ART. IV.—*Geology of the Muddy Mountains, Nevada, with a Section to the Grand Wash Cliffs in Western Arizona*¹; by CHESTER R. LONGWELL.

INTRODUCTION.

The area with which this paper is concerned is in southeastern Nevada and northwestern Arizona, as indicated on the accompanying index map (fig. 1). The general region of which this area is a part has more than one strong appeal to the geologist. It is practically unmapped, and hence has the lure of the unknown. The pioneer scientists who traversed the Plateau and Great Basin regions gave only passing notice to the Virgin and Muddy mountains, and the inaccessibility of the region has discouraged later efforts. As a result, a large area still presents opportunities for scientific work of an exploratory nature. Moreover, the location of the region near the edge of the Basin Range country and immediately adjacent to the Plateau Province gives it a critical interest, because the stratigraphic, structural, and physiographic relations of Basin to Plateau must be determined largely by a study of this border zone. Are the rocks west of the Grand Wash Cliffs fundamentally different from those to the east? What is the nature and what the age of structure lines dividing the two provinces? To what extent does the physiography of the region help in unravelling the more recent geological history? These questions concern matters which are not only of interest in themselves, but are fundamental in the larger problems touching the origin and development of the Plateau, the eastern part of the Great Basin, and the Colorado River system.

Previous reports.—The Whipple, Ives, and Wheeler parties did not map the area considered in this report, but made reconnaissance surveys of closely adjacent areas. Dutton included in his atlas of the Grand Canyon district a generalized geologic map of the Grand Wash and the eastern part of the Virgin Mountains. The first representation of the geology of the Muddy Mountains and the lower Virgin Valley appeared in 1903, on Spurr's map of southern Nevada, included in Bulletin 208 of the U. S.

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Fig. 2

Geological Survey. The portion of the map representing the Muddy and Virgin mountains was based on scant information, and the author made no claim of its accuracy.

Nature of this paper.—The report of which this paper is an abstract will appear as a publication of the U. S. Geological Survey, and will present in detail the results obtained in five months of field work in 1919. This abstract will state only the most essential facts and conclusions regarding the topography, stratigraphy, structure, and physiography of the region mapped.

Acknowledgments.—The writer wishes to express his thanks to members of the Geological Department of Yale University, who secured research funds for prosecuting the field work on which this paper is based. Acknowledgment is also due the U. S. Geological Survey, which furnished surveying instruments and field equipment, although the writer was not a regular employee of that organization. Mr. Harold S. Cave, at that time a graduate student in the University of Missouri, spent several weeks in the field and gave valuable assistance. During the preparation of the report continued interest and advice from Professors Charles Schuchert and H. E. Gregory were of especial assistance. The most sincere thanks are due them and other members of the faculty who gave helpful suggestions.

GEOGRAPHY.

Climate and drainage.—Southeastern Nevada has an average annual rainfall of less than 6 inches, and is part of a large arid region. Due to the proximity of Colorado River, however, the drainage is entirely exterior. Virgin River is a permanent stream, receiving its supply in part from the mountains of southern Utah, and in part from its principal tributary, Muddy Creek, which has its source in a number of large springs. Other stream channels reach every part of the area, but all are dry except at times of infrequent rains.

Topography.—The general uniformity of surface which characterizes the Colorado Plateaus ends abruptly at the Grand Wash Cliffs. To the west, rugged, barren ranges, trending generally north and south, are separated by wide structural valleys of low elevation. The Virgin Mountains have a number of sharp peaks, the highest reaching an elevation of 7,700 feet. St. Thomas Gap, a low pass of

structural origin, permits easy passage between the Grand Wash and Virgin valleys. The highest part of the Muddy Range is Callville Mountain, an abrupt mass shaped roughly like a large letter "C" with the opening toward the south. The general elevation of the mountain above sea-level is about 3,000 feet, but many peaks rise to an elevation of 4,000 feet or higher. Muddy Peaks, the highest points, are nearly 5,800 feet above sea-level. Both north and south of Callville Mountain the average elevation is slightly more than 2,000 feet, and abrupt ridges rise several hundred feet higher. Everywhere the surface is nearly destitute of vegetation and has been carved into extremely rugged forms.

The valleys of Grand Wash, Virgin River, and California Wash are each several miles in width, and have a total area approximately equal to that of the intervening ranges. The stream courses occupy comparatively narrow inner valleys, from which there is a gradual rise toward the mountain walls on a series of broad terraces, partly dissected into badlands. Colorado River has cut canyons through the ranges, but its valley is wide and comparatively open in crossing the intermontane troughs. South of the Muddy Range the Colorado is less than 700 feet above sea-level.

ROCK SERIES AND FORMATIONS.

