above, consists of lacustrine (fine-grained) and alluvial (coarse-grained) facies, whose geographic distributions are shown on figure 10. These two depositional facies can be considered to be temporally equivalent. Analysis of the distribution and character of the alluvial facies shows that the Thumb had a northern source chiefly of upper-plate rocks above the Cretaceous Muddy Mountain thrust and a southerly source of lower-plate carbonate rocks and granitic and gneissic basement rocks in the Gold Hill area of the southern Virgin Mountains. Figure 15 is a diagram of the northern basin margin of the Thumb against the Muddy Mountains.

In the northern part of the Gale Hills, the alluvial facies is very coarse grained at its contact with the resistant Paleozoic rocks of the Muddy Peak area (figure 16*A*). Although this contact is chiefly faulted and has been termed the Gale Hills fault (Bohannon, 1979), at some localities it appears to be a steep buttress unconformity. At other localities, thrust relations exist along the Gale Hills fault where intact mountain-size blocks of Paleozoic rocks have been emplaced above parts of the Thumb. The predominant clast type in the alluvial facies is Paleozoic carbonate rock from the upper plate of the Muddy Mountain thrust, but some Aztec-like clasts of red sandstone, probably from the lower plate, also occur. The Gale Hills fault locally marked the margin of the Thumb basin, and the apparent steepness of the marginal contact as well as the coarse grain size of the alluvial facies suggest that it was a high-relief margin. The trend and location of this margin are shown on figure 15 by the solid dots southwest of Muddy Peak.

North of Echo Wash two resistant ridges of Paleozoic rocks, East and West Longwell Ridges, extend southwest from the eastern part of the Muddy Mountains, forming hogbacks that dip to the southeast. The rocks of the alluvial facies of the Thumb rest depositionally on the older rocks of West Longwell Ridge on a steep buttress unconformity (fig. 16*B*). The alluvial facies rocks

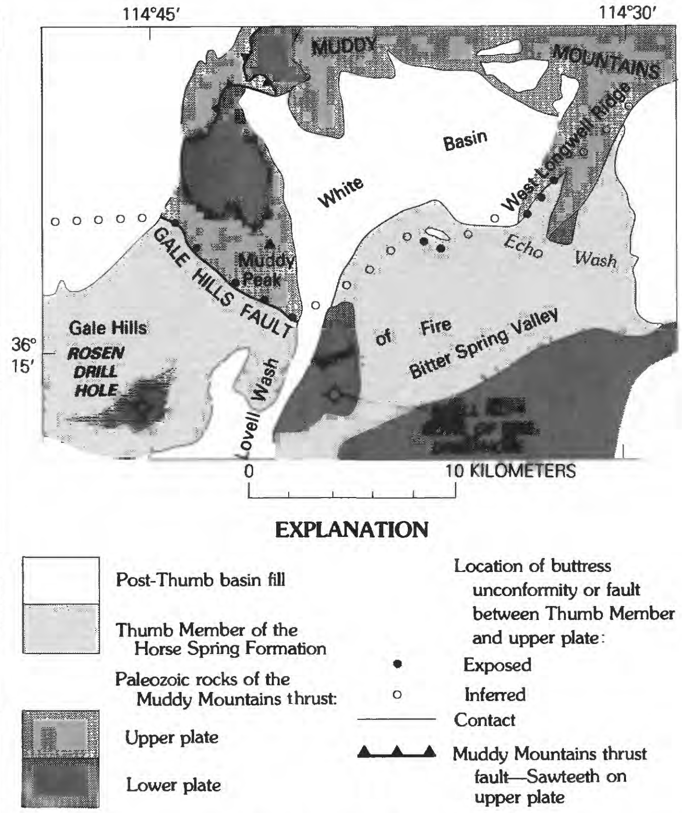


FIGURE 15.—Location of the northern basin margin of the Thumb Member of the Horse Spring Formation. The margin is marked by buttress unconformities or faults where the alluvial facies of the Thumb abuts the Paleozoic rocks in the upper plate of the Muddy Mountain thrust. The location of the margin is inferred where it is covered or eroded. Rocks in the upper plate of the Muddy Mountain thrust are distinct stratigraphically from those in the lower plate. The allochthonous stratigraphy is defined by geologic mapping. The autochthonous stratigraphy is defined from lithologic logs of core from the two drill holes shown here.

abruptly interfinger with the rocks of the lacustrine facies in the valley between the two ridges. Clasts in the alluvial facies are composed of local Paleozoic rocks, indicating that the facies was derived from the ridge or from the White Basin area beyond the ridge to the west. Presently White Basin is a graben in which younger members of the Horse Spring Formation are exposed. However, the buttressing of the coarse-grained alluvial Thumb on the narrow, basin-bounding hogback suggests that the area now occupied by the basin may have been an uplifted source area for at least the oldest part of the Thumb. The solid dots north of Echo Wash on figure 15 show the location of the buttress unconformity.

In northern Bitter Spring Valley, between the Gale Hills fault and the buttress unconformity described above, a small outcrop of Paleozoic rocks is overlain by

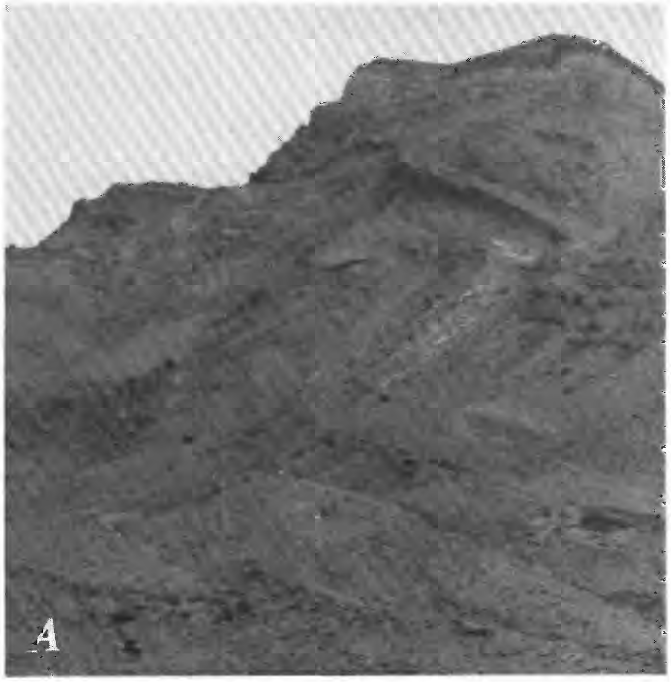


FIGURE 16.—Rock strata along the northern margin of the the Thumb basin. *A*, In the area of Muddy Peak, the conglomerate facies of the Thumb Member (low hills in foreground) abuts Paleozoic strata in the upper plate of the Muddy Mountain thrust (mountains in backgound). The contact is the Gale Hills fault. *B*, Along West Longwell Ridge, a prominent, southwest-trending ridge north of Echo Wash, rocks of the alluvial facies of the Thumb (at top and right) have been deposited on these same upper-plate rocks (at bottom and left). The contact is a buttress unconformity.

conglomerate of the alluvial facies deposited on a buttress unconformity. Both the unconformity and the conglomerate have been faulted. The youngest part of the Thumb, which is lacustrine, overlaps the outcrop of Paleozoic rock, the older Thumb conglomerate, and the faulting. The overlapping lacustrine facies dips north under White Basin, but the outcrop of Paleozoic rocks and its associated conglomerate may indicate that the basement of the Thumb is close to the surface and that a steep, high-relief basin margin probably existed in northern Bitter Spring Valley during the deposition of the oldest part of the Thumb Member. The younger lacustrine facies apparently lapped across this margin into the area of southern White Basin, although evidence of equivalent rocks on the northern side of the basin is limited. Thin, discontinuous conglomerate beds occur beneath the Bitter Ridge Limestone Member in northern White Basin and possibly are Thumb equivalents. Two dots on figure 15, southwest of the outcrop of Paleozoic rocks in northern Bitter Spring Valley, indicate the location of the faulted buttress unconformity.

The pattern of conglomerate indicates that a high-relief basin margin existed south of the Muddy Mountains during much of the deposition of the Thumb and that the youngest lacustrine facies overlapped that margin at some locations. The margin was apparently irregular, extending from the site of the Gale Hills fault in the Gale Hills, through northern Bitter Spring Valley, northwest to Echo Wash. North of this margin the highland was composed of the Paleozoic rocks of the upper plate of the Muddy Mountain thrust (fig. 15). South of the margin the Thumb and Rainbow Gardens Members were deposited upon Mesozoic rocks that occur in the lower plate of that thrust. This contrast and the significance of the Gale Hills fault are illustrated by examination of the area between Muddy Peak and the Bowl of Fire.

North of the basin margin and Muddy Peak, the Muddy Mountain thrust dips south, towards the Bowl of Fire. Cambrian, Ordovician, Devonian, and Mississippian rocks above the thrust also dip south. Upper-plate stratigraphy is distinct from that exposed in the lower plate at Frenchman Mountain. Although rocks of the upper plate dip south and the thrust apparently roots in that direction, the Shell #1 Bowl of Fire drill hole in the Bowl of Fire (only about 6 km south of Muddy Peak) penetrated a lower-plate sequence similar to that at Frenchman Mountain (Bohannon and Bachhuber, 1979, p. 592). This finding suggests that the Gale Hills fault formed a high-relief basin margin and was an important structural boundary. This structural boundary extends from the Gale Hills to Echo Wash and forms the southern margin of the upper plate of the Muddy Mountain thrust. Its trace, shown on figure 15, has been made irregular by later fault displacements.

Exposures of Precambrian granite and gneiss and Paleozoic carbonate rocks at Gold Butte apparently were the source of conglomerate and breccia both locally in the Virgin Mountain region and 65 km to the southwest in Rainbow Gardens. In Rainbow Gardens, the alluvial facies contains granitic and gneissic clasts, and breccia lenses are commonly composed entirely of rapakivi granite. Anderson (1973, p. 12–13) and Longwell and others (1965, p. 43) concluded that the conglomerate and breccia of the Thumb in Rainbow Gardens were derived from the south. This conclusion seems compatible with the transition of the alluvial facies into sandstone of the lacustrine facies from south to north. Anderson (1973) also concluded that the conglomerate, with its abundant clasts of Paleozoic and Mesozoic rocks, could not have been derived from the nearby River Mountains or northern Black Mountains, because volcanic rocks equivalent to and older than that conglomerate rest on the gneissic and granitic basement rocks there. Recent radiometric ages of the Thumb confirm this conclusion. Anderson (1973) further reasoned that the rapakivi granite-bearing breccia could not have come from due south of Rainbow Gardens because such granite does not occur there in the basement terrane. The Gold Butte area south of the Virgin Mountains is the closest locality where volcanic cover is absent and rapakivi granite is exposed. Because the coarseness of the conglomerate and breccia suggests a nearby source, Anderson (1973) proposed that the Frenchman Mountain area has been transposed 65 km southwest from the Virgin Mountains by strike-slip displacement on northeast-trending faults. This thesis was further refined by Bohannon (1979) and is elaborated upon in a later section of this paper.

Clasts of rapakivi granite occur in small isolated lenses in the Thumb in Lovell Wash. These occurrences of granite are not a part of the alluvial facies in the Gale Hills, but are part of the lacustrine facies. Anderson (1973) suggested these granite-clast lenses had a source in the Gold Butte area south of the Lake Mead fault system. I concur.

Conglomerate and breccia of the Thumb Member in the Virgin Mountains appear to have been locally derived from the Gold Butte area. Coarse-grained breccia thought to be part of the Thumb occurs directly north of the Gold Butte fault and probably records activity on that fault. This breccia apparently fines to the north into alluvial rocks interbedded with lacustrine rock in Wechech Basin. The clasts in both the alluvial rocks and the breccia match lithologies exposed in the Gold Butte area.

BITTER RIDGE LIMESTONE MEMBER

DISTRIBUTION AND THICKNESS

The Bitter Ridge Limestone Member is exposed only north and northwest of the Lake Mead fault system (fig. 17), unlike the Rainbow Gardens and Thumb Members, which are widespread in the Virgin Mountains. At some locations, such as in the western Muddy Mountains, the

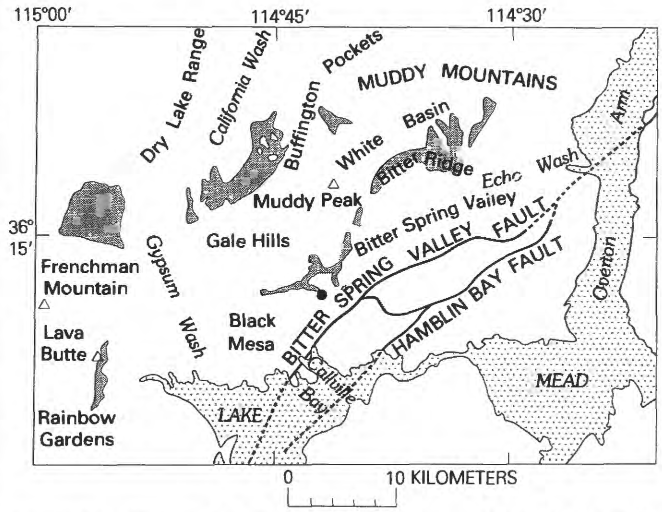


FIGURE 17.—Geographic distribution of outcrops (shaded) of the Bitter Ridge Limestone Member of the Horse Spring Formation. Two major faults of the Lake Mead fault system are shown for reference. The solid dot in the southern part of Lovell Wash indicates the position of conglomerate that interfingers with limestone.

Bitter Ridge Limestone Member rests depositionally on Paleozoic rocks beyond the northern depositional limits of both older members. The easternmost exposures of the member occur at Bitter Ridge, its type section, between White Basin and Bitter Spring Valley. West of there it occurs near Buffington Pockets in narrow ridges throughout the southeastern Gale Hills, and in numerous exposures south of California Wash and north of Frenchman Mountain. Although isolated from and lithologically dissimilar to other exposures of the member, the rocks exposed in the same stratigraphic interval near Lava Butte are included with the Bitter Ridge Limestone Member herein. The Bitter Ridge Limestone Member rests conformably on the Thumb Member except where it unconformably overlies Paleozoic rocks, and the Lovell Wash Member is conformable above the Bitter Ridge Limestone Member at most locations.

At its type section the Bitter Ridge Limestone Member is about 375 m thick and dips north under White Basin. In the eastern part of White Basin it abuts against the White Basin fault. At the western side of the basin, near Buffington Pockets, the Bitter Ridge dips to the southeast, indicating that the basin is synclinal and that the member is present in the subsurface in at least the western part of the basin. The member probably occurs in the subsurface of much of the northern part of the basin as well, but it is not exposed along the northern basin margin. At the northern margin the overlying Lovell Wash Member and the informal unit of red sandstone appear to buttress against the Paleozoic rocks. This relation indicates that the

Bitter Ridge Limestone Member either was eroded or was not deposited there.

In the northern Gale Hills, south and southwest of California Wash, the Bitter Ridge Limestone Member dips slightly to the north and onlaps Paleozoic rocks west of Muddy Peak. It projects into the subsurface under southern California Wash, and although its maximum northern extent is not known, it could be continuous throughout California Wash. The Bitter Ridge Limestone Member overlaps the Gale Hills fault and is depositional on Paleozoic rocks to the north and on the Thumb Member to the south. The unit is exposed throughout the northwestern Gale Hills to the region north of Frenchman Mountain.

Near Lava Butte, rocks in the same stratigraphic position as the Bitter Ridge Limestone Member are 180 m thick and dip east, but they are not continuous at the surface with other exposures of the member. These lithologically distinct rocks are probably present in the subsurface east of Lava Butte, but it is not known whether they continue into typical Bitter Ridge strata there. Northeast of Lava Butte, the underlying Thumb Member and the overlying Lovell Wash Member are in contact, and no rocks equivalent to the Bitter Ridge Limestone Member are exposed.

LITHOLOGY

The sole rock type of the Bitter Ridge Limestone Member at most localities is uniform light-brown, yellow, and pale-pink crystalline limestone. A thin unit of red and yellow sandstone occurs near the top of the member at Bitter Ridge. This sandstone unit thickens in the Lovell Wash area, where it is gypsiferous. In Lovell Wash there is an abrupt lithofacies change from limestone to conglomerate (fig. 17). Near Lava Butte the member consists of brown and pale-red-brown arenaceous limestone, intraformational arenaceous limestone breccia, and calcareous sandstone. These beds also include a minor amount of dark brown conglomerate.

Calcareous Lithologies

Light-tan, yellow, and pale-pink limestone of the Bitter Ridge Limestone Member has parallel, wavy, continuous, uniform bedding that ranges from about 1 to 20 cm in thickness. Some bedsets, which are commonly 15 to 80 cm thick, weather differentially and masquerade as individual thick beds, but close inspection shows these bedsets commonly consist of as many as 20 individual beds (fig. 18). Individual beds can be distinguished from one another by differences in weathering which are probably due to grain size and (or) textural differences. Texturally the rock is highly porous and has both laminated and unlaminated aspects (figs. 18*B* and *C*). The laminations are very thin, wavy, relatively continuous in some beds but discontinuous in others, and nearly parallel to bedding surfaces. Unlaminated beds have large vugs and resemble tufa.

In thin section the Bitter Ridge is composed of very fine- to coarse-grained crystalline limestone. This limestone consists of a rhythmic alteration of thin laminations of very fine grained crystalline calcite (possibly micrite) and thicker laminations of medium-grained crystalline calcite (spar) with an interlocking grain texture. In most rocks, the primary bedding and grain types have not been well preserved, owing to post-depositional disruption of the laminations and recrystallization. However, some fine-grained thin laminations preserve laterally linked micro-hemispheroids, which impart a stromatolitic texture. Thinner laminations are generally dark because of impurities, and coarser grained laminations consist of relatively clear calcite crystals. Laminations are wavy, discontinuous, nearly parallel, and of uniform thickness. Figure 19 is a photomicrograph of a sample in which some original texture is observable. Where original depositional features have not been well preserved, the laminations are less distinct and are discontinuous and wavy. Lumps of fine-grained mud or crystalline carbonate with diffuse edges are alined to form the irregular laminations. These lumps consist of rounded masses of the disrupted original laminae, long stemlike features that may be plant fragments, and rounded individual sand-size crystals of calcite. Impurities such as medium-grained, angular, well-sorted quartz, feldspar, and biotite constitute roughly 5 percent of the limestone. These grains are supported by carbonate cement and are evenly disseminated. Medium- to coarse-grained crystalline carbonate minerals fill some of the pores and have cemented many of the grains.

Other carbonate rocks occur in the Bitter Ridge Limestone Member in Lovell Wash and near Lava Butte. Intraformational limestone breccia is interbedded with limestone in the upper part of the member in Lovell Wash. This breccia occurs in several 1- to 2-m-thick beds that have well-defined, even-surfaced, parallel bases and tops. Its clasts are well sorted and locally matrix-supported; they range from a few centimeters to 20 cm in diameter and are composed of limestone similar to that common elsewhere in the member. Southeast of Lava Butte, arenaceous limestone, limestone intraformational breccia, and calcareous sandstone exhibit discontinuous, wavy, nonparallel, nonuniform bedding. Unbedded limestone intraformational breccia is also common and in many places grades

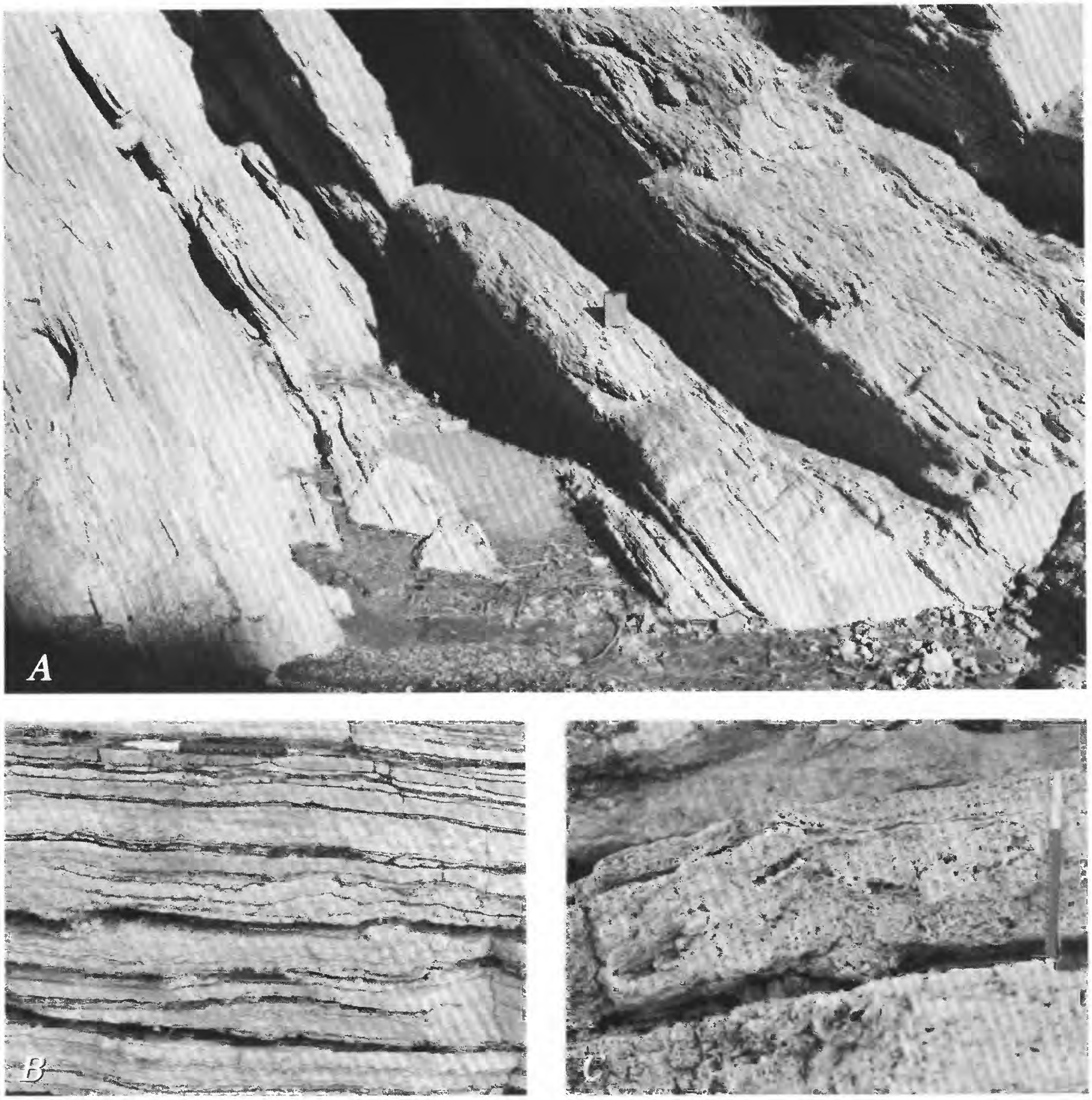


FIGURE 18.—Bedding characteristics in the Bitter Ridge Limestone Member of the Horse Spring Formation. *A*, Typical bedding in the member at its type section at Bitter Ridge. Notebook in center of photograph is 22 × 13 cm. *B*, Detailed view of typical bedding and laminations within the member in the area south of California Wash. Pencil near top is about 15 cm long. *C*, Detailed view of tufa-like bed in the member south of California Wash. Pencil at right provides scale.