West of the Grand Wash Cliffs sedimentary formations are separated into two especially distinct groups. The first is a thick series resting on pre-Cambrian schists and ending upward with Mesozoic sediments. This group clearly corresponds to the series exposed in the Grand Canyon and on adjacent plateaus, and, as in the case of that series, the limestones, sandstones, and shales belonging to many periods have remarkable conformity among themselves. The second group has a distinctly younger aspect, and is separated from the older series by an unconformity of the first order. Below this break the youngest rocks exposed are not higher in the time scale than middle Mesozoic, whereas the oldest rocks of the younger series are probably later than middle Tertiary. Other unconformities within the younger group indicate continued unrest and an incomplete sedimentary record since the disturbances which first tilted the older rocks.

Era	Period	Epoch	Formation	Thickness (in feet)
Cenozoic	Quaternary		Various alluvial deposits	0- 400
	Tertiary	Pliocene?	Unconformity	
			Saline clays, silt, and sand	200-1800
		Miocene?	Unconformity	
			Horse Spring formation	1000-2800
Mesozoic	Jurassic		Overton fanglomerate	20-3500
			Great Unconformity	
			(Equivalent to) Cross-bedded sandstone (the LaPlata)	750-2000
			Chinle formation	800-3200
			Shinarump conglomerate	10- 200
Paleozoic	Triassic		Disconformity	
			Moenkopi formation	1200-1600
			Disconformity	
			Kaibab limestone	400- 700
	Permian		Coconino sandstone	0 - 75
			Supai sandstone	1000+
			Not exposed. Unknown thickness	
	Pennsylvanian		Callville limestone	1100+
			(No unconformity observed)	
	Mississippian		Bluepoint limestone	900±
			Rogers Spring formation	600±
	Devonian (and older?)		Disconformity	
			Muddy Peaks limestone	1200+
	Cambrian (and later)		Sandstone, quartzite, shale, and limestone. In Virgin Mountains.	

Rocks of the Virgin Mountains.

Exposures of pre-Cambrian rocks occupy large areas both north and south of St. Thomas Gap. The rocks are schists and gneisses, injected with coarse-grained granite. Above these crystalline rocks lie 70 to 100 feet of red arkose, 150 feet of gray quartzite and sandstone, several hundred feet of greenish shale, and limestones thousands of feet thick. The limestones are in large part Pennsylvanian, Mississippian, and Devonian, but probably the Ordovician and Cambrian periods are also represented. The clastic sediments at the base probably

correspond to the Middle Cambrian Tapeats sandstone and Bright Angel shale of the Grand Canyon district.

Rock formations younger than the Paleozoic are exposed in St. Thomas Gap. They are identical with formations in the Muddy Mountains.

Rocks of the Muddy Mountains.

Paleozoic Formations.

Devonian System.—Limestones of Devonian age are the oldest rocks recognized in the Muddy Mountains. They are in Callville Mountain, a great block which has been thrust over Jurassic sandstone. All of the beds between the overthrust plane and recognized Carboniferous are here referred to the Devonian, but further work may show that some of the lower strata belong to older periods. Devonian fossils were found in a zone about 50 feet thick, more than 300 feet below the base of the Mississippian. Below this fossiliferous horizon there are 900 feet of limestone in which no fossils were found except a few algæ. As the beds are of the same general nature and as no unconformity could be found in the series, the entire thickness of 1,200 feet is tentatively included in one formation, which will here be called the *Muddy Peaks limestone* because of its prominence in the Muddy Peaks mass.

The limestone is dense and hard, and many beds have a siliceous appearance. Layers are regular and heavy, ranging from 2 to 20 feet in thickness. In color they are either very dark from included carbonaceous matter, or decidedly light, beds or zones of the two alternating. Lenses and thin layers of sandstone occur at intervals, especially near the top of the formation. At the base brecciation and shattering are extreme through a thickness of 100 to 500 feet.

Most of the fossils collected from the formation have been misplaced, and therefore a complete list is not available for publication in this paper. The following partial list has been identified by Dr. E. O. Ulrich: *Helio-phyllum* sp. undet. (calyx less than 1/2 inch in diameter), *Zaphrentis* sp. undet. (calyx 1 inch or less in diameter), small Stromatoporoid of undetermined genus and species, *Atrypa* aff. *reticularis* (differs from the typical form in

having finer plications), and *Platyschisma? ambiguum* Walcott.

If the writer's field determinations are correct, the fauna also contains *Spirifer whitneyi*. Dr. Ulrich states that this fauna evidently represents that of the Devonian Nevada limestone found at Eureka, Nevada. The horizon is Upper Devonian.