laterally into bedded and laminated limestone. Normal bedding has apparently been disrupted to form the clasts in the intraformational breccia; such disruption also commonly occurs in lenses associated with clayey fine-grained limestone. Discontinuous, large-scale trough crossbeds are common in the calcareous sandstone and arenaceous limestone. However, some of the thicker, ledge-forming sandstone units have parallel, discontinuous bedding with only low-angle crossbedding. Most of the sandstone is composed of detrital

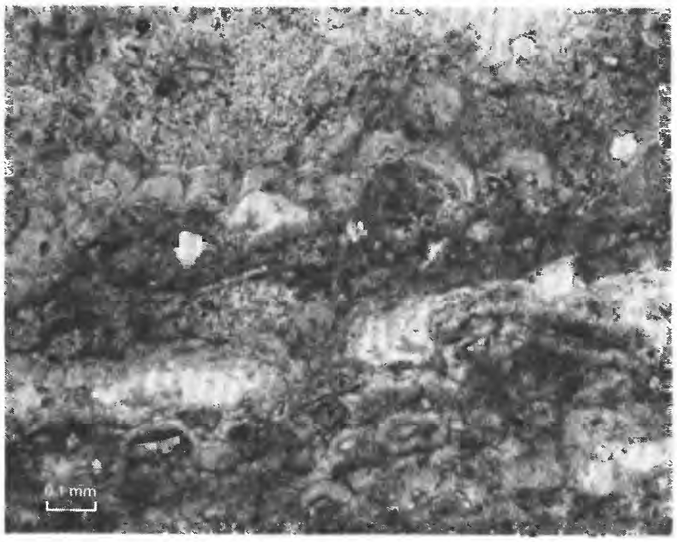


FIGURE 19.—Photomicrograph of sample from the type section of the Bitter Ridge Limestone Member at Bitter Ridge. The laterally linked micro-hemispheroids are visible in the photograph, as are light-hued pore fillings of crystalline carbonate. Plane-polarized light.

grains of limestone and dolomite that were probably derived from nearby Paleozoic rocks.

NONCALCAREOUS LITHOLOGIES

A unit of red and yellow sandstone and gypsum within the upper part of the Bitter Ridge Limestone Member in Lovell Wash is 110 m thick, but thins to less than 30 m on the north side of Bitter Ridge. The sandstone occurs in parallel, even, continuous, uniform beds that average 20 cm thick; it is red to red brown where the cement is calcareous, but yellow where gypsum is the cement. Gypsum occurs in the middle part of the unit and has disrupted bedding, but the disrupted beds are internally stratified. Gypsum and sandstone are gradational vertically.

In southern Lovell Wash the entire upper part of the Bitter Ridge Limestone Member and the lower part of the overlying Lovell Wash Member grade into conglomerate near the trace of the Bitter Spring Valley fault and an unnamed fault that trends towards Frenchman Mountain (fig. 17). The lithofacies change between limestone and conglomerate is abrupt, taking place within about 30 m, as congomerate south of Lovell Wash interfingers with limestone in the wash bottom. Conglomerate is only a minor constituent north of the wash. Bedding in the conglomerate is roughly parallel on a large scale, but is discontinuous, nonparallel, and curved on a small scale. Scour features, channels, and large-scale trough crossbeds are present. The texture of the conglomerate is clast-supported and the clasts are of dominantly Paleozoic carbonate rocks, which range from 50 cm to less than 5 cm in diameter, are moderately sorted, and are rounded. One of the most interesting features of the clasts in the area of the facies change is a concentrically laminated rindlike coating of carbonate minerals (fig. 20).

A thin unit of dark-brown conglomerate containing clasts of the dacite of Lava Butte occurs in the Bitter Ridge Limestone Member near Lava Butte. These clasts are set in a hard siliceous matrix. The presence of this conglomerate confirms the subaerial exposure of the dacite plug at Lava Butte during deposition of the Bitter Ridge. The subaerial exposure of the dacite indicates that it did not intrude the Bitter Ridge and that it predates that unit.

SEDIMENTARY STRUCTURES

Rare laterally linked micro-hemispheroids, apparent in some thin sections (fig. 20), and the wavy, stromatolitic bedding characteristic of the Bitter Ridge suggest that stromatolitic features are widespread. Another common sedimentary structure is a "teepee" structure, which, in cross-sectional view, is an upward convergence of beds forming an inverted V with coarse crystalline carbonate minerals in the central part of the V (fig. 21*A*). The "teepees" range from a few centimeters to as large as 50 cm in height, and they may involve one bed or several. They are not closely spaced either laterally or vertically. They are exposed on at least one bedding-plane surface, where they form a polygonal pattern of pressure ridges about 10 to 50 cm in height and about 25 m across (fig. 21*B*).

Several other rare, but important, sedimentary structures occur in the upper part of the Bitter Ridge Limestone Member in Lovell Wash. Large circular depressions (fig. 22) are exposed on some bedding-plane surfaces. The largest is nearly 25 m in diameter, and its center is 1.5 m lower than the surrounding bedding-plane surface. Several also have raised rims ½ m above the surrounding surface. All are oriented along a curved line, and several large cracks in the limestone correspond to the trend of the depressions. All have large cracks in their centers. The depressions appear to be a local phenomenon, but it is not possible to tell how widespread they may be without further detailed study. Also, several types of large stromatolitic features occur in the upper limestone unit above the red and yellow sandstone. The most notable of these are large clusters of both laterally and vertically linked hemispheroids that form stromatolites as high as 50 cm shaped like ice-cream cones (figs. 23 *A*, *B*, and *C*). These clusters are

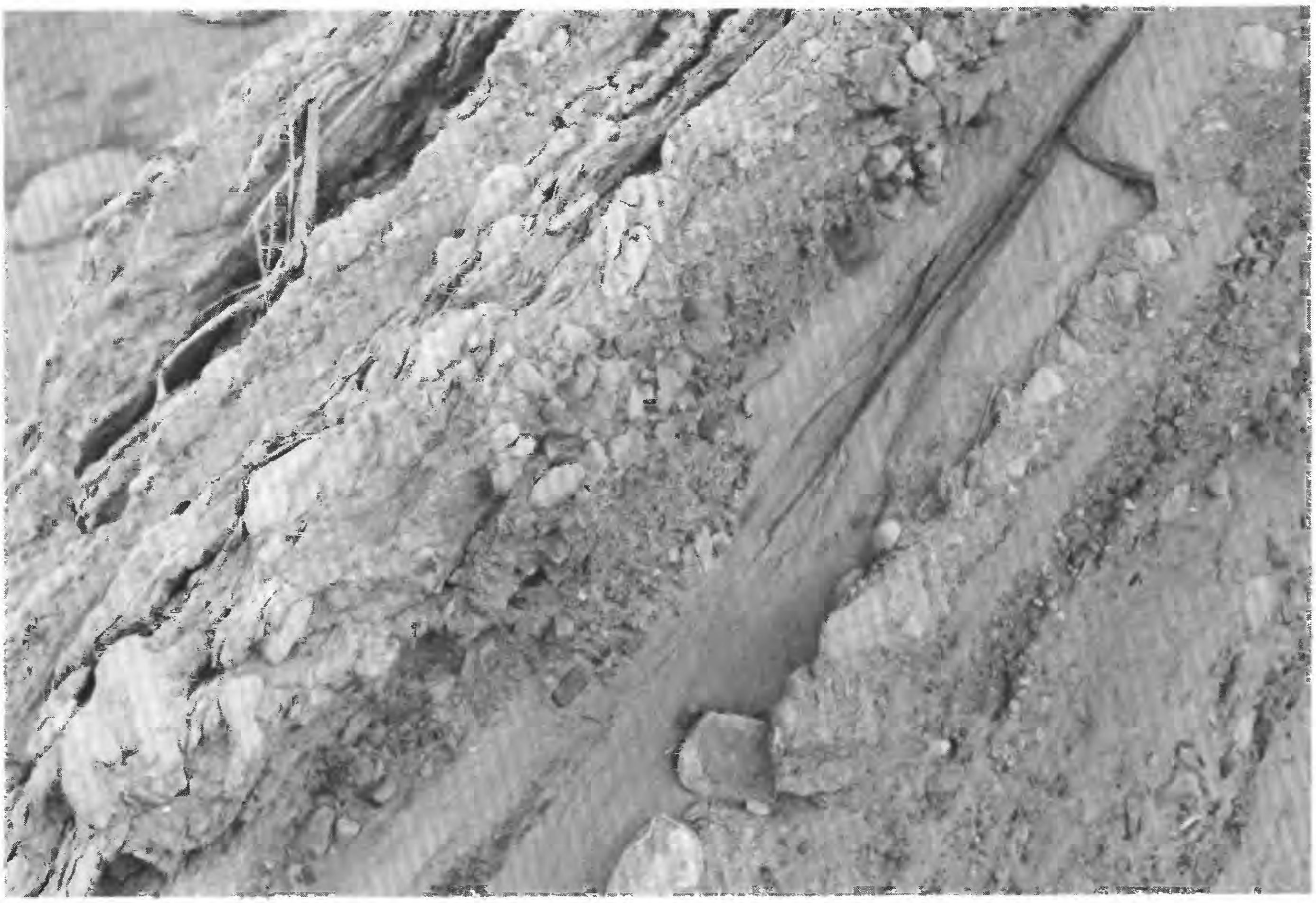


FIGURE 20.—Conglomerate interfingering with the Bitter Ridge Limestone Member in the southern part of Lovell Wash. Note the calcareous coating on many of the clasts. Largest clasts are about 15 cm in diameter.

laterally separated from one another by as little as a few centimeters to as much as 20 m, and the normal bedding between them bows upward at their margins. Many of the beds associated with the clusters contain smaller laterally linked hemispheroids that weather into eggshell-like chips (algal rinds). These smaller stromatolitic features are much more abundant than the larger clusters. Below the red and yellow sandstone unit, other occurrences of stromatolites include bedding-plane exposures of small (1–2 cm) domes that are associated with a minor amount of chert (fig. 23*D*) and low-relief hemispheroids that form a polygonal pattern on the bedding plane (fig. 23*E*).

FACIES AND DEPOSITIONAL ENVIRONMENTS

The Bitter Ridge Limestone Member is chiefly stromatolitic limestone, which can be subdivided into two subfacies: the wavy-bedded subfacies, which is the most widespread, and the stromatolitic mound subfacies, which apparently occurs only in the upper one-fourth of the member in Lovell Wash. A conglomeratic lithofacies, also exposed in Lovell Wash, is the southern stratigraphic equivalent of the stromatolitic mound subfacies, and it is distributed near large faults. Near Lava Butte the Bitter Ridge consists of sandstone and intraformational breccia, which are grouped with the conglomerate as the clastic lithofacies.

Both subfacies of the stromatolitic limestone appear to have originated as sediment in a lacustrine environment. The tabular nature of the member; the parallel, continuous bedding; and the fine, uniform laminations of the wavy-bedded subfacies support the lacustrine origin. A lacustrine environment provides the even, widespread surface necessary to develop such bedding, whereas few other nonmarine environments could. Apparently the lake was relatively free of detrital influx, because the limestone contains only widely dispersed grains of siliceous clastic material and no sand-sized

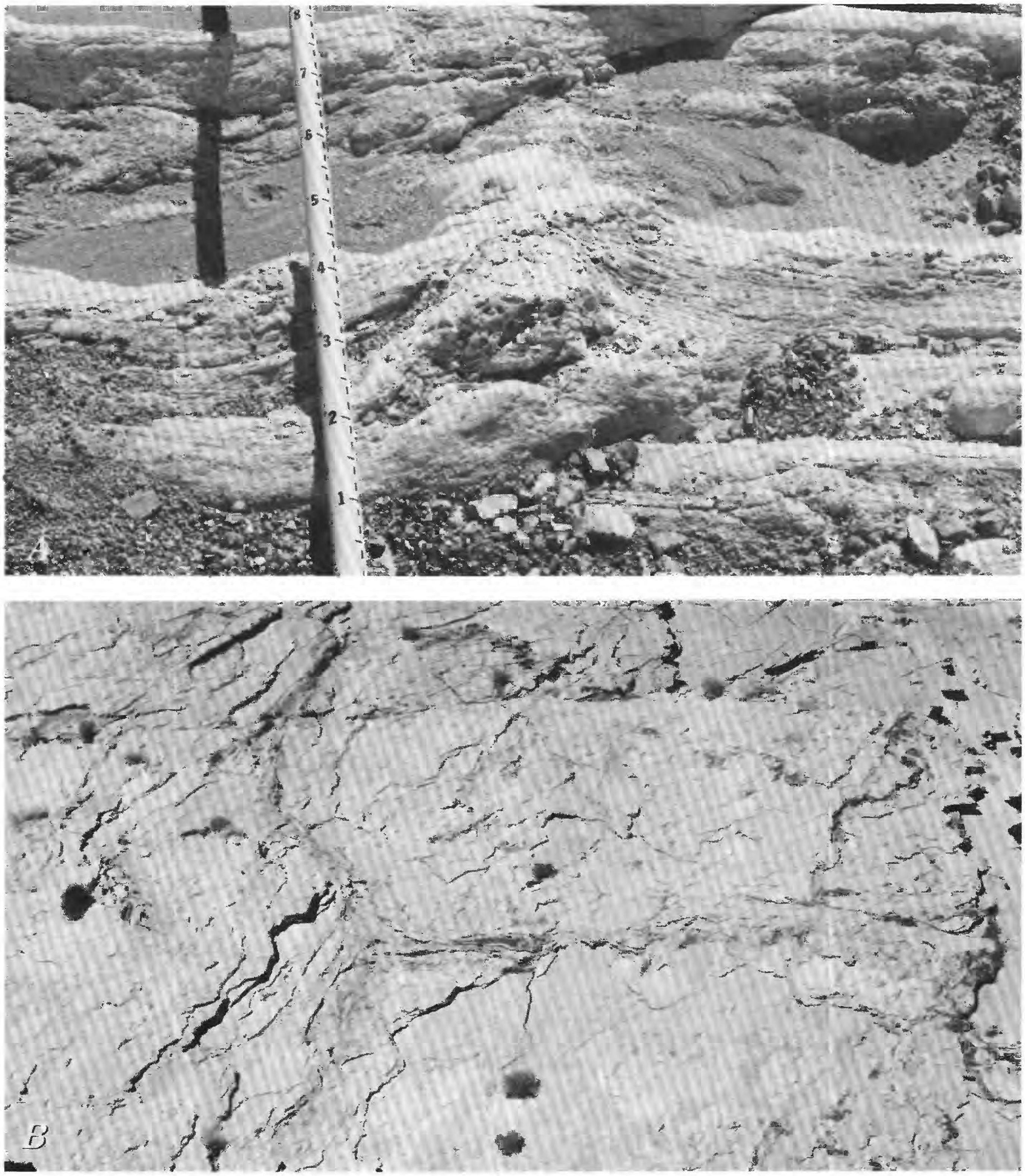


FIGURE 21.—"Teepee" structures (pressure ridges) in the Bitter Ridge Limestone Member. *A*, Cross sectional view of a "teepee" in the Bitter Ridge area. The measuring stick is marked in decimeters. Feature is formed by the displacing action of crystallizing carbonate matrix minerals. *B*, View of a bedding-plane exposure of the polygonal pattern made by the teepee structures in Lovell Wash. The polygons are about 25 m across.

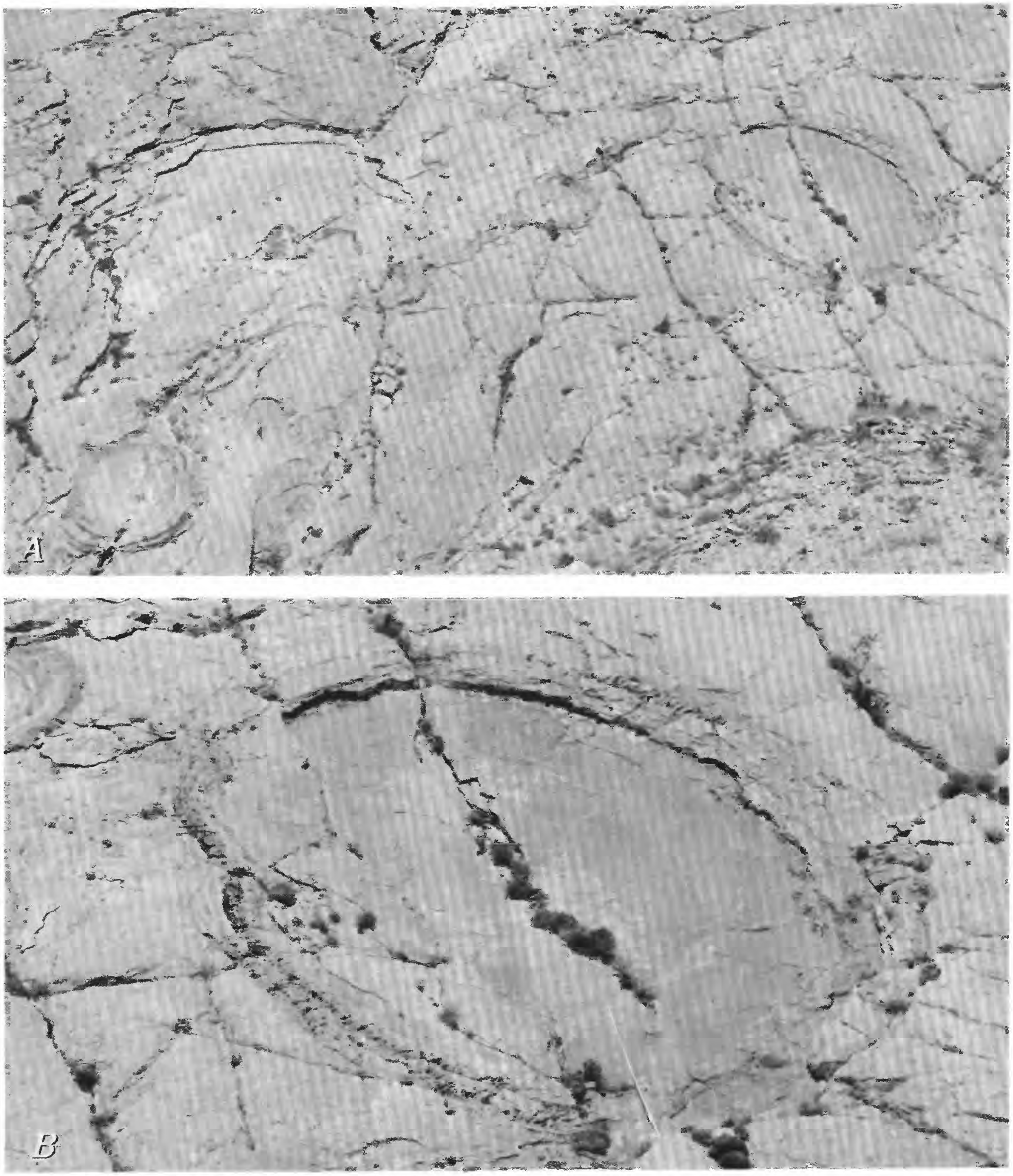


FIGURE 22.—Large circular depressions on a dip slope in the Bitter Ridge Limestone Member exposed in the north bank of Lovell Wash. *A*, Distant view of most of the features. Note their arcuate alinement along cracks, the size range of the features, and the man standing in the largest of them for scale. *B*, Closeup view of the largest depression. The measuring rod in the lower part is 6.5 m long.

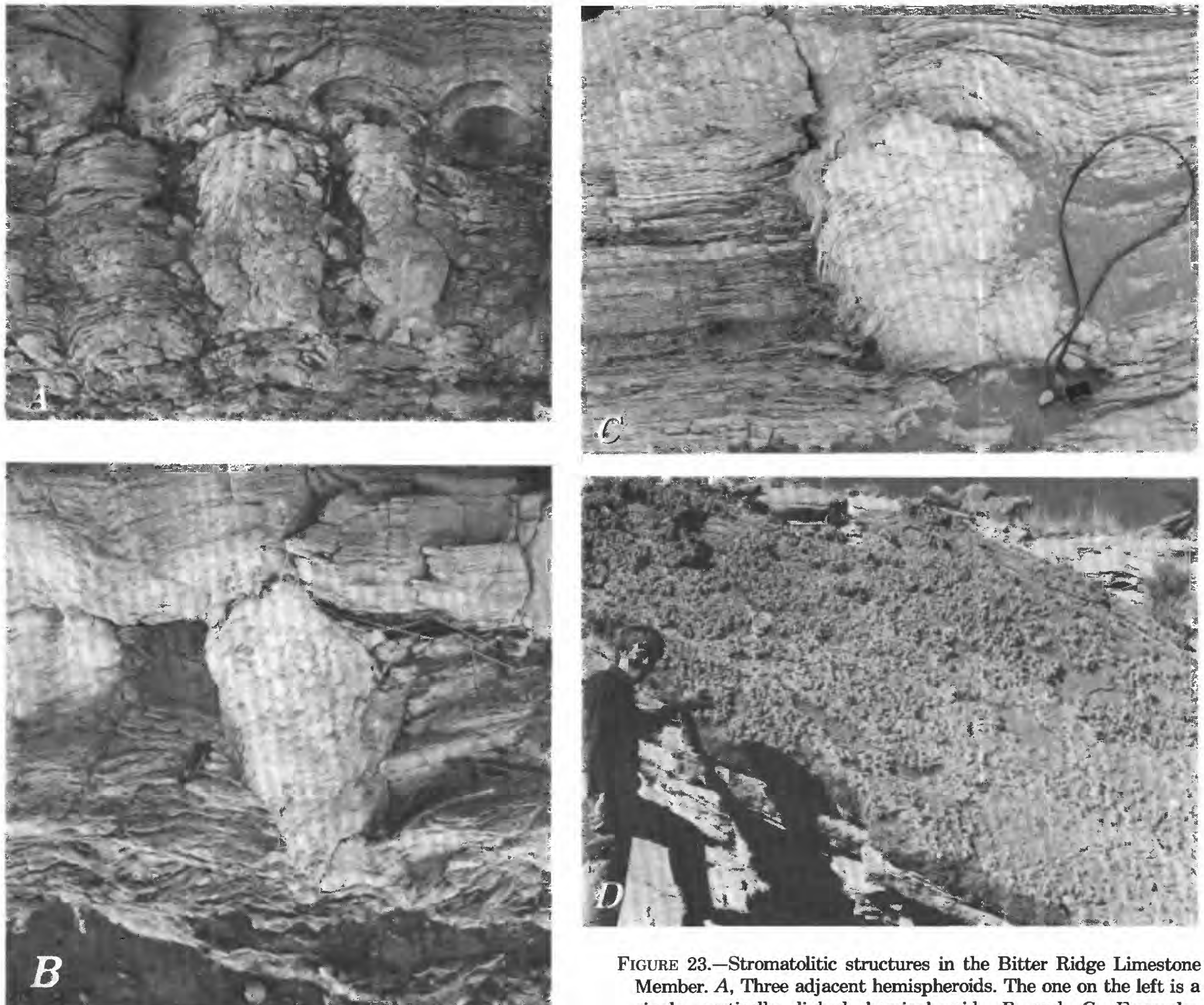


FIGURE 23.—Stromatolitic structures in the Bitter Ridge Limestone Member. *A*, Three adjacent hemispheroids. The one on the left is a single vertically linked hemispheroid. *B* and *C*, Examples demonstrating the ice-cream-cone shape of most of these features. *D*, Small mounds exposed in relief on a bedding-plane surface. *E*, Polygonal pattern made by small stromatolitic mounds on a bedding-plane surface.

grains of detrital carbonate. Siliceous grains and the fragments of plant material are thought to have been transported into the lake by eolian processes. The wavy bedding, laterally linked micro-hemispheroids, large ice-cream-cone-shaped stromatolitic clusters, large vertically linked hemispheroids, and the beds containing eggshell-like chips are interpreted to be algal in origin. Because these stromatolitic features are widespread, the algal lacustrine environment is considered to characterize the member, and the lake was probably shallow enough that most of its bottom was within the photic zone. Coarse-crystalline, vuggy limestone is interpreted to have formed as tufa deposits whose origin is closely tied with local spring activity. Other features possibly indicative of spring activity are the large circular depressions that occur near the conglomeratic facies, which is interpreted below to be a basin-margin deposit. These depressions may have originated by dissolution of limestone at the site of springs, and their raised rims may be the result of carbonate mineral precipitation during overflow of spring water. Similar features are known in modern spring environments, but the water surrounding these types of springs is commonly no deeper than the marginal rim of the spring depression.

The depth of water present during Bitter Ridge deposition is not known, but if the stromatolitic features are indeed algal, standing water, no deeper than the photic

zone, was probably present throughout deposition. Thin laminations in the limestone may indicate seasonal variations in carbonate mineral precipitation in an alkaline lake with little or no indigenous biota. Wave action might have caused the disrupted and redeposited laminations. The domes and clusters of small domes probably indicate a water depth at least as great as the relief on any individual dome, which is as much as 5 cm, or they could have formed near the alternately wet-dry lake margin.

The "teepee" structures are interpreted to have formed as a postdepositional feature. Cementation and the growth of crystalline carbonate minerals in the intergranular spaces is thought to have caused an increase in volume of the newly deposited bed. This volume increase resulted in its lateral expansion and the formation of a polygonal network of "pressure ridges" on the bedding surface. Shinn (1969) attributed these features in the marine environment to a similar process of submarine cementation.

The clastic facies is interpreted to have originated in a localized alluvial fan that spread northward into the lake. Probably this conglomerate indicates activity and uplift on the Bitter Spring Valley fault and (or) the unnamed fault between Lovell Wash and the north side of Frenchman Mountain. At Lava Butte the clastic rocks, which show evidence both of clastic influx and reworking of previously deposited limestone, may be the result of a similar type of activity probably on the unnamed north-trending fault that passes east of Lava Butte (fig. 3*C*).

LOVELL WASH MEMBER

DISTRIBUTION AND THICKNESS

The Lovell Wash Member, like the Bitter Ridge Limestone Member, occurs only northwest of the Lake Mead fault system (fig. 24). However, unlike the Bitter Ridge it is not widely distributed or continuous between exposures. It is exposed in White Basin, in Lovell Wash, around Black Mesa north of Callville Bay, and between Lava Butte and Gypsum Wash. In the southeast limb of the syncline in White Basin it is 450 m thick and dips to the northwest and west. The Lovell Wash is also exposed in the west limb in western White Basin, where it rests depositionally on Paleozoic rocks at the northern margin of the basin. It probably occurs throughout the subsurface of the basin, but no outcrops of it are known north of White Basin. At its type section in Lovell Wash at least 250 m of the member is exposed in a syncline, but its top is not exposed there. Between Lava Butte and Gypsum Wash the member measures 170 m, but numerous small faults and covered intervals make this value speculative. At Lava Butte the Lovell Wash dips east and southeast, and it is probably present in the subsurface east of there. Several isolated

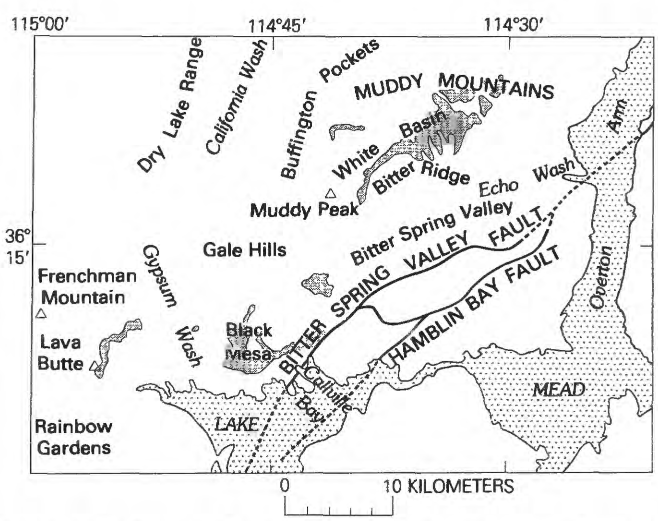


FIGURE 24.—Geographic distribution of outcrops (shaded) of the Lovell Wash Member of the Horse Spring Formation. Two major faults of the Lake Mead fault system are shown for reference.

exposures occur between Lava Butte and the widespread outcrops at Black Mesa, where the member undergoes a facies change to clastic rocks near the Bitter Spring Valley fault. Although widely separated by areas of erosion, the isolated outcrops of the Lovell Wash Member are probably remnants of a once continuous deposit, as is manifest from their lithologic similarity. The Lovell Wash Member is conformable above the Bitter Ridge Limestone Member in Gypsum Wash, where it and the Thumb are in contact. The Lovell Wash Member is unconformably overlain by the red sandstone unit in White Basin and at Lava Butte and unconformably overlain by the Muddy Creek Formation at Black Mesa.

LITHOLOGY

The Lovell Wash Member is chiefly white limestone and dolomite; gray and white claystone; and gray and brown tuff, tuffaceous sandstone, and arenaceous tuff. Brown chert occurs with the carbonate rocks at many locations. At Black Mesa, near the Bitter Spring Valley fault, there is a facies change from the above rock types into pink, brown and red-brown sandstone and siltstone. In southern Lovell Wash, in a similar change, conglomerate and sandstone interfinger with the above rock types. Northwest of Black Mesa, several small intrusive igneous bodies have slightly altered the carbonate and clay minerals of the Lovell Wash.

Carbonate Rocks, Claystone, and Chert

Carbonate rocks and claystone are combined for purposes of discussion because they are interbedded in the two most common of four definable carbonate-rich lithofacies. These lithofacies are all gradational into one another, but they can be defined by their bedding thickness, the presence or absence of claystone, and the nature of the carbonate rock. In the most widespread lithofacies (medium-bedded limestone-claystone lithofacies), limestone, dolomite, and claystone are present in medium, nonresistant, rhythmically interstratified beds in which the ratio and relative bedding thickness of the carbonate and claystone varies (fig. 25*A*). Dolomite is the less common of the two carbonate mineral species present, but appears to occur over a wide area. Most of the carbonate beds are resistant, and these define the wavy, parallel, uniform bedding; some beds are discontinuous. Bedding commonly varies from 5 to 20 cm in thickness, but thins considerably in places where it is gradational into a lithofacies composed of thin-bedded limestone and claystone interbedded in ½- to 2-cm beds (fig. 25*B*). In the thin-bedded lithofacies the relative resistance between limestone and claystone is about equal, claystone is commonly more abundant than limestone, and bedding is parallel, discontinuous, and wavy.

Both the medium- and thin-bedded claystone-bearing lithofacies occur with two carbonate-rich lithofacies in which claystone is absent. One of the claystone-free lithofacies is medium-bedded limestone similar to that in the medium-bedded carbonate-claystone facies, and the other claystone-free lithofacies is poorly bedded to unbedded limestone. The two claystone-free lithofacies are not known to occur together. In the medium-bedded claystone-free facies, which is common in the northern part of White Basin, parallel, wavy, continuous beds range from 5 to 15 cm in thickness, but bedsets as much as 30 cm thick weather differentially, giving the rock a thick-bedded appearance. This facies resembles the Bitter Ridge Limestone Member, but it is distinguished from the latter by its stratigraphic position and slightly lighter color. The unbedded to poorly bedded claystone-free lithofacies occurs in isolated lenses and amorphous masses that range from a few meters in width and 1 m in thickness to tens of meters in thickness and width (fig. 25*C*). The gray and brown coarse crystalline limestone of the unbedded lithofacies is abruptly gradational into both of the clay-rich facies and is common throughout the Lovell Wash except in the northern part of White Basin. Bedding in the unbedded to poorly bedded lithofacies is discontinuous, extremely wavy (undulatory), nonparallel, and not of uniform thickness. Many vertically stacked hemispheroids as large as 1.5 m across occur, and chert is also present in the limestone of this facies.

Petrographic analysis reveals that unordered to poorly laminated crystalline carbonate minerals (mostly calcite) are dominant in the unbedded to poorly bedded limestone facies and common in the other facies. In this vuggy dismicrite,[7] sparry calcite and chert form irregular masses between larger zones of fine-grained crystalline carbonate material (micrite) that is irregularly structured and contains undulatory laminations (fig. 26*A*). The vuggy dismicrite is commonly fragmental, and the micrite forms large clumps cemented by sparry calcite. Other common textural types in the medium-bedded carbonate-claystone and medium-bedded claystone-free facies include oolitic grainstone as well as packstone and grainstone composed of a variety of carbonate fragments. The oolitic grainstone (fig. 26*B*) consists of loosely packed, grain-supported ooids that vary in their degree of preservation: in some,

[7]Texture is like that described by Folk (1968), but the use of this term here does not imply disruption of previously deposited sediment.

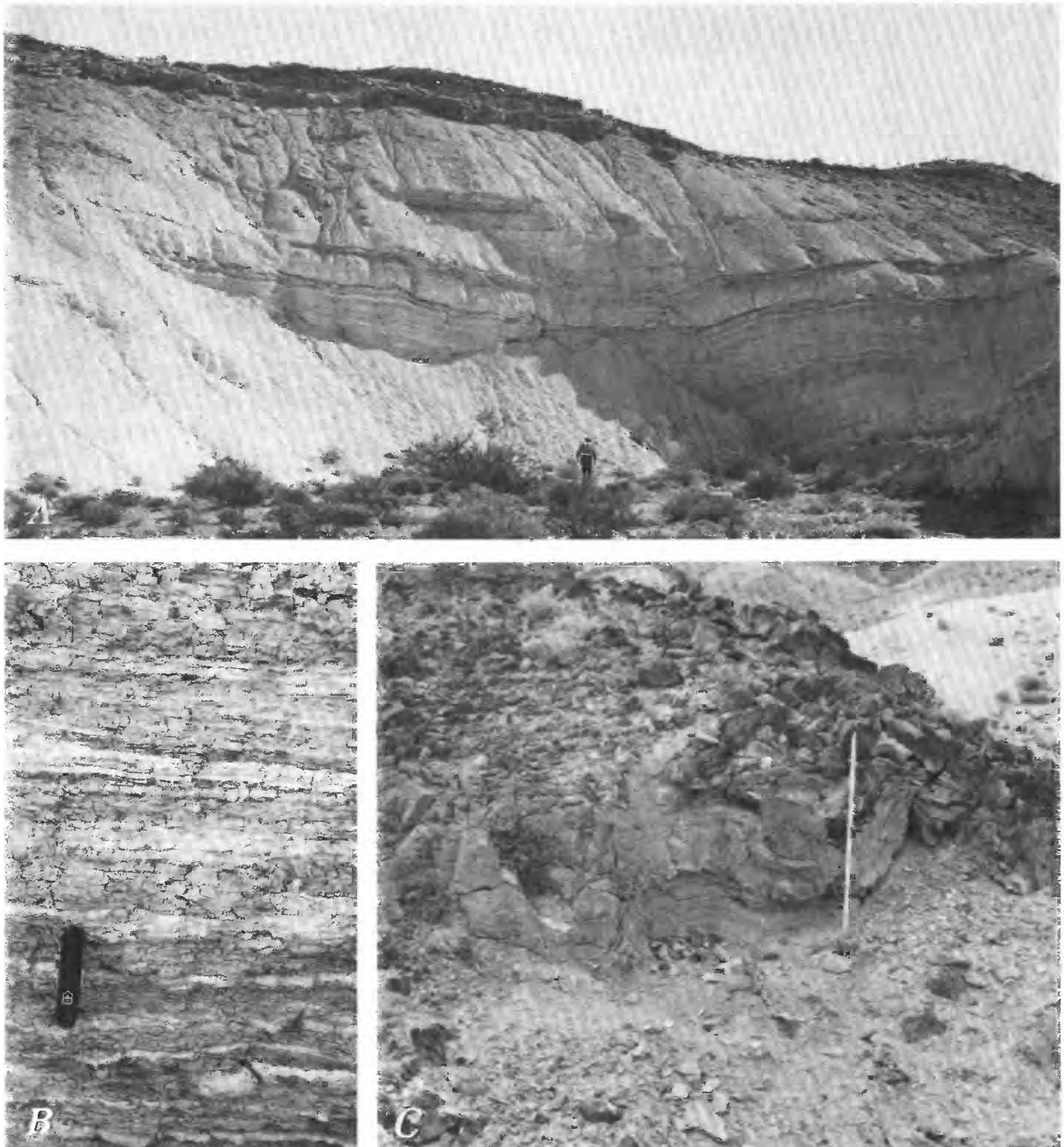


FIGURE 25.—Three of the four lithofacies in the carbonate and claystone beds of the Lovell Wash Member. *A*, Medium-bedded lithofacies of carbonate rocks and claystone rocks showing parallel, even, wavy, uniform, and mostly continuous bedding. Rhythmically interbedded carbonate rocks and claystone are visible. *B*, Thin interbeds of limestone (light bands) and claystone (dark bands). *C*, Large lens of poorly ordered limestone that contains chert. Measuring tape is 1.5 m long.

both radial and concentric banding, a central core or grain, and well-defined outlines are preserved, but at the other extreme are those in which internal structures and sharp outlines have been erased by recrystallization or were not initially formed. The ooids range from 0.5 to 0.1 mm in diameter, are very well sorted, and are

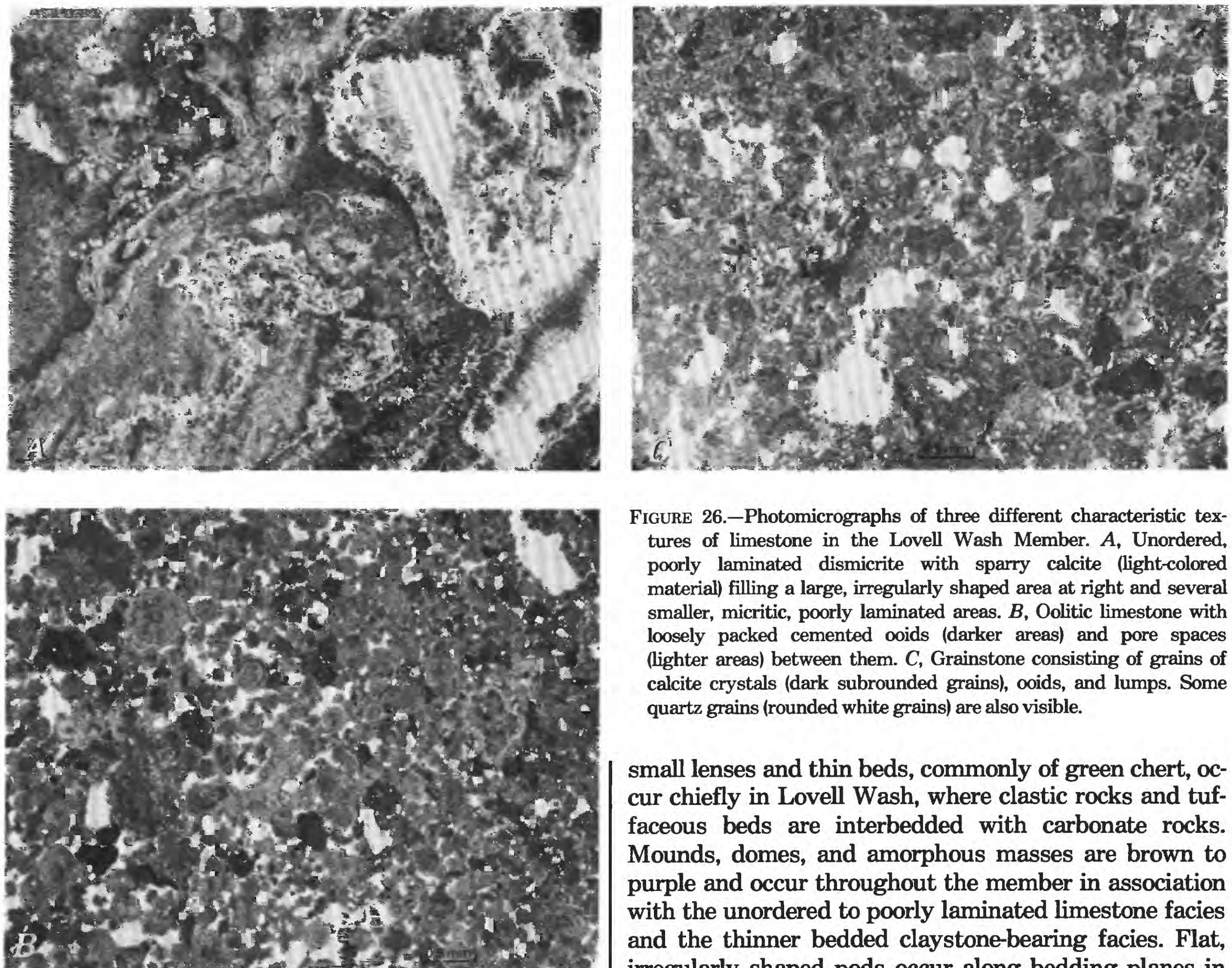


FIGURE 26.—Photomicrographs of three different characteristic textures of limestone in the Lovell Wash Member. *A*, Unordered, poorly laminated dismicrite with sparry calcite (light-colored material) filling a large, irregularly shaped area at right and several smaller, micritic, poorly laminated areas. *B*, Oolitic limestone with loosely packed cemented ooids (darker areas) and pore spaces (lighter areas) between them. *C*, Grainstone consisting of grains of calcite crystals (dark subrounded grains), ooids, and lumps. Some quartz grains (rounded white grains) are also visible.

cemented by fine-grained crystalline calcite and chert. The grainstone and packstone consist of grain-supported calcite crystals, whole and fragmental ooids, microcrystalline lumps, and large, unoriented fragments of rock showing laminations that contain some laterally linked micro-hemispheroids (fig. 26*C*). Many grains have eroded, irregular boundaries that indicate dissolution, and most are cemented by fine-grained calcite. The limestone and dolomite contain 1 to 5 percent medium- to fine-grained, subangular detrital quartz, andesine, sanidine, volcanic lithic fragments, biotite, and hornblende. In most samples these grains are dispersed throughout the rock. However, in some dismicrite samples the grains are floating in the crystalline carbonate mineral matrix that apparently fills pores.