Mississippian System.—A plain disconformity separates the Muddy Peaks limestone and higher sediments. Above this break at least 1,500 feet of carbonaceous limestone, containing an abundance of chert at many horizons, yields fossils of Mississippian age. No physical break was seen in this series of beds, but the faunas of the upper and lower portions are so strikingly different that the limestone may be separated into two formations. The following forms were found in the lower 600 feet: *Triplophyllum* sp., *Leptopora* aff. *typa*, *Leptæna analoga*, *Schuchertella* aff. *chemungensis*, *Chonetes loganensis*, *Productus* sp., *Camarotoechia metallica*, *Spirifer centronatus*, *Spiriferina solidirostris*, and *Reticularia cooperensis?*

Dr. G. H. Girty, who identified the forms, refers this fauna definitely to the Lower Mississippian, correlating the horizon with the Madison limestone. This formation is prominently exposed near Rogers Spring, and will be called the *Rogers Spring formation* in this paper. In addition to its faunal peculiarities it is characterized by the presence of a considerable thickness of dark quartzite in the upper half.

The younger Mississippian formation yielded the following forms: *Triplophyllum* sp., *Cyathaxonia* sp., *Fenestella* sp., *Derbya* aff. *kaskaskiensis*, *Chonetes* aff. *loganensis*, *Composita* aff. *subquadrata*, *Productus* aff. *scitulus*, *Pustula* aff. *indianensis*, *P.* aff. *arkansana*, *Spirifer* sp., *Conocardium* n. sp., *Leptodesma* aff. *spergenensis*, *Pleurotomaria* n. sp., *Paraparchites* sp., and *Bairdia* sp. Dr. Girty pronounces this fauna Upper Mississippian, corresponding to the fauna of the Brazer limestone of northern Utah. The formation will be referred to as the *Bluepoint limestone*, because it forms the corner of Callville Mountain which is locally called Bluepoint.

Pennsylvanian System.—In Callville Mountain the Bluepoint limestone is overlain by at least 1,100 feet of dark gray, heavy bedded limestone containing the follow-

ing fossils: *Triplophyllum* sp., *Productus cora*, *Pustula nebraskensis*, *P. nebraskensis* var., *Dielasma bovidens*, *Spirifer cameratus*, *S. rockymontanus*, *S. sp.*, *Composita subtilita*, *Edmondia* sp. On the basis of this fauna Dr. Girty correlates the limestone with the Magdalena group of New Mexico. In this paper the formation will be called the *Callville limestone*, because of its prominence in Callville Mountain. An indeterminate thickness has been eroded from the sections studied in the Muddy Mountains, and the contact with the overlying Supai sandstone was not seen at any place. Limestone with similar fossils and lithology was recognized in the Virgin range. In the Grand Wash Cliffs, limestone containing Pennsylvanian fossils lies immediately beneath the typical Supai sandstone, but the limestone does not resemble the Callville formation lithologically. The thick series of strata in the lower cliff contains an abundance of dolomite, and does not resemble any part of the Callville Mountain Carboniferous section.

The lower part of the Supai sandstone may be of Pennsylvanian age but for convenience the entire formation will be discussed under the Permian.

Permian System.—The *Supai sandstone* is prominently exposed in the upper Grand Wash Cliff, and in tilted fault blocks to the west. In the upper cliff the sandstone is more than 1,000 feet thick, and practically all of it is bright red, fine-grained, and regularly bedded. In the Virgin and Muddy mountains cross-bedding is very prominent in the formation, gypsum and gypsiferous shale occur at several horizons, and in the most westerly exposures the typical red color is largely replaced by grey. No fossils were found in the sandstone, but at least a part of it is assumed to be Permian, corresponding to the Upper Supai described by Schuchert in the Grand Canyon district. In the lower Grand Wash Cliff, Pennsylvanian fossils were found near the top of beds which apparently correspond to Noble's basal Supai in the Grand Canyon. These beds may mark the upper limit of the Pennsylvanian, or the Pennsylvanian-Permian contact may lie at a higher horizon, within the typical red sandstone.

Typical *Coconino sandstone* lies above the Supai in the Upper Cliff, in Grand Wash Valley, and in the Virgin Mountains. In these exposures the maximum thickness

observed was 75 feet, and the formation thins consistently westward, losing its identity in the Muddy Range.