Macroscopic chert, associated with carbonate rocks, occurs in small lenses, thin beds, mounds, domes, amorphous masses, and flat, irregularly shaped pods. The small lenses and thin beds, commonly of green chert, occur chiefly in Lovell Wash, where clastic rocks and tuffaceous beds are interbedded with carbonate rocks. Mounds, domes, and amorphous masses are brown to purple and occur throughout the member in association with the unordered to poorly laminated limestone facies and the thinner bedded claystone-bearing facies. Flat, irregularly shaped pods occur along bedding planes in the thin-bedded carbonate-claystone facies. Much of the chert occurs as thin rinds on the largest domes and mounds, but smaller domes (5 to 25 cm) are commonly all or nearly all chert. Original bedding is preserved in the chert at places where a small percentage of the original calcite is also preserved. Figure 27 is a photograph of a vertically linked hemispheroid in a small chert dome whose interior is bedded calcite.

TUFFACEOUS AND CLASTIC LITHOLOGIES

Tuffaceous rocks are gradational from unaltered tuffs, some of which might represent unreworked ash falls, to slightly tuffaceous sandstone. Most of the tuffaceous rocks are reworked to some extent, and many include grains derived from Paleozoic and Mesozoic rocks in addition to pumice shards and phenocrysts. Nontuffaceous clastic rocks are present around Black Mesa (north of Callville Bay) and in southern Lovell

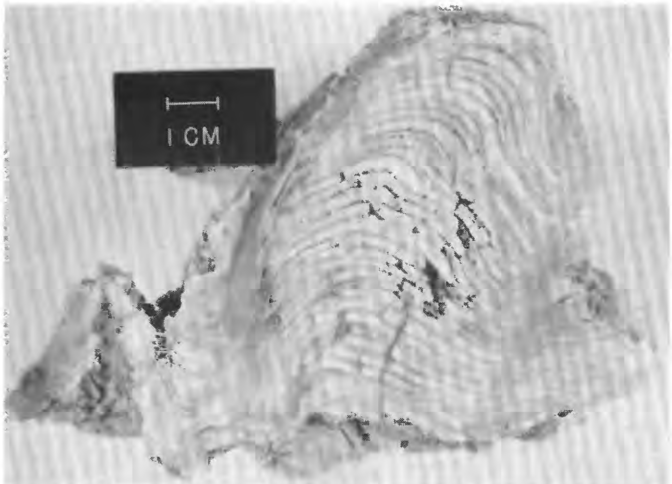


FIGURE 27.—Small chert dome from the Lovell Wash Member in which original bedding is preserved. The light bedding in the interior of the dome is composed of bands of calcite that are only partially replaced by chert. At the margins of the dome the bedding and the calcite are totally replaced.

Wash. They include sandstone, siltstone, and a minor amount of conglomerate. The latter occurs near the Bitter Spring Valley fault.

Units of gray tuff and tuffaceous sandstone vary from a meter to tens of meters thick and have parallel, continuous, even bedsets of low- and high-angle cross-laminae that vary from 25 cm to 1 m thick (fig. 28). The most common type of cross-stratum is low angle and has flat, parallel, even, continuous surfaces. Unstructured, thin, laterally discontinuous tuff beds at the base of thicker tuffaceous sandstone units may represent primary air-fall tuff.

Petrographic analysis reveals contrasts in mineralogy and texture that may represent degrees of reworking of the tuffaceous material. Although some samples are composed almost entirely of coarse-grained shards and (or) pumice lapilli as much as 1 mm in diameter, most have medium- to coarse-grained phenocrysts or reworked grains of quartz, andesine, sanidine, biotite, and hornblende. The percentage of phenocrysts and reworked grains ranges from less than 1 to nearly 100 percent. In the higher percentage samples, shards and lapilli are absent. Other rocks contain variable percentages of coarse-grained carbonate lithic fragments composed of fossiliferous micrite, apparently derived from Paleozoic carbonate rocks, and rounded quartz, apparently derived from Mesozoic sandstone, in addition to tuffaceous fragments. Shard- and lapilli-rich samples generally have a sparry matrix in which the shards and phenocrysts are supported (figs. 29*A* and *B*); but in samples with more alteration or apparent reworking, grain support is common, and both clay and fine-grained crystalline calcite matrices occur (figs. 30*A* and *B*). Where present, shards are generally delicately preserved, phenocrysts and detrital grains are angular to subangular, and carbonate lithic fragments are rounded. The coarse-grained shards contain fresh glass and have unaltered margins, but nearly all of the pumice lapilli are wholly or partially altered to clay (fig. 31). Because the lapilli have fine texture, it is apparent

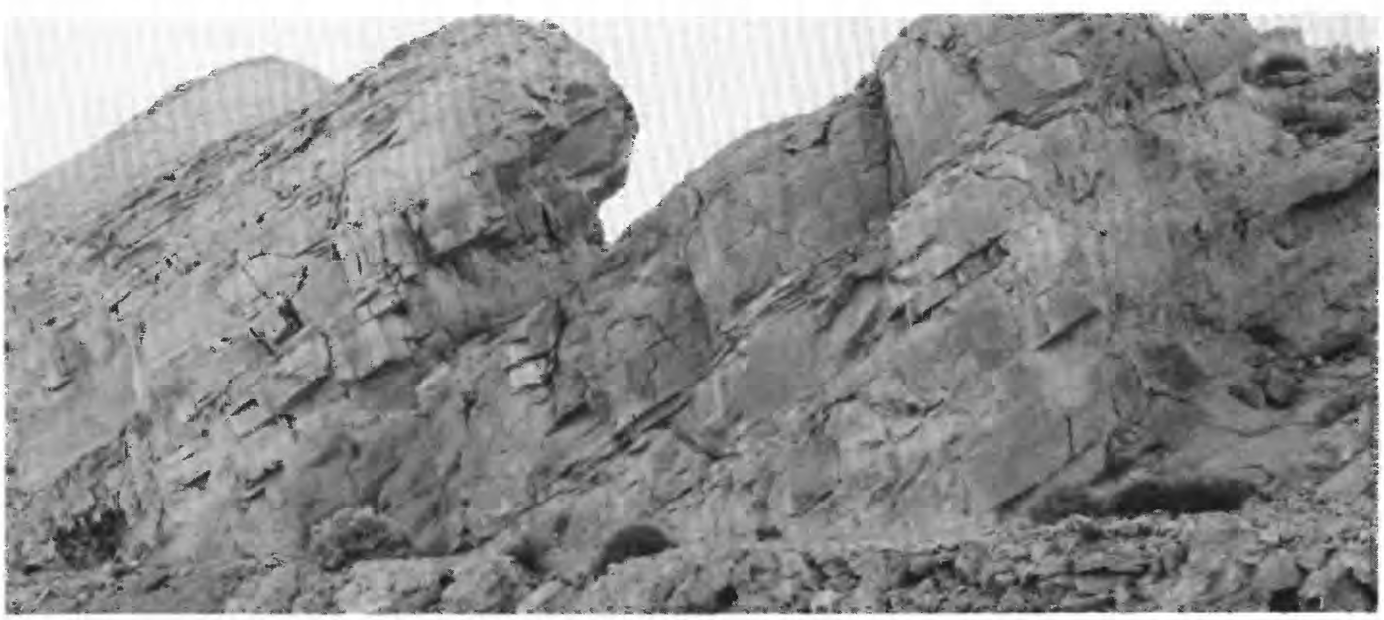
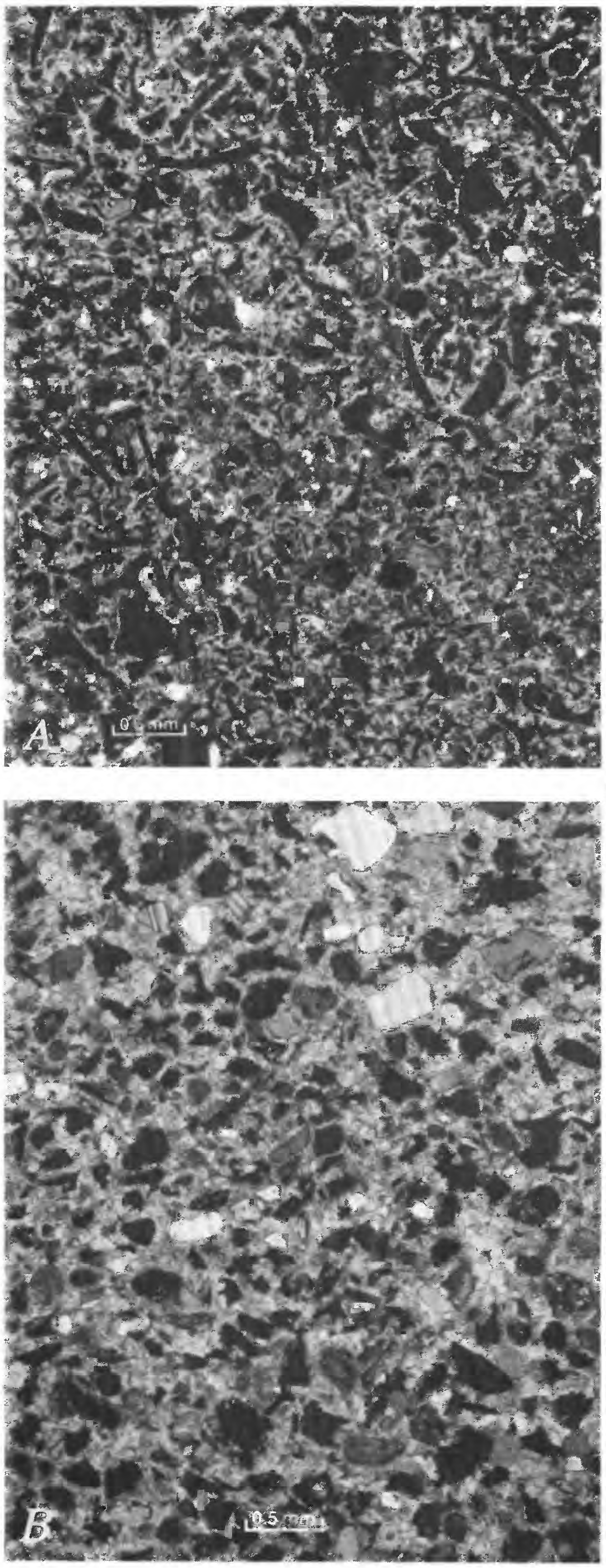


FIGURE 28.—One of the thickest, best-exposed units of tuffaceous rocks in the Lovell Wash Member, photographed at the type section in Lovell Wash. The parallel thick bedding, defined by erosional differences in individual beds, is evident, but the beds are also parallel laminated and cross laminated. Many beds have current lineations on their surfaces.



that the amount of readily alterable surface area controlled alteration patterns.

At Black Mesa north of Callville Bay, pink, brown, and red-brown sandstone and siltstone are abundant next to the Bitter Spring Valley fault, and they grade northward into white and gray carbonate rocks and tuff away from the fault. Widespread younger volcanic cover, complex pre-volcanic structure that affects the Lovell Wash Member, and local alteration of the member near small intrusive igneous bodies make detailed investigation of this facies change difficult, and none was attempted. Like the sandstone and siltstone of the Thumb Member, the Lovell Wash Member next to the Bitter Spring Valley fault consists chiefly of medium- to very fine-grained subangular to subrounded carbonate lithic fragments and quartz grains. Lenses of granite-bearing breccia are present at Callville Bay, but appear to be contained within the Bitter Spring Valley fault zone and may not relate to the lithofacies change described here. Conglomerate with a rindlike coating of carbonate matter on its clasts (fig. 20), which probably is related to this facies change, interfingers with both the Lovell Wash and Bitter Ridge Limestone Members in Lovell Wash. This rock type and the facies change associated with it were described in the section on the Bitter Ridge Limestone Member.

Sedimentary Structures

In the medium- and fine-bedded carbonate-claystone and the medium-bedded limestone facies, "teepee" structures, small-scale disrupted bedding, "eggshell" stromatolitic beds, and vertically stacked cherty hemispheroids and domes are the most conspicuous sedimentary structures. "Teepee" structures are commonly 25 to 50 cm high, involve one or several individual beds, and appear to form large polygonal patterns on bedding-plane surfaces (fig. 32). Many of the thin limestone beds, especially those interbedded with claystone or with claystone partings, are contorted into small-scale folds and boudins (fig. 33), but overlying and underlying beds are not deformed. Some limestone beds contain very thinly laminated stromatolitic structure that consists of many laterally linked and vertically

FIGURE 29.—Photomicrographs of shard-rich, matrix-supported tuffaceous rock from the Lovell Wash Member. Both photographs are in cross-polarized light. *A*, Delicately preserved shards (dark areas) set in a sparry calcite matrix (lighter areas). Shards do not appear to be abraded; sample may represent an ash fall. *B*, Slightly abraded shards set in a sparry calcite matrix. Some reworking is evident in the roundness of many shards and in the fact that the sample was taken from a cross-stratified rock.

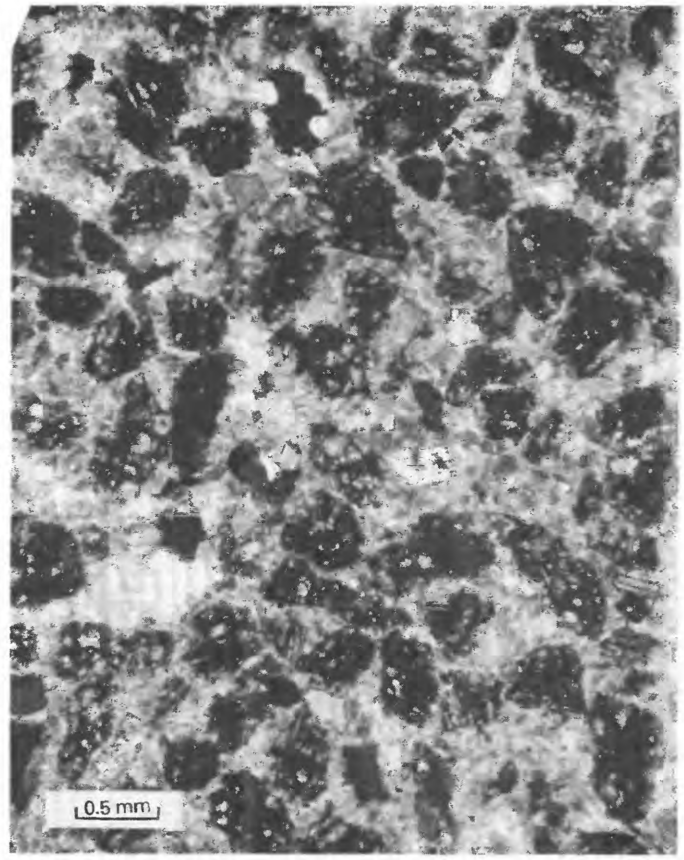


FIGURE 31.—Photomicrograph of pumice lapilli from the Lovell Wash Member, set in a sparry calcite matrix. The lapilli are slightly altered to clay. Calcite occurs in some vesicles and holes. Cross-polarized light.

stacked hemispheroids no larger than a few centimeters across (fig. 34). These limestone laminae that resemble stacked eggshells commonly are separated by claystone, but claystone is not always present. Small, high-relief stromatolitic mounds occur in the beds with eggshell laminae, and these attain a maximum height of about 10 cm and a relief above the surrounding bedding of as much as 2 cm. Other stromatolitic features are the chert-rich vertically stacked hemispheroids like those described above and shown in figure 27. However, chert is also commonly present in amorphous masses and irregular shapes that have no stromatolitic structure.

Many outcrops of the unbedded to poorly bedded limestone facies could be termed carbonate mounds because they vertically and laterally interrupt the more

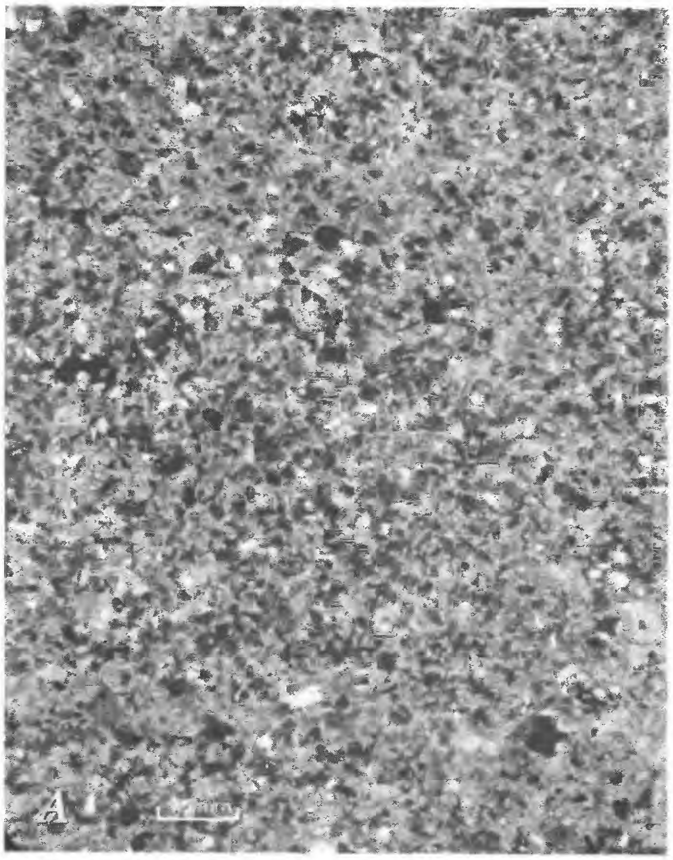


FIGURE 30.—Photomicrographs of reworked, partially altered tuffaceous rocks from the Lovell Wash Member. *A*, Fine-grained abraded shards and phenocrysts or reworked grains set in a fine grained, crystalline, calcite matrix. Cross-polarized light. *B*, Delicately preserved, grain-supported shards with clay matrix. The clay is thought to have been altered from very fine grained shards and pumice lapilli. Plane-polarized light.

FIGURE 32.—"Teepee" structure in a thick bedset of limestone in the Lovell Wash Member. The "teepee" is about 60 cm high and has a relief above the surrounding bedding of possibly 20 cm. Part of the bedding plane is visible and the "teepee" extends onto that plane in two directions, to form part of a polygonal pattern.

widespread, more consistent bedding and lithology of other facies, but are isolated from one another geographically (fig. 35*A*). Local upturning of the lowest flanking beds marginal to the mounds suggests that they stood in syndepositional relief. Common internal sedimentary structures include large domes, large vertically stacked hemispheroids, and large dish-shaped structures. The domes, which are as much as 70 cm tall and 1 m across, occur in lines and groups and are differentially resistant (fig. 35*B*). Chert rings the tops of many domes and covers others in a thin rind. Large vertically stacked hemispheroidal laminations make up the internal structure of most domes. The large dish-shaped structures are commonly 3 m across and may be as deep as ½ m; some apparently had as much as ½ m of relief above surrounding bedding (fig. 35*C*). Chert commonly occurs around the margins of these circular features, and most of them have teepee-like internal structure. They vary in size, but rim height is exaggerated around many of the smaller ones, and the resultant structures are large grotesque mounds with small central depressions. Clusters of these irregularly oriented mounds commonly form large chert-rich masses.

Sedimentary structures in tuff and tuffaceous sandstone include parallel, planar, large-scale, low-angle cross-stratification, rare high-angle cross stratification, current lineations on bedding-plane surfaces, and rip-up structures at the base of some beds. Figure 36 illustrates an example of rip-up structure.

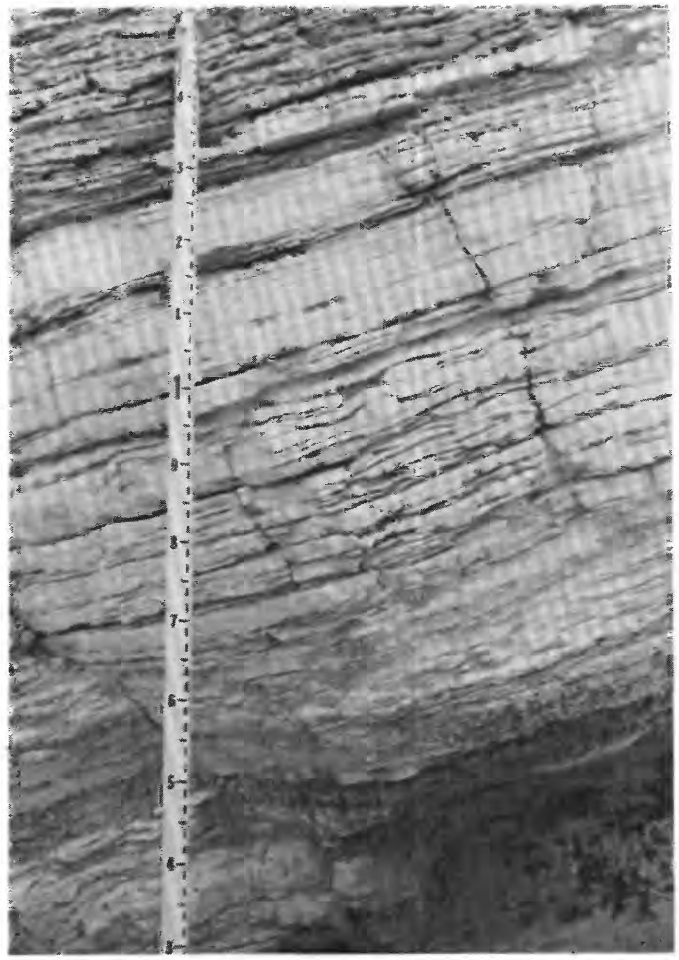


FIGURE 33.—Contorted thin bedding of the Lovell Wash Member. Claystone partings are evident as dark, less-resistant rocks. Numbered intervals on measuring rod are decimeters.