The *Kaibab limestone* has two thick limestone members, both composed of dark gray, cherty limestone in heavy beds. In Grand Wash these members are separated by red sandstone, but in the Virgin and Muddy Mountains the dividing horizon is occupied by massive gypsum which is locally 100 feet thick. At the base the formation has alternating layers of sandstone and limestone, forming a variable thickness. The total thickness of the formation ranges from 400 to 700 feet. Fossils are

FIG. 3.—Upper Grand Wash Cliff, 10 miles north from the mouth of the Grand Canyon. Thickness of strata exposed about 900 feet. 1, upper part of Supai sandstone; 2, Coconino sandstone; 3, alternating sandstone and limestone layers at base of Kaibab limestone; 4, lower heavy limestone member of the Kaibab; 5, upper heavy limestone member. Bench between 4 and 5 due to weak shale and sandstone.

abundant in the heavy limestone members. Dr. Girty has identified the following list: *Fistulipora* sp., *Leptopora* n. sp., *Phyllopora* n. sp., *Cystodictya* sp., *Enteletes?* n. sp., *Derbya* sp., *Productus ivesi*, *P. occidentalis*, *P. semireticulatus*, *Marginifera lasallensis?*, *Pustula subhorrida*, *P. montpelierensis*, *Squamularia* aff. *guadalupensis*, *Composita subtilita*, *C. mexicana*, *Griffithides* sp., and *Acanthopecten coloradoensis*.

Dr. Girty states that this fauna is Permian, corresponding to that of the typical Kaibab and also to the

fauna of the San Andreas limestone in the Manzano Group of New Mexico.

Mesozoic Formations.

Interval between eras.—A distinct disconformity separates the Kaibab limestone from Mesozoic sediments. Local depressions or valleys 50 to 100 feet deep, cut into the Kaibab in early Triassic or pre-Triassic time, are filled with chert and limestone fragments from the underlying rock. No angular divergence was found between Paleozoic and Mesozoic formations.

FIG. 4.—“Magnetite” of the Horse Spring formation, in Muddy Valley. Beds dip 32° N.E. Thickness of 300 feet shown in figure.

Triassic System.—The lower Triassic is represented by thin-bedded limestone, shale, and sandstone forming a total thickness ranging from 1,200 to 1,600 feet. In the Muddy Mountains limestone makes up practically half of the thickness. Typically the layers are regular, but are very thin, beds more than a foot thick being exceptional. Shale, sandstone, and gypsum members occur at intervals, and abundant ripple-marks indicate shallow water during deposition. Marine fossils, dominantly pelecypods, are found at many horizons. The upper part of the deposits are continental, and consist mainly of shale, with abundant gypsum. Tracks of small reptiles occur in the shales.

The following forms, found in the limestones, were identified by Dr. Girty: *Aviculipecten utahensis*, *A.* spp. 1 and 2, *A.* n. sp., *Pseudomonotis* n. sp., *Myalina* n. sp., *Pteria?* sp., *Sedgwickia?* n. sp., *Myophoria* n. sp., *M.* aff. *lineata*, *Pleurotomaria?* n. sp., *Pleurophorus?* n. sp., *Pseudomelania?* n. sp., *Murchisonia?* sp., and casts of starfishes.

Although this list is not diagnostic in itself, it serves to correlate the horizon with beds in Arizona, Utah, and Idaho in which, Dr. Girty states, ammonites have been found, proving a Lower Triassic age for the horizon. Very clearly the formation corresponds closely to the

FIG. 5.—Unconformable contact of Pliocene(?) intermontane deposits and Horse Spring beds. Valley of Muddy Creek.

Kanab Valley "Permian," to the "Lower Shinarump" of northern Arizona, and to the Moenkopi formation of Arizona, New Mexico, and Utah. The name *Moenkopi* has been applied to the beds of this horizon over a large region, and this name will also be used here for the formation in the Muddy Mountains, inasmuch as there is no reasonable doubt regarding the correlation.

A disconformity separates the top of the Moenkopi formation from the *Shinarump conglomerate*, which ranges in thickness from 10 feet to 200 feet and varies in composition from coarse conglomerate to conglomeratic sandstone. Pebbles are mainly quartzite and chert, and are

well rounded. Beds are local and lenticular, and the entire formation is characterized by extreme crossbedding. Fragments of silicified wood are abundant, and large logs are common, especially near the top. Descriptions of the conglomerate in the Navajo country, 300 miles to the east, are equally accurate for the formation in the Muddy Mountains. With the exception of the petrified wood no fossils were found, and the conglomerate is called Upper Triassic merely to agree with its present classification in the Colorado Plateaus.

The Shinarump conglomerate is overlain, without apparent unconformity, by the *Chinle formation*, a thick series of sandstones and gypsiferous shales. Near Colorado River this formation is 800 feet thick, and at least a third of the thickness is made up of coarse sandstone layers, many of them conglomeratic. Northward the thickness increases to 3,000 feet within 20 miles, and the coarse materials almost disappear. Near Muddy Creek the greater portion of the formation consists of red gritty shale and fine-grained sandstone, with an abundance of gypsum, both primary and secondary. Ripple-marks are common, and silicified wood occurs at some horizons. Evidently the deposits are continental, and the source was in highlands which lay to the south, probably in central or southern Arizona. The formation corresponds closely in lithologic character and in stratigraphic relations to the Chinle formation of the Navajo country and to the Dolores of southwestern Colorado; and in this report the name *Chinle* is extended to the horizon in the Muddy Mountains, although no faunal evidence of its age was found in that region.