DEPOSITIONAL ENVIRONMENTS

Despite the complexity of the lithofacies of the Lovell Wash Member and the different local conditions implied by it, the majority of the rocks appear to have originated as sediment deposited in a lacustrine environment. The parallel, uniform bedding of the medium-bedded limestone-claystone facies, the stromatolitic beds, the "teepee" structures, and the abundance of in situ carbonate units collectively indicate lacustrine sedimentation. Lithologic complexities, such as different textural types and sedimentary structures, suggest that several subenvironments probably coexisted in the lake. Unordered to poorly laminated dismicrite is interpreted to be lithified tufa deposited in the lake by direct precipitation of carbonate minerals near springs. Oolitic limestone is thought to have lithified from oolitic sand that formed in clear saline and alkaline water with oscillatory wave action. Other types of grainstone and

FIGURE 34.—Thin limestone laminae with eggshell texure in the Lovell Wash Member in Lovell Wash. Thin claystone partings are evident, as are the individual domes and the relief on those domes. The knife at left is about 10 cm long.

packstone appear to have resulted from in situ reworking of fragments from previously formed beds. All the stromatolitic features are interpreted to be of algal origin, and the chert that is commonly associated with them is almost certainly diagenetic. "Teepees" probably resulted from subaqueous cementation, which increased the volume of the bed and led to its lateral expansion and compression. Dismicrite, in the carbonate mounds of the unbedded to poorly bedded limestone facies, is thought to have developed directly at spring orifices, as are the large bowls, which are interpreted to be spring pots.

Tuffaceous rocks appear to be composed chiefly of reworked material that is thought to have been derived from regional ash falls that were locally concentrated in the lake. Rip-ups and parallel laminations suggest high flow regimes and rapid deposition. Contaminants from local sources, chiefly Paleozoic carbonate rocks, appear to have mixed with the tuffaceous material during transportation, because deposits thought to be original ash falls do not contain them. Much of the claystone that is associated with the carbonate rocks is interpreted to be an alteration product of fine-grained shards and pumice lapilli.

Sandstone, siltstone, and conglomerate that occur near the Bitter Spring Valley fault are interpreted to have been derived from south of that fault and shed north into the lake. These deposits may record activity on the Bitter Spring Valley fault.

INFORMALLY NAMED ROCK UNITS

Informally named rock units overlie the Horse Spring Formation near Lava Butte, in White Basin, and in the vicinity of the Grand Wash Cliffs. Although existing maps show them to have been included locally with the Horse Spring Formation or Muddy Creek Formation, they are herein separated from those stratigraphic units and are subdivided into two geographically separated informal units (fig. 37) based on reasoning explained in the section on stratigraphic nomenclature. Near Lava Butte one of the units, the red sandstone unit, overlies the Lovell Wash Member on a possible angular unconformity and is in turn overlain by the Muddy Creek Formation. Although an accurate stratigraphic measurement has not been obtained, the unit appears to be thinner than 100 m. In the western part of White Basin, the red sandstone conformably overlies the Lovell Wash Member. However, it is apparently unconformable above that member in the central part of the basin, where it is 500 m thick and is unconformably overlain by Quaternary(?) rocks. Based on lithologic similarities and equivalent ages, the separated outcrops of the red sandstone unit are thought to have once been continuous between White Basin and Lava Butte. Those near Lava Butte dip east and are probably continuous in the subsurface for several kilometers. Although in White Basin the red sandstone is confined by present basin geometry in most directions, to the south it was once probably more extensive. The other geographically separated unit, the rocks of the Grand Wash trough, occurs throughout the Grand Wash–Grapevine Mesa region, where it rests on an angular unconformity above the Rainbow Gardens Member of the Horse Spring Formation. An accurate measurement of the total thickness of the rocks of the Grand Wash trough is not possible because subsurface information is not available, but the exposed part of the unit is thicker than 500 m in the Grapevine Mesa area.

RED SANDSTONE UNIT

Red sandstone rhythmically interbedded with siltstone and claystone composes most of the red sandstone unit, but gray and white air fall and reworked air-fall tuff beds and bedsets are common in its lower part. At the western margin of White Basin, adjacent to the

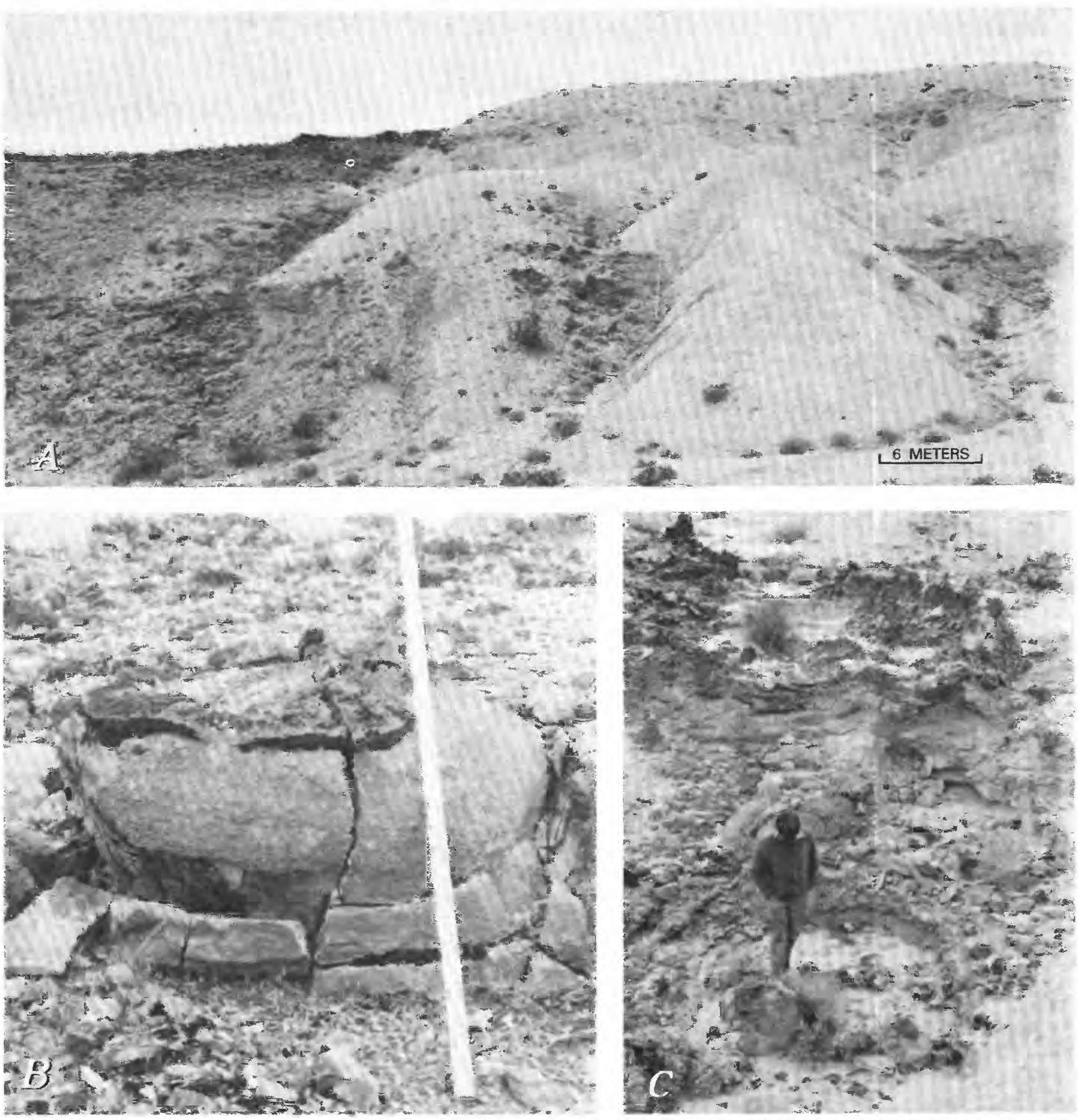


FIGURE 35.—A large carbonate mound in the Lovell Wash Member 1 km southeast of Lava Butte, and some of its internal structure. *A*, The facies change between the coarse-grained crystalline limestone on the south (dark beds at left) and the medium-bedded carbonate and claystone on the north (light-colored beds in center and at right). The darker, unbedded coarse-grained limestone interfingers with the lighter colored medium-bedded carbonate and claystone in this exposure, but at some places the contact is abrupt and nearly vertical. *B*, An example of one of the large domes in the mound. Both a chert ring and a rind are evident. Numbered intervals on measuring rod are in decimeters. *C*, Large, circular, dish-shaped structures with chert rims.

Muddy Peak fault, a basin-margin conglomerate lithofacies interfingers with a unit at least 100 m thick that consists of the red sandstone, tuff, and gypsiferous sandstone. Gypsum and gypsiferous sandstone are present in central White Basin near the contact with the underlying Horse Spring Formation (fig. 38). Detailed

FIGURE 36.—Rip-up structure in the tuff of the Lovell Wash Member in Lovell Wash. Clasts of the underlying limestone bed are incorporated into the tuff. Hammer at right is about 35 cm long.

geologic mapping of the area near Lava Butte is incomplete, but both red sandstone and tuff are known to be exposed there.

The red sandstone, siltstone, and claystone are interbedded in parallel, nonuniform beds that vary in thickness from 2 cm to 1 1/2 m. Resistant, even-surfaced sandstone beds are the thickest, averaging 20 cm, whereas the erosionally recessive claystone and fine-grained siltstone beds average 5 to 7 cm. Nearly all beds appear to be massive internally and most are continuous, but some of the thinnest ones are discontinuous (fig. 39). Bedsets as much as 1 m thick of uniform, even, 10- to 20-cm-thick sandstone beds are also common. Petrographic analysis of the sandstone indicates subrounded to angular, grain-supported, very well sorted grains of quartz, plagioclase, and carbonate lithic fragments with minor amounts of diopside, biotite, chert, and hornblende. These grains are chiefly cemented by clean sparry calcite, but in some cases large crystals of gypsum surround grains, giving those

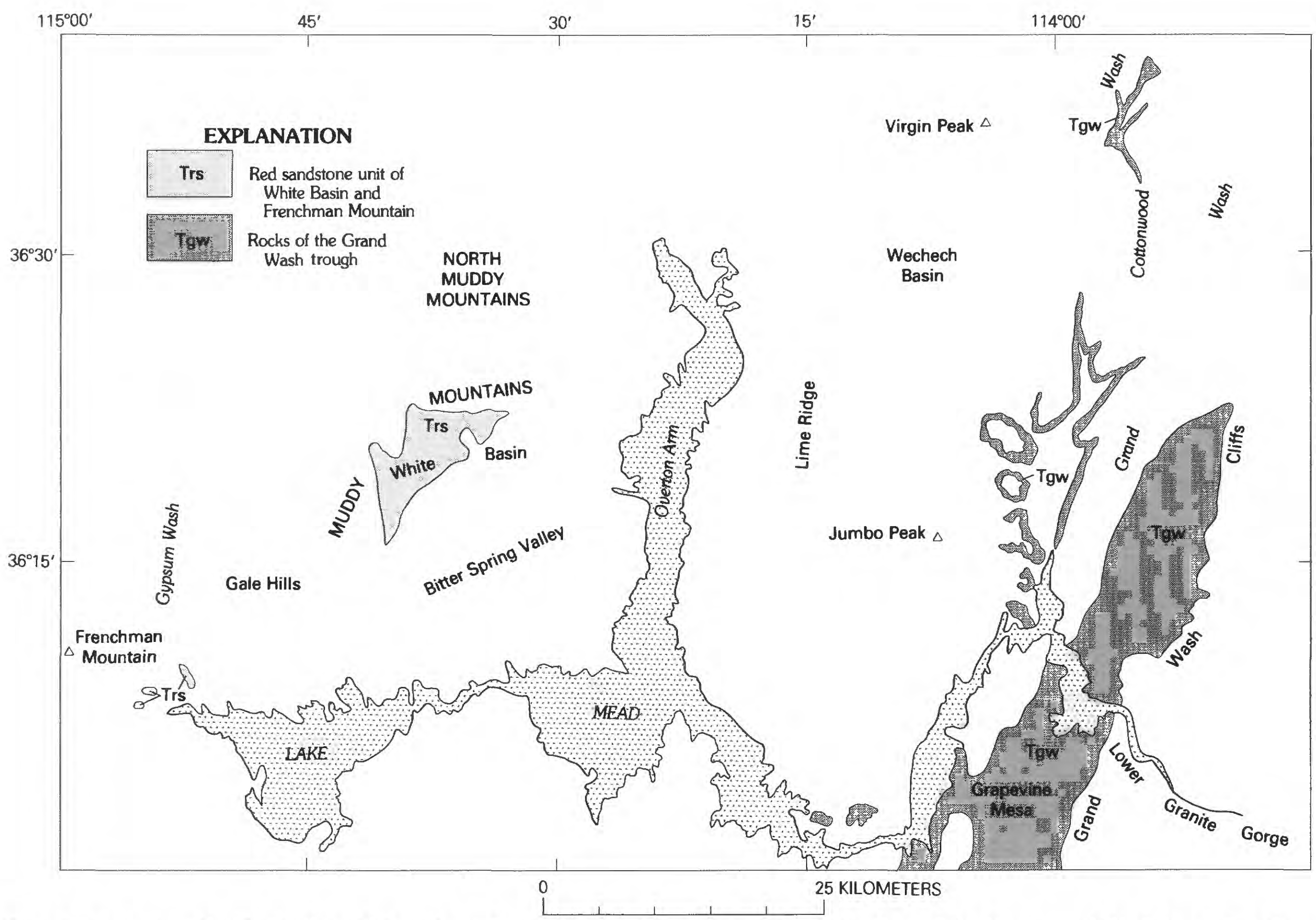


FIGURE 37.—Geographic distribution of informal Tertiary rock units discussed in the text. Geology of the Cottonwood Wash-Grapevine Mesa region after Lucchitta (1966) and Blair (1978).

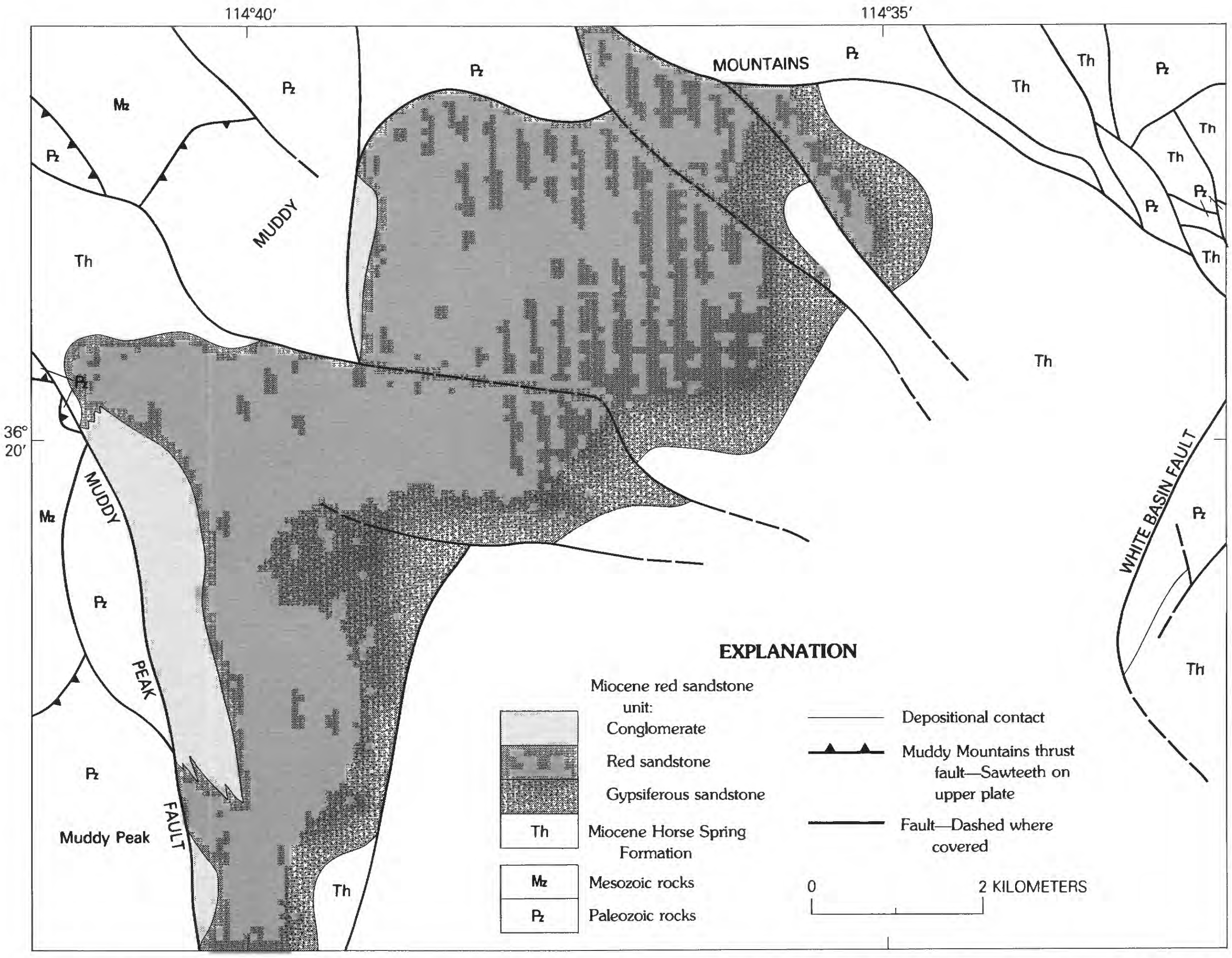


FIGURE 38.—Generalized geology of the red sandstone unit in White Basin. Three major lithologic facies are shown, as are some of the faults that cut the unit or were active during its deposition. This is the largest single exposure of this unit and represents 85 percent of known outcrop area.

samples a texture similar to poikilitic texture in igneous rocks. Grain size ranges from 0.05 to 1.0 mm in diameter, and clay or silt matrix is not present (fig. 40).

White and gray reworked tuff beds and bedsets total less than 5 percent of the unit, but are a distinct part of its lower half. These beds range from 25 cm to 2 m in thickness and most have thin, parallel, even, discontinuous internal bedding. Unbedded tuffs a few centimeters thick occur at the base of many beds and bedsets and are interpreted to be unreworked ash falls. Low-angle, large-scale cross-strata are also common in some tuffs, as are contorted beds and wavy laminations. Unaltered, delicately preserved glass shards and partially altered pumice lapilli, the two most abundant constituents of the tuffs, commonly occur in a matrix of clay, but they are chiefly grain-supported. Phenocrysts and detrital grains are angular and include feldspar, biotite, sanidine, diopside, and quartz. The clay-mineral matrix, which is chiefly smectite, is interpreted to be an alteration product of very fine grained glass fragments and pumice lapilli because such alteration is observable in the coarser-grained lapilli present in most thin sections.

Adjacent to the Muddy Peak fault in western White Basin, conglomerate interfingers to the east with the other lithologies of the red sandstone unit (figs. 38 and 41). Bedding, although not well defined, appears to be discontinuous, nonparallel, and nonuniform, ranging from a few centimeters to several meters thick. Texture of the conglomerate is clast-supported, and the subangular clasts of Paleozoic carbonate rocks range from 5 to 40 cm in diameter. The conglomerate occurs only

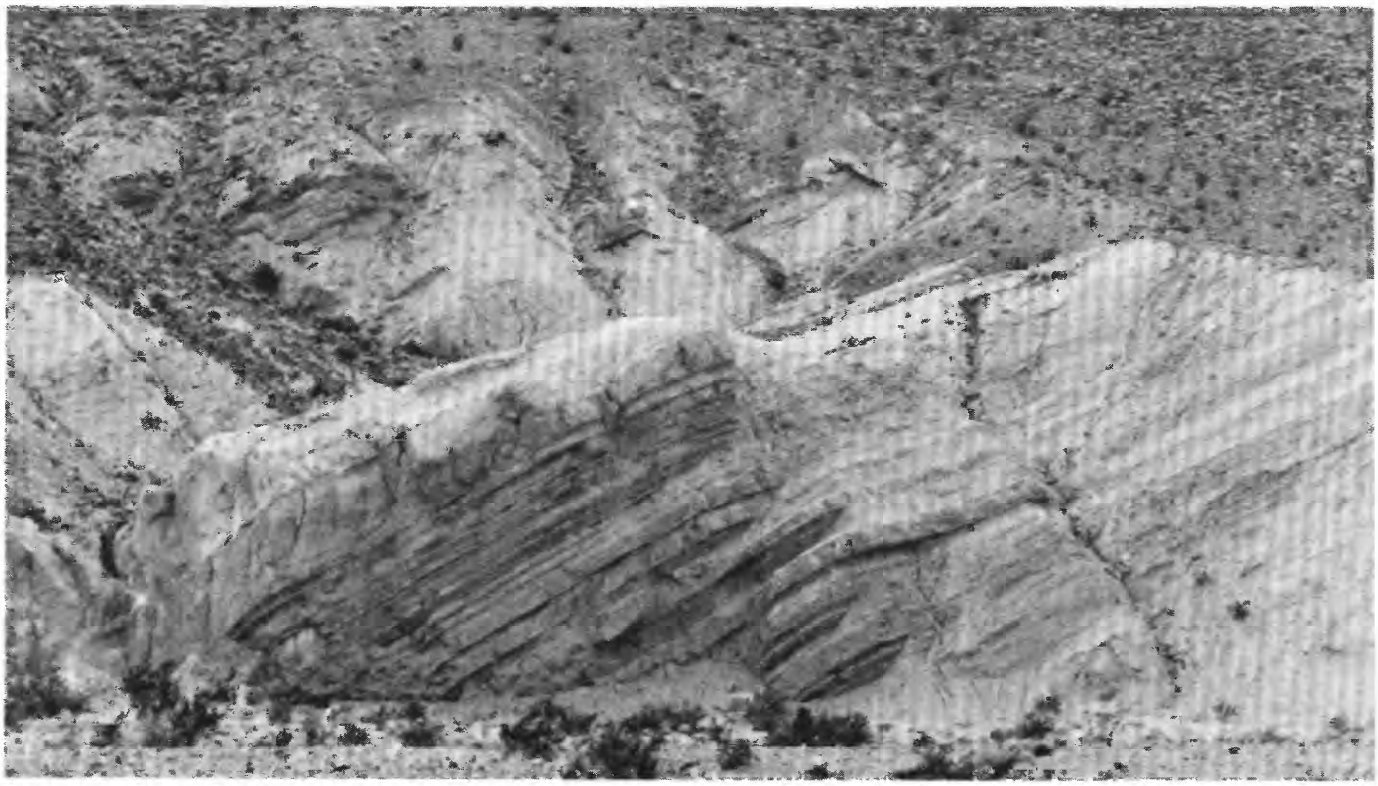


FIGURE 39.—Red sandstone, siltstone and claystone in the red sandstone unit about 2 km northeast of Lava Butte. Parallel, nonuniform, continuous beds are evident. A tuff bed (lighter gray bed at top of small cliff) 1 m thick is visible in the central part of the view.

where resistant Paleozoic carbonate rocks, which were its source, are present directly across the fault to the west (figs. 38 and 41). North of Muddy Peak, these Paleozoic rocks have been tectonically removed from the area north of the intersection of the Muddy Mountain thrust with the high-angle Muddy Peak fault. The Triassic(?) and Jurassic Aztec Sandstone is juxtaposed to the red sandstone unit and upper Horse Spring Formation in this area. At the point of fault intersection, the conglomerate of the red sandstone unit undergoes an abrupt facies change into sandstone and tuff. This relation suggests that the Muddy Peak fault incurred only vertical displacement (Bohannon, 1979).

Gypsum and gypsiferous sandstone in the lower part of the unit in central White Basin are poorly bedded and coarsely crystalline. Veins and irregular deposits of gypsum are common.

The red sandstone, siltstone, and claystone and the white and red-brown gypsum and gypsiferous sandstone are interpreted to have been deposited in a playa-lake environment. (In this paper, a playa is considered to be dry virtually all of the time.) The fact that bedding is parallel and continuous suggests a flat surface of deposition, but the lack of water-related sedimentary structures suggests the predominantly dry environment. The paucity of internal stratification within sandstone beds possibly indicates sediment disruption by burrowing creatures or by expansion of the sediment during cement crystallization. The latter interpretation is favored because the gypsum, gypsiferous sandstone, gypsum cement, and carbonate cement are all thought to have crystallized between grains of previously deposited sediment in the vadose zone. Most of the gypsum and gypsiferous sandstone lacks well-defined bedding and is coarsely crystalline, and much of it is sandy and silty. Gypsum cement with "poikilitic" texture and clean sparry calcite cement in the sandstone both suggest postdepositional introduction and crystallization. Inasmuch as the gypsum and carbonate minerals form nearly pure deposits in some places and are merely cement or pore-space filler in others, the vadose crystallization apparently was variously effective, and the occurrence of gypsum veins indicates postdepositional recrystallization and remobilization. The chief precement sediment was clean, well-sorted sand interbedded with silt and clay. The good sorting of this sand suggests eolian transport, and its grain mineralogy indicates a combination of volcanic and carbonate sources. The presence of clay and silt is also compatible with these sources. The tuff beds and bedsets are interpreted to be ash-fall deposits largely reworked by streams from the surrounding terrain. The conglomerate on the west

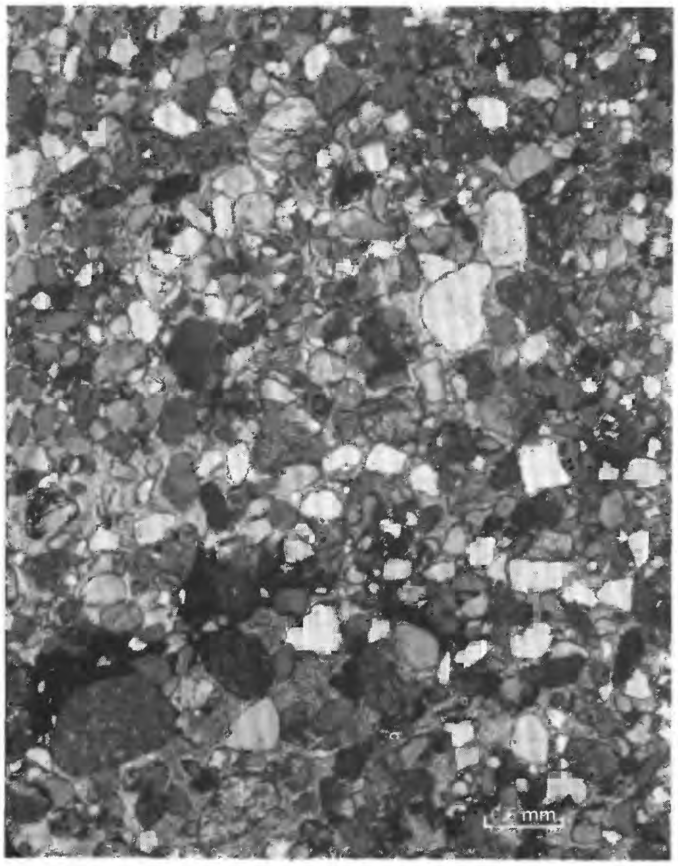


FIGURE 40.—Photomicrograph of sandstone from the red sandstone unit. Well-sorted, grain-supported grains of quartz, plagioclase, carbonate lithic fragments, biotite, hornblende, rare pumice, and rare diopside are present in the rock. The cement is clean sparry calcite. Crossed nichols.

side of White Basin is thought to have developed as a short, steep alluvial fan shed to the east into the playa lake during uplift of the Muddy Peak block by activity on the Muddy Peak fault. The total geographic extent of the playa environment is not well known, but it may have continued as far south as the Lake Mead fault system and as far west as Lava Butte. No evidence of it exists south of the Lake Mead fault system except possibly in the Grand Wash area, where some of the rocks of the Grand Wash trough are lithologically and temporally similar to the red sandstone unit.

ROCKS OF THE GRAND WASH TROUGH

Although not part of this study, the rocks of the Grand Wash trough have been mapped, described, and interpreted with those of the Muddy Creek Formation by Lucchitta (1966, 1972, 1979), Blair (1978), Blair and others (1979), Blair and Armstrong (1979), and Bradbury and Blair (1979). Brief descriptions provided herein are based chiefly on Lucchitta's work, but the other authors have contributed much information on the Hualapai Limestone. The basic lithologic subdivisions shown on figure 42 are slightly modified from Lucchitta (1966, p. 87, fig. 18).

FIGURE 41.—Paleozoic carbonate rocks in the steep, rugged east flank of Muddy Peak (background) abut the smooth-surfaced conglomerate of the red sandstone unit (foreground) along the Muddy Peak fault, a high-angle vertical-slip fault. These Paleozoic rocks are the probable source of the clasts in the conglomerate, which interfingers with red sandstone and other fine-grained lithologies about ½ km east of the area shown here. View is to the northwest.

The red sandstone and siltstone facies shown on figure 42 bears a strong resemblance to the red sandstone unit of White Basin. The two units have a similar rock type, bedding, and color and both contain nearly identical, coeval tuff beds in the their lower parts. Lucchitta (1966, p. 85–86) describes these rocks as "gypseous, bright-red to brick-red sandstone-siltstone * * * composed chiefly of quartz grains coated with iron oxide * * * interbedded with layers of impure limestone" east of the Wheeler fault, a large fault bounding the west side of Wheeler Ridge. "These rocks are persistently fine-grained even near areas of considerable relief." Lucchitta (1966, p. 92 and 93) also describes the tuff beds as "ranging in thickness from less than an inch to more than 5 feet * * * commonly very pure, persistent, and of uniform thickness * * * colored variously tan, pale blue, pale green, light gray, and white * * * commonly composed almost exclusively of very fresh delicate glass shards. Unbroken

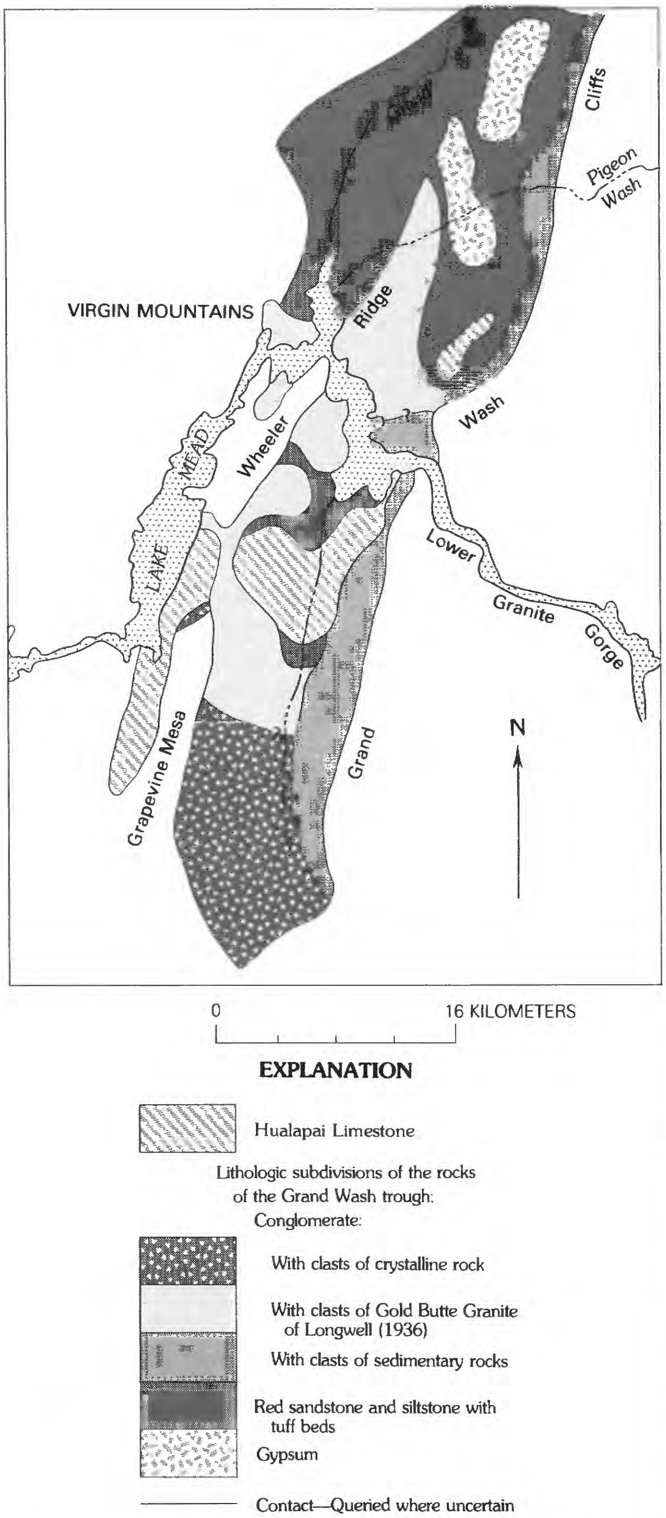


FIGURE 42.—Generalized geology of the Grand Wash trough area, modified from Lucchitta (1966, p. 87, fig. 18). Vertical order of lithologies in the legend does not imply relative age; no chronologic sequence has been established, and many of the lithologic units on the map are laterally equivalent facies.

glass bubbles are locally prominent. Green to brown biotite, commonly euhedral, is the other abundant constituent, but rarely exceeds 5 percent of the rock. In places, nodules and laminae of hard, vitreous, dark gray material, probably chert or chalcedony, are abundant. Euhedral to subhedral, little-abraded crystals of quartz, feldspar, biotite, and amphibole were noted * * *."

Three distinct conglomerate lithofacies, described by Lucchitta (1966), are differentiated on the basis of clast lithology and include one with Gold Butte Granite of Longwell (1936) (rapakivi granite) and other crystalline clasts, another dominated by several types of crystalline clasts but lacking Gold Butte Granite, and one dominated by sedimentary clasts (fig. 42). Lucchitta (1966, p. 88, table 6) describes the overall nature of the conglomerate as red brown, pinkish brown, and light gray with very poorly sorted, subrounded to angular clasts that range from clay-size particles to boulders 30 feet (9.2 m) in diameter. Stratification ranges from chaotic to distinct and generally becomes better defined upward.

Lucchitta (1966, p. 88, table 6) describes the Hualapai Limestone as impure, vuggy to dense, and finely crystalline with strata ranging from thin laminae to beds 10 feet (3.1 m) thick. He refines his description (Lucchitta, 1979) by adding that the Hualapai is the uppermost member of the Muddy Creek and in most places forms the thin upper cap of that formation, but it is also present as thick masses and as interbeds lower in the section. It is a maximum 300 m thick and consists of silty and sandy limestone that grades downward and laterally into limey sandstone, siltstone, and mudstone.

Blair (1978), Blair and others (1979), Blair and Armstrong (1979), and Bradbury and Blair (1979) offer no further basic lithologic description of the Hualapai, but they have examined the chert, present in western exposures, and some sedimentary structures in the limestone at Grapevine Mesa, in detail. They found several different types of diatoms and some colloform algal stromatolites. Analysis of these organic constituents indicated to them that the Hualapai Limestone formed in brackish to saline water and possibly even in marine conditions. In addition, their interpretations of carbon and oxygen isotope data indicate saline, if not marine, conditions. They further infer that the Hualapai Limestone was deposited in a marine estuary formed as part of the Bouse embayment (Bouse Formation of southwest Arizona). All of the interpretations presented by Blair (1978), Blair and others (1979), Blair and Armstrong (1979), and Bradbury and Blair (1979) are equivocal, and a marine origin for the Hualapai Limestone is still uncertain.

Longwell (1936), Lucchitta (1966, 1979), and Hunt

(1969) disagree with marine interpretations for the origin of the Hualapai. These authors have proposed that the Hualapai Limestone was deposited in one or several inland lakes that developed above the playa deposits of the red sandstone in the Grand Wash trough and above Precambrian crystalline rocks and clastic beds of the Muddy Creek Formation to the west of the trough. Hunt (1969) further suggested that the Hualapai lake was fed directly by the ancestral Colorado River. Longwell (1936) and Lucchitta (1966, 1979), on the other hand, suggest that the lack of fluvial or deltaic deposits in the Hualapai indicates that the Colorado was not in existence during its deposition. Also, Lucchitta (1979) has proposed several different subbasins that were controlled by local tectonics and that contain facies indicative of local sources and interior drainage.

Although published interpretations of the origin of the Hualapai Limestone are conflicting, none place constraints on the relation between the red sandstone unit of White Basin and the red sandstone that underlies the Hualapai Limestone in the rocks of the Grand Wash trough. Conversely, information presented herein on the Tertiary rocks of the Lake Mead region does not severly constrain interpretations of the origin of the Hualapai. The constraining factor in the direct comparison of the two red sandstone lithologies is the lack of regionally consistent descriptive information bearing on the internal characteristics of the rocks of the Grand Wash trough. These two isolated units appear to be similar both lithologically and temporally, and both apparently formed during the same graben-forming tectonic regime. However, any postulated depositional ties between these two units are conjectural because of the large distance separating them and the intervening Lake Mead fault system. Formally assigning the rocks of the Grand Wash trough to the Muddy Creek Formation is also not warranted. The Muddy Creek and the rocks of the Grand Wash trough may partially overlap in age and both were deposited in interior basins, but no direct connection of the two has been demonstrated, and they are lithologically dissimilar in many ways.

MUDDY CREEK FORMATION

The distribution and probable maximum extent of the Muddy Creek Formation is depicted on figure 43. Although widespread, it is chiefly confined to lower elevations such as Mormon Mesa, where its exposed stratigraphic top is no higher than about 540 m. The highest known occurence is the Fortification Basalt Member at Fortification Hill at an elevation of 1128 m. From its type locality north of Glendale, it is continuous into the valleys of the Muddy and Virgin Rivers and California Wash, and it is interpreted to be continuous into Detrital Valley, Las Vegas Valley, and the valley of the Colorado River south of Fortification Hill. The probable original extent shown on figure 43 was drawn at the major break in slope along margins of the above valleys. In places, such as the Virgin and Boulder Basins, the Muddy Creek may have accumulated to higher elevations and thus had a greater extent. At Mormon Mesa its top is exposed and the maximum extent shown is probably realistic. The base of the Muddy Creek Formation is exposed only at the margins of the valleys, and its true thickness is not known; however, dissection in the valleys of the Muddy and Virgin Rivers reveals exposures that indicate it is at least 215 m thick. Drilling in Detrital Valley indicates a minimum thickness of 425 m.

The most widespread rocks of the Muddy Creek are interbedded pink sandstone, siltstone, and claystone. Gypsum, gypsiferous sandstone and siltstone, and arenaceous gypsum are common, and conglomerate is also present at most of the basin margins. These rock types are gradational into one another, but large areas of homogeneity occur. In the Muddy and Virgin River valleys and the north half of California Wash the dominant rocks are sandstone, siltstone, and claystone, but conglomerate is present at the east flank of Overton Ridge, on the northwest flank of Black Ridge, and in southern California Wash. The gypsiferous facies occurs sporadically around the Overton Arm and is dominant in northern Detrital Valley and in the vicinity of Virgin Basin. Around Boulder Basin, Frenchman Mountain, and Las Vegas Valley all three facies occur, but their distribution is poorly understood.

Bedding in the pink sandstone, siltstone, and claystone is chiefly parallel, even, continuous, and moderately uniform in thickness. Discontinuous wavy bedding, lenses, and channels are prominent near basin margins. Bedding thickness ranges from 1 cm to ½ m, and internal parallel laminations occur at a low angle to bedding in most of the beds. Small-scale trough cross-laminae occur in many of the lenticular beds and channel deposits. Bedding is defined by abrupt grain-size changes and resistant sandstone beds, but bedsets consisting of several beds of uniform grain size also occur. Petrographic analysis reveals that most of the sandstone is clay-rich arkose and subarkose with 0.1- to 0.02-mm grain-supported, moderately sorted grains of quartz, feldspar, calcite, muscovite, biotite, chert, and clay lithic fragments. Carbonate-clay matrix constitutes as much as 90 percent of some samples, but most are 30 percent matrix.

Halite and glauberite are known from surface ex-

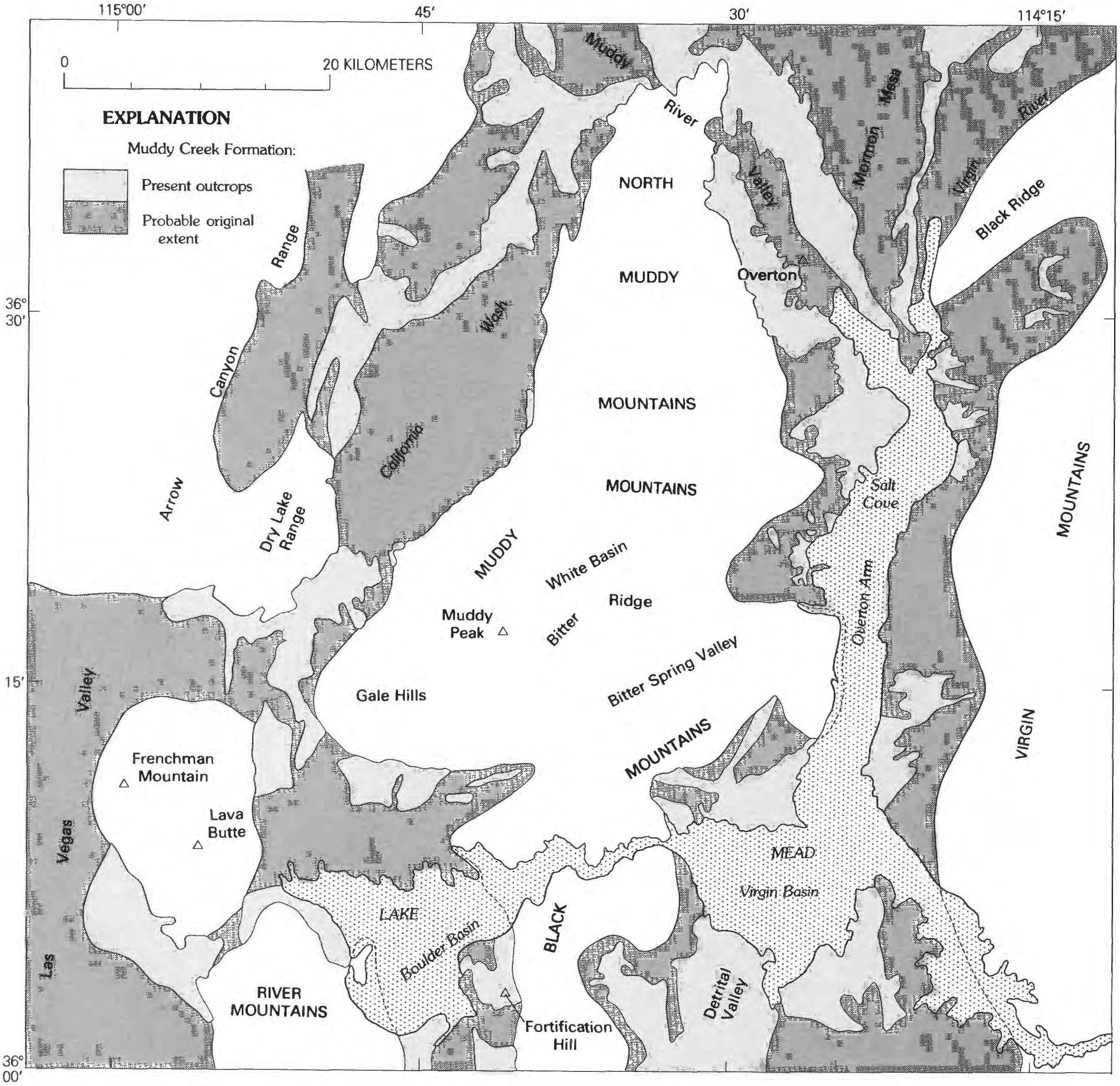


FIGURE 43.—Present distribution and probable original extent of the Muddy Creek Formation in the Lake Mead region.

posures (Longwell and others, 1965) and drill-hole data (Mannion, 1963) in the vicinity of Overton Arm. Salt outcrops at Salt Cove are parts of small domes that have evidently been emplaced by salt tectonics into upper stratigraphic levels of the Muddy Creek during the Quaternary, as evidenced by nearby tilted terrace deposits and intense local deformation within the Muddy Creek. The age of the parent salt beds is not known. Analysis of Stauffer Chemical Corp. drill-hole data suggests that salt is interbedded with tuff-bearing Tertiary clastic rocks south of Salt Cove. Although no tuff is known in surface exposures of the Muddy Creek in this area, this does not preclude the salt from being part of the basal Muddy Creek in which tuff beds may occur. Basalt flows are also part of the Muddy Creek Formation in the vicinity of Overton Arm, in Detrital Valley, and at Fortification Hill. In the Overton Arm region, these flows are olivine and olivine-augite basalt with subophitic and glomerophyric-pilotaxitic texture. Plagioclase phenocrysts range from an_{45} to an_{75}, and the olivine is altered to iddingsite and chlorophaeite. Samples from other areas were not obtained.