Jurassic System.—No unconformity was found between the Chinle formation and the overlying Jurassic sandstone, which is heavy bedded, cross-bedded on a large scale, and typically bright red, although gray is the predominant color locally. As a rule the false beds are straight and meet the true bedding planes at high angles; but tangential cross-bedding also occurs, and in some sections it is very conspicuous. The sand grains are fine to medium in size and show indications of wear by the wind. Probably both wind and water had a part in the final deposition of the sand. Without doubt the formation was laid down in an arid climate, and its great thickness—ranging from 800 to at least 2,000 feet—required neigh-

boring highlands of considerable elevation to furnish the materials. The sandstone corresponds to the La Plata Group of Arizona, New Mexico, and Utah; and it is probable that these widespread deposits of remarkably similar character had a common source in a mountain range to the south, perhaps the same highlands which furnished materials for the Chinle formation. The sandstone is here referred to the Jurassic period to agree with the present classification of the La Plata Group.

Cenozoic Formations.

Tertiary deposits.—The general structural conformity of sedimentary beds in the Muddy Mountains ends with the Jurassic sandstone. Younger sediments record a new order. A widespread surface of erosion was cut across the upturned edges of Mesozoic and Paleozoic strata, and on this surface the first record is found in a coarse, heavy alluvial fan deposit which embodies fragments of all the older local rocks. In its most typical phase the deposit consists mainly of limestone fragments, angular or slightly worn, with sand filling the interstices, and with a firm cement of calcium carbonate. Beds are lenticular, and fragments of many sizes are jumbled together with evidence of only the rudest attempt at sorting. Limestone masses 3 to 25 feet in diameter are not uncommon. Exposures of the deposit are distributed over the entire area, but the thickness varies greatly. Near Bitter Spring it is 20 feet thick, whereas near Overton the thickness is more than 3,000 feet. Adjacent to the Virgin Mountains the formation has a nearly uniform thickness, averaging 25 feet. Because of the peculiar character and evident origin of the deposit, Lawson's term *fanglomerate* is especially appropriate as a lithologic designation, and in this paper the formation will be called the *Overton fanglomerate*, from its typical development near the settlement Overton in the Muddy Valley.

The Overton deposits indicate rugged topography and arid or semi-arid climate. Near the end of the fan stage relief became more subdued, for the coarse sediments grade upward into fine playa and lake deposits which have a total thickness of at least 2,500 feet. These beds consist of sandstone, limestone, magnesium carbonate, shale, tuff, and gypsum, and the change from one type of sedi-

ment to another is often abrupt horizontally as well as vertically. Limestone and magnesian beds make up about a third of the thickness, and form the most conspicuous part of the formation. Much of the limestone is practically pure calcium carbonate, lies in heavy, regular beds, and has a delicate pink color on fresh surfaces. Oolitic or concretionary structure is common. No fossils were found, and it is probable that the limestone formed as a chemical precipitate in basins of brackish water. In many parts of the area the limestone horizon is occupied by 100 to 300 feet of a snow white deposit which is almost pure magnesium carbonate; and in other sections the two types of deposit interfinger. Thin beds of volcanic ash occur at short intervals in the limestone and "magnesite" and are also found at higher horizons.

For this series of beds the name *Horse Spring formation* is proposed, because of the prominent exposures near Horse Spring, in the Virgin Mountains. No fossils were found in these deposits or in the Overton fanglomerate, and their exact age is therefore undetermined. In lithology, in degree of deformation, and in general regional relationships the Horse Spring deposits compare well with the Siebert and Esmeralda formations of southwestern Nevada. Both of the latter formations are of Upper Miocene age, and the Overton and Horse Spring sediments will be referred tentatively to the same epoch.

All of the large intermontane valleys contain thick deposits of silt, clay, and sand which have suffered much less deformation than the next older formations. Wherever contacts were observed the intermontane sediments, lying horizontally or only moderately folded, rest on the bevelled edges of steeply tilted Horse Spring and Overton beds. For the most part the silt is in massive layers 6 inches to 2 feet thick, separated by lenticular layers of sand imperfectly cemented. Clay free from grit occurs in very minor quantity. Adjacent to the mountains the base of the sediments consists of coarse, unassorted gravel; but at a higher horizon the finer materials are in direct contact with solid rock ridges and have thin lamination, indicating that at least a part of the deposition occurred in lakes deeper and more permanent than playa lakes. In the Virgin Valley, beds of rock salt 50 to more than 100 feet thick occur in the lower 400 feet of the sediments, and gypsum layers are common through a much

greater thickness. Apparently the maximum exposed thickness of the sediments is nearly 2,000 feet, and an undetermined amount has been removed by erosion. The formation has the essential characteristics of interior basin deposits in an arid or semi-arid climate. No diagnostic fossils were found in these beds, and reference of the formation to the Pliocene is made tentatively, because of apparent correspondence to deposits of that age near Panaca, 100 miles to the north.