The Muddy Creek Formation is thought to have accumulated during the formation of the Basin and Range province in alluvial, fluvial, and lacustrine environments associated with valleys that had internal drainage. The conglomerate facies is interpreted to have been deposited as alluvial fans at the basin margins. These coarse rocks are interpreted to have graded laterally into fluvial and lacustrine rocks in the central parts of the basins. The sandstone, siltstone, and claystone have (1) lenticular, discontinuous bedding with internal cross-laminae suggestive of fluvial deposition, and (2) widespread continuous and parallel bedding suggestive of flat depositional surfaces. The gypsiferous facies and possibly the halite facies grade into the fluvial beds and might represent areas of vadose crystallization in a playa, or evaporative lacustrine crystallization in a lake.

PALEOGEOLOGIC AND PALEOTECTONIC EVOLUTION

Figure *A* on plate 1 is a generalized geologic map of the Lake Mead region which, despite oversimplification, depicts astounding large-scale structural complexity. A good deal of this complexity is caused by a few major structures, including the Lake Mead fault system, the Las Vegas Valley shear zone, a region of crustal extension described by Anderson (1971) south of Lake Mead, basins and ranges of the Basin and Range structural province, and stratal tilting associated with all of the above structures. Study of the Tertiary paleogeologic and paleotectonic evolution of this structurally complex region is best approached from a regional viewpoint. In the following pages, several paleogeologic maps representing successive time periods are constructed to portray the regional development of the geology (pl. 1). Maps representing the oldest pertinent time periods show palinspastic restorations of large-scale displacements and distortion caused by the above structures. Paleogeologic maps representing subsequent times depict the development of the structures and deformation caused by them. Maps are constructed to represent pre-Horse Spring Formation time, Rainbow Gardens Member time, Thumb Member time, Bitter Ridge Limestone and Lovell Wash Members time, the time period of the informally named rock units, and the time period at the end of Muddy Creek Formation deposition.

Anderson (1973) and Bohannon (1979) have proposed that the northeast-trending Lake Mead fault system has a minimum of 65 km of left-slip displacement. This system, as defined by Bohannon (1979), includes several major branches and associated faults: the Bitter Spring Valley fault, the Hamblin Bay fault, the Gold Butte fault, the Lime Ridge fault, the Bitter Ridge fault, the Cabin Canyon fault, and an unnamed fault between the Eldorado and River Mountains (fault A, pl. 1, fig. *A*). Bohannon (1979, figs. 1 and 2, p. 130–131) speculated on the existence of a fault between Frenchman Mountain and the River Mountains which is no longer considered part of the system and is not shown on subsequent diagrams. A major branch, not shown on earlier maps, is now thought to lie north of Black Ridge and the Virgin Mountains beneath valley fill, based on unpublished petroleum industry seismic information (fault B, pl. 1, fig. *A*). The important systemic branches and some offset features described by Anderson (1973) and Bohannon (1979) are shown on plate 1, figure *A*. The Hamblin-Cleopatra volcano (HC on fig. *A*) is offset 20 km by the Hamblin Bay fault, and the granite clasts at Frenchman Mountain and Lovell Wash (gc on fig. *A*) relate to outcrops of granite (g on fig. *A*) near Jumbo Peak (Anderson, 1973). The plunging lines made by the intersection of planar Mesozoic contacts with the overlying planar base of the Rainbow Gardens Member are diagramatically depicted by the arrows at Frenchman Mountain and in the Virgin Mountains. These plunging lines form offset piercing points with faults of the Lake Mead system (Bohannon, 1979). In addition, a particular distinctive facies of the Rainbow Gardens Member (called basal subunit of the lower clastic unit by Bohannon, 1979) is exposed at three widely separated places along the Lake Mead fault system: at Frenchman Mountain, in the northern Black Mountains, and in the Virgin Mountains (columns *A*, *H*, and *D*, fig. 5). These outcrops, which also indicate offset in the system, are shown by R's on figure *A* (pl. 1).

If the Colorado Plateau is considered a fixed reference frame, then a palinspastic restoration of displacement on the Lake Mead fault system that satisfies the above data places Frenchman Mountain a little north of the present position of the town of Overton; it was displaced primarily along the Bitter Spring Valley fault and the fault north of Black Ridge. The Lake Mead fault system is assumed to continue northeast along the margin of the Colorado Plateau and the Basin and Range province into Utah, and to the southwest it is thought to terminate in the valley east of the McCullough Range.

The Las Vegas Valley shear zone has been proposed as a right-slip fault beneath the alluvial fill of Las Vegas Valley and a right oroflexural fold system within the ranges bordering the valley (Longwell, 1960). Longwell (1960), Ross and Longwell (1964), Stewart (1967), Stewart and others (1968), Osmond (1962), Poole and others (1967), and Ketner (1968) have provided estimates of the magnitude of slip on the shear zone that range from no greater than 20 km (Ketner, 1968) to

65 km or greater, with all but Ketner in agreement of 40 km or more. Evidence cited includes the offset of isopach lines, facies trends, general stratigraphy, and Sevier-age thrust plates between the Spring Mountains and the ranges bordering Las Vegas Valley on the north. Along the southeast projection of the Las Vegas Valley shear zone are two faults (the Gale Hills fault and the unnamed fault north of Frenchman Mountain labeled 1 and 2 on pl. 1, fig. *A*) that I described as possible representatives of that zone (Bohannon, 1979), but neither of these continues to the southeast beyond the Lake Mead fault system. Thus, the maximum length of the shear zone is only 140 km, and the possible length of a fault buried under the fill of Las Vegas Valley is no greater than 105 km. Diasgreement over the precise magnitude of slip stems from the reconnaissance nature of early studies and the lack of precisely documented offset piercing points. All authors however, agree on the importance of oroflexural bending in providing a large part of the displacement, and most agree on the apparent offset of thrust plates originally described by Longwell (1960).

A palinspastically restored geologic map must account for 40 to 65 km of right-oroflexural bending and right-slip faulting on the Las Vegas Valley shear zone west of the Lake Mead fault system. If the map is to restore conditions to their post-thrusting (Sevier orogeny of Armstrong, 1968) state, it must depict the three plates of the Sevier thrust belt shown on figure *A* (pl. 1) in an approximate north-trending alinement. With respect to the fixed reference frame of the Colorado Plateau, such a restoration places the eastern part of the Spring Mountains approximately adjacent to the southwestern part of the Muddy Mountains. This is accomplished by unfolding the bent rocks of the Dry Lake Range, Sheep Range and Spring Mountains and by restoring displacements on surface faults in the Lake Mead region. Assumptions involved in utilizing specific surface faults in the Lake Mead region for such a restoration are described below in conjunction with the separate paleogeologic maps.

Synchronous activity on the Las Vegas Valley shear zone and the Lake Mead fault system is suggested by Fleck (1970), who concluded that the former zone was active from 15 to 10.7 m.y. ago; by Anderson (1973), who postulated activity on the Hamblin Bay and directly related faults from at least 12.7 to 11.1 m.y. ago; and by Bohannon (1979), who concluded that the entire Lake Mead system was active between 13 and possibly 6 m.y. ago. These conclusions are somewhat refined using information presented herein.

Little evidence of syndepositional faulting or folding is recorded by the Rainbow Gardens Member, which, although undated, is not thought to be much older than about 18 to 20 m.y. Further, this member has apparently suffered maximum fragmentation by the Lake Mead fault system, which indicates that fault activity totally postdates it. Coarse clastic rocks within the Thumb Member, which ranges from about 17 to 13.5 m.y., indicate possible activity on the Gold Butte and Lime Ridge faults, which are interpreted to be associated with the Lake Mead fault system. Similar facies indicate synchronous activity on the Gale Hills fault, which appears to be directly related to other faults thought to be part of the Las Vegas Valley shear zone. Thus, incipient and (or) related activity on the major strike-slip fault systems possibly began as early as 17 m.y. B.P. The confinement of the Bitter Ridge Limestone Member to the northwest side of the Lake Mead fault system and the presence of conglomeratic facies within the member near northern branches of that system suggest major activity on those branches around 13 m.y. ago. It is not known whether the Gold Butte and Lime Ridge faults were still active at this time, but there is no evidence to suggest that they were not. The Gale Hills and related faults, on the other hand, are overlapped by the Bitter Ridge Limestone Member, indicating that their activity had ceased by about 13 m.y. B.P. However, the Las Vegas Valley shear zone may have been active at this time, because facies of the Bitter Ridge Limestone Member are strongly controlled by the fault zone north of Frenchman Mountain (faults 1 and 2, pl. 1, fig. *A*), and that fault may have been part of the shear zone. If so, activity on the Las Vegas Valley shear zone may simply have been transferred from one fault to another. Like the Bitter Ridge Limestone Member, the Lovell Wash Member is confined to the north side of the Lake Mead fault system and it also changes facies adjacent to northern branches of that system. Thus, these fault branches were probably active as late as 12 to 11.5 m.y. ago. Apparently the Lovell Wash Member overlaps the fault north of Frenchman Mountain, indicating that the fault was inactive during deposition. The member is not only present, but is similar in character and thickness on both sides of that fault. The Muddy Peak and White Basin faults, which formed the graben of White Basin during the deposition of the red sandstone unit, show evidence of deformation by the Bitter Spring Valley fault of the Lake Mead fault system, and this evidence suggests that activity continued on the latter system between 12 and possibly 10 m.y. ago. Cessation of activity on both the Lake Mead fault system and the Las Vegas Valley shear zone is indicated by the overlapping of both systems by the Muddy Creek Formation. The age of the overlap is not certain, but could have occurred as early as 10 m.y. ago.

South of the Lake Mead fault system, Anderson

(1971) documented a widespread region of Tertiary surficial crustal extension that took place within abundant, distinct, fault-bounded structural units that are highly distended by closely spaced, north- to northwest-trending listric normal faults. This surficial crustal extension was accompanied at depth by intrusion of igneous rocks. The stratigraphy south of Lake Mead consists of three units: (1) 20- to 14.5-m.y.-old Patsy Mine Volcanics (Anderson and others, 1972), which are andesite formed in a large stratovolcano or system of such volcanos constructed on a nearly featureless platform of Precambrian crystalline rocks; (2) the tuff of Bridge Spring, a 14.5-m.y.-old ash flow (Anderson and others, 1972) erupted over the andesite; and (3) the 14.5- to 11.8-m.y.-old Mount Davis Volcanics (Anderson and others, 1972), which consist of a eastward-thickening wedge of andesitic and rhyodacitic lavas. Anderson (1971) offered no estimate of the magnitude of the extension, but pointed out that detailed measurements indicate a consistent S. 70° W. orientation of the least principal stress direction and that this stress orientation is applicable over a broad region south of Lake Mead. He concluded that the period of extension apparently spanned the time of the volcanism and plutonism of the Mount Davis Volcanics, from about 14.5 to 11.8 m.y. ago.

Although the magnitude of crustal extension described by Anderson (1971) is not known, extension in that area is a major regional tectonic feature that must be considered in palinspastic restorations. Within the resolution limits of the available age data, it and the two major fault systems described above were synchronously active and are thus assumed to be genetically related. Anderson (1973) and Bohannon (1979) suggested that strike-slip displacement on the Lake Mead fault system was absorbed successively southwestward by the crustal extension, an idea consistent with the ultimate termination of the Lake Mead strike-slip system east of the McCullough Range. Thus, I think that the Lake Mead system represents an intracontinental transform fault that arises from the extension. If so, it is logical to infer that the amount of extension relates geometrically to the magnitude of the strike-slip. Sixty-five km of left-slip on the S. 30° W. to S. 50° W. trending Lake Mead fault system transposes by Euclidian geometry into 55 km of crustal extension in a S. 70° W. direction. Therefore, palinspastic restorations relative to the fixed reference frame of the Colorado Plateau, to satisfy this inference, would place the southern part of the McCullough Range in the approximate present position of Wilson Ridge by compressing (or more exactly, "un-extending") much of the area between the southern Spring Mountains and the Colorado Plateau.

Another major structural feature that must be removed from successively older paleogeologic maps is stratal tilt generated after the time period represented by each map. Throughout the Lake Mead region, the Rainbow Gardens Member is steeply tilted (as much as 50°) and is subparallel to the underlying older rocks, and significant amounts of stratal tilt must thus be removed from pre-Rainbow Gardens maps. Younger units are also tilted to various degrees, and where initial dips are negligible, as in the lacustrine beds, these tilts must also be removed. Increasing tilt with age gives a record of tilting history.

At Frenchman Mountain, unpublished mapping by C. R. Longwell conclusively indicates that 30° to 50° easterly dipping bedding within the Rainbow Gardens and Thumb Members parallels bedding in the underlying Mesozoic and Paleozoic beds to within a few degrees. This tilting is best interpreted, based on Longwell's mapping, to have originated as stratal rotation on abundant northeast-trending, west-dipping normal strike faults. Younger members of the Horse Spring, such as the Lovell Wash, dip slightly less than the older members, and the overlying red sandstone dips significantly less. Thus, at Frenchman Mountain the normal strike faults and the associated east tilting are thought to have originated some time after the deposition of the Thumb and to have continued activity through the deposition of the red sandstone.

A similar situation exists throughout the southern part of the Virgin Mountains, where easterly dips of bedding range from 10° to 60° (Longwell and others, 1965; Morgan, 1964). Unpublished mapping by the author indicates that bedding in the Rainbow Gardens and Thumb Members parallels that of the Paleozoic and Mesozoic rocks in this area also. As at Frenchman Mountain, tilting in the Virgin Mountains is attributable to stratal rotation on abundant north- to northeast-trending normal strike faults and low-angle listric normal faults whose dip commonly opposes that of the strata (Morgan, 1964). Morgan's (1964, pl. I) detailed geologic map distinctly shows the north-trending normal faults and listric normal faults to be truncated by, or to join abruptly with, the northeast-trending Gold Butte and Lime Ridge faults. These latter are interpreted to be strike-slip faults (Bohannon, 1979). Presumably a similar type of relation also occurs at the northeast-trending Bitter Ridge fault, which is north of the area mapped by Morgan. These interpretations lead to the inference that the normal faulting, the listric normal faulting, the stratal tilting, and the strike-slip faulting are all genetically related and occurred sometime after or during the late stages of deposition of the Thumb Member. A similar interpretation of structures of the same approximate age in the area south of

Lake Mead has been made by Anderson (1971) and by Anderson and others (1972). The geology of the Virgin Mountain region is interpreted to be dominated by large, discrete areas in which roughly east-west-oriented crustal extension was accommodated by normal faulting, listric normal faulting, and stratal tilting. These areas appear to have been bounded to the north and south by the northeast-trending strike-slip faults. Precise temporal control of these structures in the Virgin Mountains is not yet possible because of the local paucity of datable younger Tertiary strata and the lack of critical detailed geologic mapping. However, the structures are certainly post-Rainbow Gardens Member in age, and they may have developed synchronously with the deposition of the Thumb Member. If the conglomerate north of the Gold Butte fault is part of the Thumb and also records activity on that fault, as has been suggested, then the structures were indeed initiated during the deposition of that member and must exist on subsequent paleogeologic maps.

At Overton Ridge and the Valley of Fire the 30° northeast tilt of bedding in the Rainbow Gardens Member parallels that of the underlying Mesozoic rocks. Here, as in other areas, tilting is attributable to Tertiary rotation on abundant north- to northwest-trending normal strike faults (Bohannon, 1977a) that apparently dip to the west and southwest. West of there, in the North Muddy Mountains, steep dips and stratal overturning were probably generated during the episode of Cretaceous compressional deformation known as the Sevier orogeny (Longwell, 1949; Armstrong, 1968). Only the post-Rainbow Gardens Member rotational tilting in the Valley of Fire area is removed from pre-Thumb age paleogeologic maps. The exact time of development of this deformation is not known, but I suspect its history parallels that of similar deformation at Frenchman Mountain.

Stratal tilts in the Muddy Mountains, White Basin, Bitter Spring Valley, and the Gale Hills are very complex. Although many different magnitudes and directions of tilt are recorded, large fault-bounded areas have internally consistent tilt directions and magnitudes. The description and documentation of the overall structure of these areas is beyond the scope of this report, and so the deformation is generalized in the paleogeologic maps given here.

Figure *B* on plate 1 depicts the regional geology of the Lake Mead area as it would be if all the post-Rainbow Gardens Member stratal tilting and associated faulting were removed. In addition, Tertiary sedimentary and volcanic rocks are not shown. For purposes of illustration, however, the displacement on faults related to the Lake Mead fault system and the Las Vegas Valley shear zone and the distortion created by crustal extension south of Lake Mead have not been removed from the diagram. Figure *B* suggests the presence of a large pre-Rainbow Gardens Member arch in the autochthonous rocks east of the Sevier orogenic belt. Strike-slip faulting and associated crustal extension have fragmented the nose and west flank of this arch from its east flank and caused expansion of its core.

Figure *C* (pl. 1) illustrates some of the evidence used in constructing this arch. Its northeast-dipping eastern flank is preserved on the western edge of the Colorado Plateau and is evident on the Arizona geologic map (Wilson and others, 1969). Young (1966, 1970), Young and Brennan (1974), and Lucchitta (1966, 1972, 1979) discuss the geologic significance and temporal development of this flank of the arch and conclude that it was in existence prior to the eruption of the Peach Springs Tuff approximately 16.9 to 18.3 m.y. ago (Young and Brennan, 1974). At that time, both low-angle stratal tilting associated with arching and drainage direction were to the northeast. A topographic and structural high existed in the core of the arch in the present position of the Basin and Range province. Anderson (1969, 1971, 1973, 1977, 1978a and b) and Anderson and others (1972) describe this high area south of Lake Mead where Paleozoic and Mesozoic rocks were eroded from a large region between the Grand Wash Cliffs and the eastern part of the Spring Mountains prior to the eruption of voluminous Tertiary volcanic rocks about 20 m.y. ago. Figure *C* illustrates the eastern flank of the arch as it is presently exposed on the Colorado Plateau. Some of the contact limits there are projected to positions that they may have occupied during the early Miocene, and the extent of Precambrian crystalline rocks that are directly overlain by Tertiary volcanic cover is outlined.

The extension of the eastern flank of the arch into the Basin and Range province is less obvious. On Wheeler Ridge, a few kilometers northwest of the present Colorado Plateau boundary, are the southwesternmost exposures of the Permian Kaibab Limestone and Toroweap Formation, Pennsylvanian and Permian limestone, and Mississippian limestone. These are shown on figure *C* at locations A, B, and C respectively. These limits help to define the continuation of contacts from the Colorado Plateau into the Basin and Range province. The Rainbow Gardens Member overlies successively older strata from north to south, and the positions of important contacts beneath that member are shown on figure *C*. With this evidence, much of the eastern flank of the arch is convincingly extended into the Basin and Range province as far as the trace of the Lake Mead fault system. Displacement on that fault system has apparently offset the eastern limb southwestward to the general vicinity of Las Vegas and Frenchman Mountain (pl. 1, figs. *B* and *C*). Although the nose of the arch is poorly defined, it apparently existed somewhere between Frenchman Mountain and the eastern part of the Spring Mountains. At Frenchman Mountain, geometric relations show that the Mesozoic rocks beneath basal Tertiary sedimentary rocks must have dipped gently to the northeast in pre-Rainbow Gardens Member time (barring possible horizontal rotation of the rocks) (Bohannon, 1979). In the eastern Spring Mountains and western McCullough Range, however, they apparently dipped slightly to the northwest. Here Cambrian rocks presently dip to the northwest and are in apparent depositional contact with Precambrian crystalline rocks. Tertiary volcanic rocks rest directly on Mississippian rocks northwest of there (Stewart and Carlson, 1978) indicating a slight pre-volcanic northwestward tilt (fig. *C*).

Though somewhat simplistic, figure *B* (pl. 1) shows the arch fragmented by 65 km of left slip on the Lake Mead fault system and distorted by about 55 km of crustal extension south of Lake Mead. The Las Vegas Valley shear zone appears as a broad zone of oroflexural bending and faulting upon which approximately 50 km of right slip has displaced the major thrust plates of the Sevier orogenic belt. An unnamed major fault south of the Gale Hills fault and another unnamed fault north of Frenchman Mountain are depicted as the major branches of the Las Vegas Valley shear zone in the Lake Mead area. To make figure *B* into a true paleogeologic map that depicts the geology prior to about 20 m.y. ago, it is necessary to restore displacements and distortion caused by the above structures. This restoration entails closing the extensional area by narrowing the distance between the east and west flanks of the arch on lines parallel to the extension direction; restoring the fault displacement on the Lake Mead fault system and thereby reconnecting the offset parts of the arch; and restoring the slip and folding on the Las Vegas Valley shear zone to result in the approximate north alinement and trend of equivalent thrust plates.

An understanding of the kinematics of the deformation is necessary to provide a usable model upon which such restorations can be based. In addition to accounting for the displacement and distortion described above, the model must explain the apparent truncation of the Las Vegas Valley shear zone by the Lake Mead fault system. These features are viewed as consequences of the relative motion of three distinct, partially rigid to rigid plates, which interacted with an irregularly shaped area that deformed in an almost ductile manner. The Colorado Plateau represents a rigid plate that is considered fixed in space. The area affected by crustal extension south of Lake Mead is combined with the Virgin Mountain region, where similar deformation has occurred, to form the area of ductile expansion. Two partially rigid plates are defined northwest of the Lake Mead fault system and are separated from one another by the Las Vegas Valley shear zone.

Kinematically, the deformation between these plates can be viewed in the following manner. Ductile expansion in a S. 70° W. direction in the area south of Lake Mead appears, from the fixed reference frame of the Colorado Plateau, to have resulted in incrementally increased displacement with distance from the plateau to the southwest. The Lake Mead fault system bounds the area of crustal extension on the north. Southwestward strike-slip displacement of the area north of the fault system was accompanied by southwestward expansion of the area south of the fault system, with the result that net displacement across the fault system decreases to the southwest, even though the total displacement within the area of extension (relative to the Colorado Plateau) increases in that direction. Ultimately the net displacement across the fault system reaches zero at the system's termination east of the McCullough Range.

The dissipation of strike-slip into the extensional area suggests to me the transform nature of the system. Relative to the fixed, rigid reference frame of the Colorado Plateau, the partially rigid plate north of the Las Vegas Valley shear zone and northwest of the Lake Mead fault system probably had a strong synchronous component of southwesterly motion parallel to the S. 30° W. trend of the Lake Mead fault system due east of the plate. The partially rigid plate south of the Las Vegas Valley shear zone received a similar component of relative motion, and in addition it appears to have been pushed relatively westward due to crustal extension south of Lake Mead, resulting in a change in trend of the Lake Mead fault system to S. 50° W. south of Las Vegas Valley. This additional component of westerly motion, imparted only to the southern plate, is thought to have resulted in the Las Vegas Valley shear zone.

The termination of the Las Vegas Valley shear zone at the Lake Mead fault system can be understood if regional relative crustal motions are considered. Brittle slip occurs on the shear zone between the two differentially moving plates northwest of the Lake Mead fault system, but within the area of ductile extension southeast of that system, distortion of the crust accomodates the displacement. The westward bending of the Lake Mead fault system at the junction, some additional crustal extension south of Lake Mead and in the Virgin Mountains, and the crustal extension and severe distortion within the wedge-shaped region between Frenchman Mountain and the junction of the major fault zones are visualized as features that compensate for the lack of brittle right-slip failure within the rocks southeast of the Lake Mead fault system on line with the Las Vegas Valley shear zone. The above processes result in changes in shape and surface area of the critical zones adjacent to the deforming strike-slip faults. Tectonic holes that normally would be created by such deformation along an active strike-slip fault have been filled in this case by the ductilely deforming crust.

Two distinct structural terranes are evident on the resulting pre-Rainbow Gardens Member paleogeologic map (pl. 1, fig. *D*). One terrane consists of the allochthonous rocks in the upper plates of the Sevier thrusts, and the other consists of the gently arched strata in the autochthon east of that belt. The Sevier orogeny is thought to have terminated by the early Tertiary (Armstrong, 1968), but considerable topographic relief might still have been present during the middle Tertiary in the resistant Paleozoic rocks above the thrusts. Strong evidence, however, indicates that the arched terrane east of that belt was bevelled flat to form an erosion surface prior to the deposition of the Rainbow Gardens Member about 20 to 18 m.y. ago. Anderson (1971) documents the presence of a welded ash-flow tuff which flowed over a thin conglomerate in the core region of the arch. Although the tuff is not well dated, Anderson and others (1972) conclude that an age of about 20 m.y. is likely. Its widespread distribution attests to the flatness of the regional topography prior to its deposition. Young (1966, 1970), Young and Brennan (1974), and Lucchitta (1972, 1979) describe the Peach Springs Tuff, which is probably no older than about 18 m.y., above a similar erosion surface on the east flank of the arch. The thin, continuous Rainbow Gardens Member was also deposited on a flat erosion surface dveloped on the nose and northeastern flank. It is not known how long prior to 20 m.y. ago arching occured. Young (1966, 1970) and Young and Brennan (1974) describe pre-Peach Springs Tuff clastic rocks that fill canyons cut into older rocks on what is now considered to be the eastern flank of the arch on the western edge of the Colorado Plateau. These relations indicate vertical uplift in the core of the arch and suggest active arching. Neither the canyons nor the rocks that fill them are dated, but both are considered to be Cenozoic (Young 1966, 1970). If the arch formed after the Sevier orogeny, the thrust plates of the Sevier orogenic belt might be folded by it. This possibility is illustrated by the questioned extension of the arch axis into the upper plate rocks of the Muddy Mountains on figure *D*. Another possiblity is that the arch formed during the compressional deformation of the Sevier orogeny. Some relations between the autochthonous rocks of the western flank of the arch and the lowest Sevier thrusts in the southern Spring Mountains suggest that the thrusts overrode the western flank. These relations were not studied in detail, however, so no strong conclusion can be reached. At present, either possibility seems plausible. If the arch is of post-Sevier age, it could be a Laramide structure as suggested by Rehrig and Heidrick (1976), but it does not seem possible, based on the preceeding discussion of erosion surfaces, that arching continued during the Miocene and accompanied volcanism, as was also suggested by Rehrig and Heidrick (1976, p. 216–217).

Although precise chronologic control is not available, it is thought that the Rainbow Gardens Member was deposited in a broad, gentle sag that developed on the nose and northeastern flank of the arch sometime after 20 m.y. but before 17 m.y. ago. Figure *E* (pl. 1) is a paleogeologic map, representing this approximate time period, that shows the distribution of facies and possible depositional extent of the Rainbow Gardens Member. Depositional limits and structural conditions near basin margins are poorly understood, but the overall character of the facies suggests limited topographic relief near most basin margins except in the rocks of the upper plates of the Sevier orogenic belt, where moderate relief may have existed, as this feature apparently formed the northwestern margin of the basin. To the south and southwest the Patsy Mine Volcanics probably began to develop during Rainbow Gardens time over the core of the arch (Anderson, 1971) and they probably created the southern margin of the Rainbow Gardens basin, but the nature and location of that margin are not known. No record of the Rainbow Gardens Member is known on the Colorado Plateau, so the eastern limit of the basin cannot be located. The northern extent of the member is also unknown because it is apparently obscured by younger Tertiary cover.

Facies paleogeography within the member is defined by stratigraphic and lithologic data gathered from surface exposures described earlier in this report (areas labeled A through K on fig. *E*). Facies boundaries are not well fixed. The clastic-carbonate facies appears to compose most of the member, and the two gypsiferous facies seem to be limited to the interior of the basin. The magnesite facies is possibly a basin-margin deposit and may have been associated with spring activity. The tuff-limestone facies is localized in the southwestern part of the basin near a possible source in the Patsy Mine Volcanics.

Active faulting and steep basin margins appear to have accompanied the deposition of the Thumb Member about 17 to 13.5 m.y. ago. Figure *F* (pl. 1), a paleogeologic map representing this time period, depicts the Thumb Member as having steep fault-bounded northern and southeastern margins at the Gale Hills and Gold Butte faults. Other basin margins are poorly understood because they are covered or have been eroded. The palinspastically restored distribution of the alluvial facies of the Thumb is also shown relative to the distribution of a fine-grained lacustrine facies. Two sources are indicated for the alluvial facies: one that is associated with the Gale Hills fault and another with the Gold Butte fault.

The structure of the Gale Hills, at the northern margin of the Thumb Member, represents one of the most perplexing problems of the Lake Mead region, and it deserves special attention. As I originally described it (Bohannon, 1979), the Gale Hills fault is the high-relief contact between the coarse-grained conglomerate of the Thumb Member and resistant Paleozoic rocks of the Muddy Peak area (figs. 15 and 16). This contact marks the northern margin of the member, and fault relations (fig. 16*A*) and steep buttress unconformities (fig. 16*B*) are found along it. However, the presence of allochthonous rocks south of the Gale Hills fault requires a major fault contact between the Gale Hills fault and the Mesozoic rocks of the autochthon exposed in the southern Gale Hills and in the Bowl of Fire (fig. 15). A diagramatic cross section (fig. 44), based on unpublished detailed geologic mapping by the author between the area north of Muddy Peak and that south of the Gale Hills, illustrates the need for this fault and its inferred position. In the cross section, allochthonous Paleozoic rocks at Muddy Peak dip to the southeast parallel to the Muddy Mountain thrust, which is stratigraphically controlled and occurs beneath the Cambrian Bonanza King Formation. At the surface, southwest of the Gale Hills fault in the Gale Hills, conglomerate of the Thumb Member rests depositionally on Mississippian rocks, which are thought to occupy a structural position well above the Muddy Mountain thrust. Thus, the latter thrust must occur in the subsurface south of the Gale Hills fault, beneath the Gale Hills. In the southern Gale Hills, however, autochthonous rocks, including the Cretaceous Baseline Sandstone and Willow Tank Formation, which are thought to be forethrust deposits (Longwell, 1949), are exposed at the surface in thrust contact with the Mississippian rocks. Involvement of the Rainbow Gardens and Thumb Members with this fault indicates its Tertiary age.

Although the Tertiary fault between the allochthon and autochthon appears to be a minor south-facing thrust at the surface, the geometry depicted in the cross section (fig. 44) implies that it is best interpreted as a right-slip fault with a significant amount of displacement. Interpretations of fault motion involving only vertical slip demand several episodes of faulting with opposing directions of offset. For example, an early episode, in which there is a significant amount of pre-Rainbow Gardens Member north-side-down normal faulting, is required to juxtapose the upper plate of the Muddy Mountain thrust (which, prior to faulting, had been structurally higher) to the autochthonous Baseline Sandstone. After erosion of the Muddy Mountain thrust from the southern block and deposition of the Rainbow Gardens Member and at least part of the Thumb Member, a second episode of reverse displacement is necessary to thrust the allochthonous rocks of the northern block over the lower part of the Thumb on the southern block. This necessary reversal of displacement appears inconsistent with the down-to-the-south normal faulting associated with the Gale Hills fault and the deposition of the Thumb. The increasing thickness of the Thumb Member to the southwest across these faults implies an apparent increase in the amount of downward relative motion in that direction. These apparent inconsistencies and the multiple displacement history are easily avoided if a single episode of right-slip faulting is considered.

On figure *F* (pl. 1) the episode of strike-slip faulting is interpreted to have occurred along the right-slip Las Vegas Valley shear zone, probably during the deposition of the Thumb Member. The juxtaposition of the allochthon and autochthon results from the eastward displacement of the plate south of the Las Vegas Valley shear zone relative to both the fixed Colorado Plateau plate and the plate north of the shear zone. Deposition of the Thumb Member is considered to have proceeded on both sides of this zone primarily in response to the down-to-basin normal faulting taking place simultaneously on the Gale Hills fault and related faults. The assignment of the right-slip faulting to this time period is based on the fact that it cuts the lower Thumb Member, while the overlying Bitter Ridge Limestone Member appears unaffected by it.

Left-slip faulting on the Gold Butte and possibly the Lime Ridge and Bitter Ridge faults appears to have accompanied vertical uplift, tilting, and erosion in the Jumbo Peak area to form the southeastern margin of the Thumb Member. Clasts of gneiss, amphibolite, rapakivi granite, and Paleozoic carbonate rocks derived from Jumbo Peak were deposited within the alluvial facies and in isolated conglomerate beds at locations 5, 7, and 9 and between locations 2 and 3 (pl. 1, fig. *F*). This distribution of clasts requires deformation of the northeastern flank of the pre-Rainbow Gardens Member arch like that shown on figure *F* south of the Gold Butte fault. Although not supported by direct evidence, the strike-slip Lime Ridge and Bitter Ridge faults are thought to have been active during this time as well, and they are so shown on figure *F*.

Geologic and chronologic evidence indicates that major left-slip fault activity on the Lake Mead fault system, a large part of the crustal extension south of Lake Mead, and probably a significant amount of right-slip faulting on the Las Vegas Valley shear zone oc-

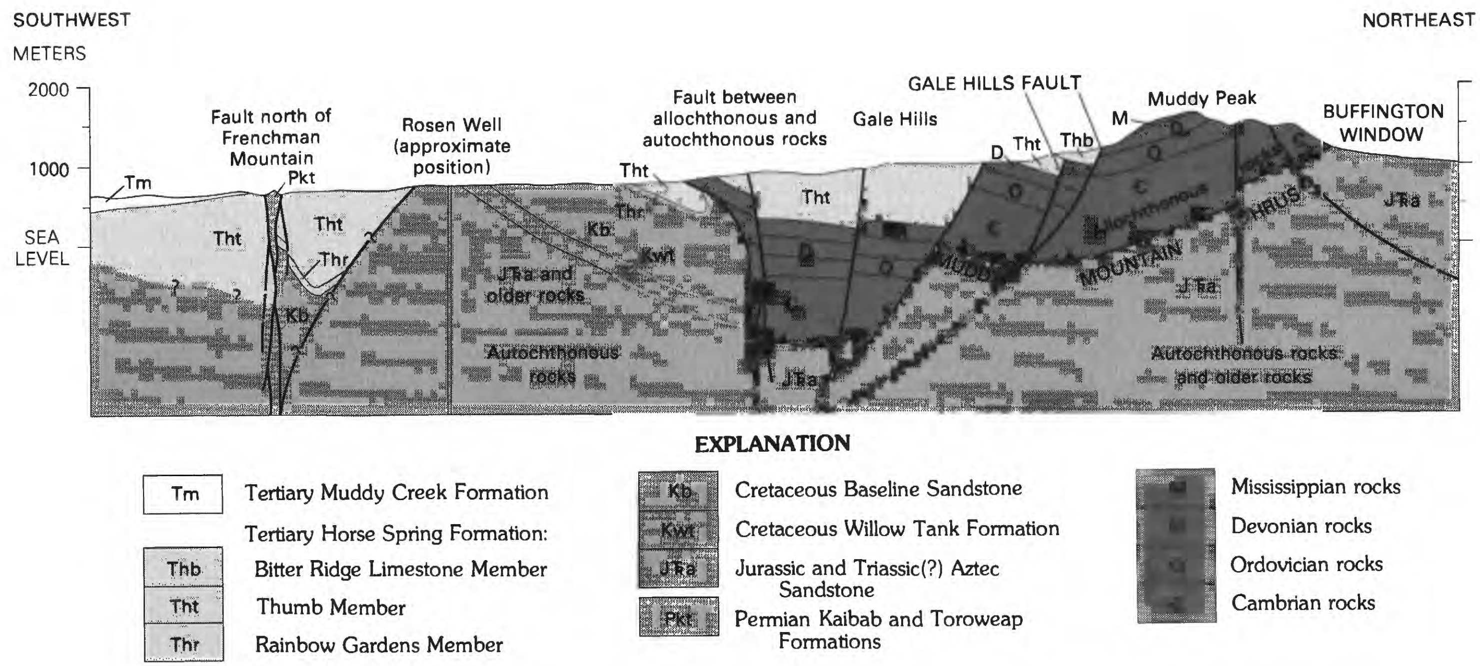


FIGURE 44.—Cross section from point north of Muddy Peak to area southwest of Gale Hills. Horizontal and vertical scales the same. Geology after Bohannon (in press).

curred during the deposition of the Bitter Ridge Limestone and Lovell Wash Members between about 13.5 and 12 m.y. ago. Both units are coeval with the Mount Davis Volcanics, which are thought to have erupted during the extensional period (Anderson, 1971); both are confined to the northwest side of the Lake Mead fault system, unlike the preceding members; and although both are chiefly carbonate, each grades laterally into a clastic facies directly adjacent to the fault system. Southeast of the Lake Mead fault system, stratal tilting, which was probably accompanied by crustal extension, strike-slip faulting, uplift, and erosion, is thought to have disrupted the earlier Thumb basin in the southern part of the Virgin Mountains. Figure *G* (pl. 1) is a paleogeologic map representing Bitter Ridge and Lovell Wash time, and it shows the major active structural and tectonic features.

The southeast margin of the Bitter Ridge-Lovell Wash basin is shown on figure *G* at the active left-slip Bitter Spring Valley fault of the Lake Mead fault system. The fault system is depicted in the process of fragmenting the earlier Thumb basin while compensating for active crustal extension south of Lake Mead. The inception of this phase of faulting has not been accurately dated, but it possibly began as early as 14.5 m.y. ago during the late stages of Thumb deposition and the early eruptions of the Mount Davis Volcanics. If so, it is highly probable that strike-slip on the Lake Mead fault system and the accompanying disruption of basin geometry were responsible for the significant change in sedimentation style between the Thumb and Bitter Ridge Limestone Members. In the interior of the Bitter Ridge–Lovell Wash basin, strike-slip faulting, which is shown on figure *G* as part of the Las Vegas Valley shear zone, exercised control over the distribution and lithology of the Bitter Ridge Limestone Member, but not over the Lovell Wash Member. The former member is rich in clastic material and is only discontinuously present south of the strike-slip faults, while the latter member apparently postdates faulting. The surface fault to which this activity is attributed is the unnamed fault that passes north of Frenchman Mountain and extends east to the Bitter Spring Valley fault (pl. 1, fig. *A*). This fault is depicted in the cross section (fig. 44) as a complex zone that is cored by Permian rocks and flanked by the Thumb Member. It occurs in the southern part of the Gale Hills. Although the sense of slip on the unnamed fault has not been determined, its geometry is strongly suggestive of strike-slip, and its trend and geographic position suggest that it is a branch of the Las Vegas Valley shear zone.

The southwestern margin of the Bitter Ridge–Lovell Wash basin is thought to have been controlled by the northern extent of the volcanic rocks related to the Mount Davis Volcanics. Some interfingering between volcanic rocks equivalent in age to the Mount Davis Volcanics and the Tertiary sedimentary rocks is present near Frenchman Mountain. The precise location of the northern boundary of the basin is not known, but both the Bitter Ridge Limestone and Lovell Wash Members lapped northward onto the allochthon of the Muddy Mountain thrust. The Gale Hills fault, which was the basin margin of the Thumb Member, is overlapped by the Bitter Ridge Limestone Member, which extended north into the area of California Wash. Both members probably existed north of White Basin, but it is not known to what extent. The west margin of the Bitter Ridge–Lovell Wash basin is buried beneath Las Vegas Valley.

From about 12 to 10.5 or possibly 10 m.y. ago, sedimentation patterns were severely disrupted by an episode of block faulting, which may represent incipient Basin and Range deformation. The red sandstone unit and the rocks of the Grand Wash trough were deposited in grabens and on the downthrown sides of tilted mountain blocks during this period. Figure *H* (pl. 1) is the paleogeologic map of this time. One large depocenter of the red sandstone unit is evident in the White Basin graben formed by the Muddy Peak and White Basin faults. These two faults are high-angle, normal slip faults with large displacement, and they show evidence of flattening in upper crustal levels. Another depocenter of the red sandstone unit occurs east of Frenchman Mountain, and it appears to be associated with normal faulting and stratal tilting in that area. The rocks of the Grand Wash trough are localized west of the Grand Wash Cliffs, where they were deposited on the downthrown side of a large tilted mountain block created by normal slip on the west-dipping Grand Wash fault (Longwell, 1945; Lucchitta, 1979). The Grand Wash fault is overlapped by upper strata of the rocks of the Grand Wash trough, which were deposited against the high-relief, eastward-retreating Grand Wash Cliffs (Lucchitta, 1979).

It is possible that active left slip on the Lake Mead fault system was accompanied by the last phases of crustal extension south of Lake Mead while at least the oldest beds of the red sandstone unit were being deposited. The Mount Davis Volcanics, which date the crustal extension, are as young as 11.8 m.y. (Anderson, 1971; Anderson and others, 1972), suggesting extensional activity coeval with the early phases of deposition in White Basin. The Muddy Peak fault, which is known to have been active at the margin of White Basin during the deposition of the red sandstone unit, appears to be deformed by the Bitter Spring Valley fault, suggesting continued activity on the latter fault as well. Synchronous activity on the Lake Mead fault system and the Las Vegas Valley shear zone is possible between 12 and 10 m.y. ago, but there is no direct evidence pertaining to the precise time activity ceased on either feature.

Las Vegas Valley, California Wash, the valleys of the Muddy and Virgin Rivers, and Detrital Valley all represent other possible depocenters for rocks equivalent in age to the red sandstone unit (pl. 1, fig. *H*). If so, the strata are now covered by younger deposits.

Figure *I* (pl. 1) is a paleogeologic map that represents a time about 6 m.y. ago after the widespread episode of basin-range faulting, during which large, north-trending horsts, grabens, and tilted mountain blocks overprinted the preexisting Tertiary structural features. It is not known exactly when this deformation began, because the Muddy Creek Formation and other rocks of equivalent age have filled the valleys to such extent that basin-bounding faults and the rocks that record their activity have all been covered except for those south of Lake Mead along the Colorado River (Anderson, 1971). If basin-range faulting occurred during the period of deposition of the red sandstone unit, basin-range deformation may be as old as 12 m.y. in the Lake Mead area. On the other hand, basin-range deformation could be much younger and may have evolved during early Muddy Creek time, but it is probably not younger than about 8 m.y. old because rocks this age appear to have overlapped basin-bounding faults. At present the age of onset of basin-range deformation in the Lake Mead region is uncertain. However, it appears likely that the active faulting associated with the development of the basin-range structure had ceased completely by about 6 m.y. ago in the region, and the basins had filled to near capacity.

By means of a careful analysis of the history of the lower Colorado River, Lucchitta (1979) concluded that the Lake Mead region was near sea level during the time period represented by figure *I* (pl. 1). He also summarized the depositional history of the Hualapai Limestone, which was strongly influenced by activity on the Wheeler fault, one of the only faults active in the Lake Mead region at this time. Lucchitta (1979, p. 90–93) also postulated that the general uplift that affected the Colorado Plateau, Sonoran Desert, and southeastern Great Basin was a widespread post-Muddy Creek event probably not related to basin-range faulting or extension. I concur.

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☆ U. S. GOVERNMENT PRINTING OFFICE: 1984—776-041/2801