Quaternary deposits.—Various alluvial deposits are distinctly younger than the sediments of probable Pliocene age, and will be grouped as Quaternary, with the following classification according to their nature and origin: (1) Coarse gravels and sand, with a thickness ranging from 10 to 300 feet, underlying high surfaces of aggradation. These deposits are practically uncemented except in the upper 4 or 5 feet, where a rich matrix of calcium carbonate or gypsum forms a resistant caliche. (2) Remnants of consolidated fan, talus, and travertine deposits adjacent to mountain walls. (3) Alluvial fans still or until quite recently in process of building. (4) Recent talus cones and slope covers. (5) Valley filling of banded silt and sand of undetermined thickness. (6) Sand dunes, in river valleys and on terrace surfaces.

Igneous rocks.—The north end of the Black Mountains is composed mainly of intrusive porphyries and buried flows, all probably of Pliocene age or later. A thin flow of augite-olivine basalt, apparently derived from the Black Mountain volcanic center, is included in the saline clays of Virgin Valley and extends northward almost to St. Thomas. In Grand Wash Valley two flows of olivine basalt, separated by a vertical interval of 70 feet, are buried in Quaternary gravels. Apparently their source was to the north.

STRUCTURE.

The region has been affected by both faulting and folding, and the structure is complicated. Four principal groups of structural features are recognized, as follows: (1) Great faults or fault zones which separate adjacent ranges. (2) Intersecting faults which divide each range into a mosaic of blocks. (3) Folding, both moderate and intense. (4) Overthrusting, apparently of a major character. The intermontane faults will be discussed first,

and other structural features will be considered in their relation to separate ranges.

Intermontane faults.—At the top of the upper Grand Wash Cliff the Kaibab limestone lies approximately 4,000 feet higher than tilted blocks of the same formation on the floor of Grand Wash Valley. The valley represents a zone of large normal faults, all with downthrow on the west. The largest of these displacements, represented in part by the Cliffs, amounts to about 7,000 feet near Colorado River but decreases to the north. Since the original faulting, the upper cliff has receded 2 to 6 miles, and the lower cliff has been greatly dissected. The greater retreat of the upper cliff is due mainly to the weak Supai sandstone at its base; but it is possible that the faulting occurred in stages separated by long time intervals, and therefore that the upper cliff has suffered much longer erosion than the lower. Lack of coarse materials in the intermontane clays near the foot of the lower cliff suggests recurrence of faulting in comparatively recent time.

Virgin Valley is also an important fault zone. Closely spaced faults parallel to the river and with large downthrow to the west are represented by high scarps on the west side of the Virgin Range. North of St. Thomas outcrops of pre-Cambrian schist end abruptly on the east side of the river, and on the Muddy Mountain side Mesozoic and Tertiary sediments dip steeply eastward. The total displacement amounts to many thousands of feet, but precise measurement is not practicable.

Faults bound the Muddy Mountains on the west, at least in part, and it is probable that California Wash is a fault zone similar to Virgin Valley.

Structure of the Muddy Mountains.

In the Muddy Mountains there are three well defined structural divisions, separated by lines extending generally east and west. The northern division, between the Arrowhead fault and Muddy Creek, is characterized chiefly by folding, with faulting an important but secondary factor. The central division consists of Callville Mountain, an irregular remnant of an overthrust block which is bounded as well as cut by large normal faults. In the southern division there is a series of folds with axes extending approximately northeast and southwest,

cut and modified by a number of normal faults. This folding continues into the Black Mountains, and hence there is no definite structural division between the two mountain groups.

Northern division.—North of Callville Mountain the outcrops of Mesozoic formations have the shape of a large letter "L", due to the intersection of two anticlines at nearly right angles. In the Narrows anticline the beds have been tightly compressed and overturned to the east, and a large strike fault has caused a duplication of formations at the surface. East-west faults have further complicated the structure, and near the Arrowhead road the Kaibab and Moenkopi limestones have been thrust over Jurassic sandstone, probably in connection with the Callville Mountain overthrust. The Arrowhead anticline is a broad asymmetric fold which plunges beneath the intermontane clays at the east end, and at the west dies out as it meets the stronger fold from the north. The Overton and Horse Spring beds are involved in the Arrowhead fold, and near the Narrows of Muddy Creek they are moderately folded parallel to the Narrows anticline. Numerous minor faults affect all formations.

Central Division.—On the north side of Callville Mountain, Devonian and Carboniferous limestones lie at an elevation many hundreds of feet higher than adjacent Mesozoic sediments, and the fault plane between formations shows large downthrow on the south, indicating that the older rocks were once in an even higher position with respect to the younger. This relation suggests overthrusting, and north of Muddy Peaks the actual thrust plane is well exposed. Devonian limestone lies on the Jurassic sandstone, and the contact is marked by a smoothly polished surface, above which the limestone is intensely shattered through a thickness ranging from 100 to 500 feet. This shattering is also conspicuous along the north base of Callville Mountain. The vertical displacement due to the overthrust is at least 9,000 feet, and yet the thrust plane is practically parallel to the bedding. This fact suggests that the movement affected a large area. Crumpling and minor thrusting indicate that the direction of overthrusting was from southwest to northeast. Evidently that portion of the block which formerly lay north

of Callville Mountain has been removed by erosion, whereas to the west and south the strata involved in the movement have been carried downward by normal faulting, leaving Callville Mountain as the only remnant now exposed.

Subsequent to the overthrusting, pronounced doming has occurred north of Muddy Peaks, permitting the stripping which has exposed the thrust plane. Normal faulting, accompanied by tilting of blocks, has also affected Callville Mountain, and many of the scarps have a remarkably fresh appearance. The Arrowhead fault is marked by a fault-line scarp, the thrown block now occupying the higher position. Exposed portions of the actual plane have striations which dip westward 40° from the horizontal, thus indicating that the shove was greater than the throw. The Rogers Spring and White Basin faults, each with displacement of at least 2,500 feet, bound a high, narrow horst. The dropping of fault blocks is chiefly responsible for the depression known as White Basin. Faults with large displacement affect the western part of Callville Mountain, and a number of these bound narrow tongues of Horse Spring limestone which have been dropped into the mountain mass.

Southern division.—The axes of Bitter Wash and Sandstone Spring anticlines are parallel, and both are essentially parallel to the long axis of Muddy Peaks dome. Moreover, the three structures are almost equally spaced, and the intensity of folding is practically the same in all. The Sandstone Spring anticline plunges sharply at both ends, and therefore it is actually a dome with elliptical plan. Without doubt the three folds belong to the same series, and thus the central and southern divisions of the Muddy Mountains and the northern part of the Black Mountains are to some degree a unit in structure. Both the Bitter Wash and Sandstone Spring anticlines are greatly modified by faulting.

Deformation of intermontane deposits.—On the south side of Muddy Valley the intermontane clays show little disturbance, but have a perceptible general inclination toward the valley ranging from 100 to 200 feet per mile. In the Virgin Valley, however, the clays have been considerably folded. Northeast of Bluepoint a zone of disturbed strata follows the direction of the Rogers Spring

fault, the net result being a monoclinal dip southeast by east, although strong dips to the northeast occur locally. Near the line of greatest disturbance dips of 20° are common and inclinations as high as 40° were observed. This folding probably occurred in connection with recurrent movement on the Rogers Spring fault within comparatively recent time.

An anticline following the course of Virgin River for several miles south of Muddy Creek is indicated by persistent dips ranging from 20° to 35° , westward on the west side of the stream and eastward on the east side. Four miles south of St. Thomas a broad, gentle swell intersects the steeper north-south fold, producing a dome. A more pronounced east and west anticline affects the clays on both sides of the river immediately north of Bitter Wash, where the underlying Horse Spring beds have been exposed by erosion. Between Callville Mountain and Virgin River the clays have a basin-like structure, produced by combination of the anticlines mentioned and the monoclinal dip eastward from the Rogers Spring fault.

Structure of the Virgin Mountains.

Only a small part of the Virgin Mountains was studied in connection with this report, and therefore the major framework cannot be fully described. Northeast of St. Thomas the end of the principal range is a large anticline with a metamorphic core, the thick sediments dipping northwest and southeast from the axis, which extends generally northeast. South of St. Thomas Gap the rocks dip steeply eastward in a great tilted block in which both faulting and folding have complicated the details of structure. One system of faults, trending nearly north and south, is responsible for a number of parallel, finger-like ridges. Faults of another important system extend N. 60° to 70° E. St. Thomas Gap has resulted from the dropping of a large irregular block or a number of adjacent blocks, and on the floor of the gap the rocks have been tilted by folding and faulting. Displacements on faults bounding the gap and affecting the adjacent highlands range from hundreds of feet to several thousand feet. In a plunging anticline near Mud Well the Overton and Horse Spring formations appear to be almost con-

formable on the Mesozoic rocks. Sawtooth Ridge is an overturned block of Kaibab limestone with local overthrust relations to younger formations. Apparently its structure is the result of intense local compression.

In general, faults do not seem to be continuous from the Muddy Mountains to the Virgin Range, but the Rogers Spring fault is a possible exception. The eastern boundary of the schist ridge northeast of St. Thomas is probably a fault, and it is directly in line with the monoclinical folding of the clays northeast of Bluepoint.

It is worthy of note that both faulting and folding appear to be much more intense in this region near the Plateaus than in known parts of the Basin Ranges farther west. Instead of a gradual dying out of the effects of deformation toward the east, those effects are intensified in a border zone, and the change to strata which are relatively little deformed appears abruptly, at a well defined line.

PHYSIOGRAPHY.

Old surfaces of aggradation and erosion.—In all of the wide intermontane valleys remnants of former aggradation surfaces are preserved as mesas, which usually have a capping of caliche, a firm conglomerate with a rich matrix of calcium carbonate or gypsum deposited on evaporation of ascending ground-water. The highest surface, represented by Mormon Mesa, lies 700 to 800 feet above present stream grades, and successively younger surfaces are 250, 100, and 40 feet above the streams. All of the surfaces are underlain by coarse gravel and sand to a depth ranging from a few feet to 300 feet. The two lower levels form narrow belts bordering streams, and may appropriately be termed terraces. The upper surfaces are much more extensive, and are not terraces in the ordinary sense of the term. Remnants of the highest surface show that it once extended through St. Thomas Gap and covered all of the area north of Callville Mountain except a few scattered peaks, and rock-cut benches bordering these higher points indicate that the base-level corresponding to the aggradation surface remained stationary for a considerable period. In Callville Mountain a distinct fall line marks the elevation at which the surface met the mountain walls. Many stream channels on the surface of the mountain have easy grades and comparatively wide

valleys, but near the edges of the block they plunge sharply by a succession of falls which total a height of 400 feet or more. The aggradation surface has a general slope conforming to the grades of the larger streams, and also slopes from the mountain walls toward the valley interiors. A considerable part of this highest surface was destroyed during the growth of the next one, which is locally 5 or 6 miles in width and connects with smooth benches cut on solid rock. The inner surfaces or terraces record comparatively short halts of base-level. Within relatively recent time both the Virgin River and Muddy Creek have incised their floodplains, which may properly be considered a third terrace level.

OUTLINE OF GEOLOGIC HISTORY.

In the Virgin Mountains the geologic record extends backward into pre-Cambrian time, but in the crystalline rocks the record is complicated and obscure. Apparently the elastic Cambrian sediments were deposited on a nearly even surface which cuts across the structure planes of the metamorphic rocks. During much of the Paleozoic era southeastern Nevada was part of the Cordilleran geosyncline, although it was east of the area which received the thickest sediments. Further study will be required to determine the amounts and kinds of sediments deposited previous to the Devonian period. The Upper Devonian sea shallowed to the east and deepened to the west and north. Earlier Devonian invasions may have covered the region, but faunal evidence is not available. Marine invasions occurred in both Lower and Upper Mississippian, in Pennsylvanian, and in Permian times. During the Permian and perhaps during the Upper Pennsylvanian, thick continental and littoral deposits accumulated under conditions of aridity or semi-aridity. At the close of the era the region was uplifted without perceptible tilting, and suffered moderate erosion.

The Californian Lower Triassic sea deposited limestone, gypsum, and clastic sediments, and a great thickness of continental deposits followed the retreat of the sea. An interval of erosion succeeded, and another epoch of continental sedimentation began with the deposition of the coarse Shinarump conglomerate. A thick series of sand,

silt, and clay was furnished by highlands which arose to the south, and the enormously thick and widespread Jurassic sandstones were probably derived from the same source. All of the Mesozoic sediments indicate aridity of climate. In post-Jurassic time the region suffered intense folding, accompanied by overthrusting, probably in connection with the Sierra Nevada disturbance. During the late Mesozoic and the first half of the Tertiary the Muddy Mountain area was probably part of a high region with exterior drainage, and received no deposits which have been preserved. Intense normal faulting occurred, and thick basin deposits were formed, probably in Upper Miocene time. After erosion had subdued the topography there was a recurrence of faulting which formed new basins, in which thick deposits of saline silts and clays accumulated. The present drainage system was established later, probably in Quaternary time, and since its establishment there have been changes of base-level amounting to several hundred feet. Comparatively recent disturbances have deformed late Tertiary and Quaternary deposits, and it is possible that considerable faulting accompanied these latest crustal movements.

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