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(WITH 4 PLATES)

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EARLY MESOZOIC PHYSIOGRAPHY OF THE SOUTHERN ROCKY MOUNTAINS[1]

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INTRODUCTION

This paper results from an attempt to work out the ancient physiographic history of a part of the Rocky Mountain region which in Mesozoic time seems to have constituted a fairly well-defined physiographic unit. Although the history of neighboring provinces must be considered in connection with this one, it is in many ways one which may appropriately be considered independently and with which others may later be compared. The area to which attention is especially directed includes the mountains of Colorado, which extend southward into New Mexico and northward into Wyoming. This has been called the Southern Rocky Mountain Province by some geologists and the Park Range Province by others. From these mountains as a center, our study will lead us in all directions for data which help to interpret phenomena observed in this province.

Stratigraphy has sometimes been called fossil physiography, and a knowledge of ancient physiographic history should be useful in solving some of the difficult stratigraphic problems of this western region. There is a certain uniformity in natural processes which may be relied upon. We may confidently assume that during the Mesozoic era the same laws were in operation that govern the present-day world. Then, as now, highlands were eroded, lowlands were built up by the débris washed onto them, and basins were filled with sediments. It seems clear that physiography might be used to better advantage than it has been used heretofore by the stratigrapher and the historic geologist. I am confident that a study of ancient geography and of the evolution of land forms will lead to conclusive results in correlation in certain places where other lines of investigation fail.

[1] Published by permission of the Director of the United States Geological Survey.

It is not easy to abandon inherited notions, even when it can be proved that they have no foundation in fact. I have found it necessary in this study, in order to harmonize relations described in a given locality, to take into account many factors, such as the date at which the description was published, the prevailing belief at the time, and the personality of the author—whether progressive or conservative; whether an independent thinker or one fearful lest he stand alone. I have attempted here to keep inherited notions in the background and to carefully distinguish between the facts and their published interpretation. I have attempted to visualize the natural processes by which the observed relations were produced. I have endeavored to follow, step by step, the sequence of events as mountains were thrown up in the midst of the sea and have tried mentally to observe the evolution of the mountainous region as it was slowly molded under the forces of erosion, peneplained, base-leveled, and finally again submerged by the sea. I have attempted to follow the processes by which vast quantities of rock waste were transported from highlands to lowlands and spread out uniformly over hundreds of thousands of square miles. In brief, I have attempted to picture the physiographic processes which resulted in the stratigraphic relations exhibited by the sedimentary rocks of Mesozoic age in the Southern Rocky Mountain region.

One of the main objects of this study is to develop a logical grouping of the sedimentary rocks and to establish a method of correlation which may be applied in certain places where other methods fail. As correlation by physiographic criteria is somewhat unusual, opposition is anticipated. It is probably inevitable that the familiar arguments of established lines of thought will find wider acceptance than those of an untried line. The stratigraphic geologist has become so accustomed to relying on the paleontologist for correlations that he is apt to reject without due consideration any suggestion which seems to be at variance with that derived from the fossils. Chamberlin[1] recognized this attitude of mind when, in urging the merits of diastrophism, he said, "New criteria must not . . . . be judged solely by their concordance with established systems; certain divergences may be but signs of superiority." No claim is made that the investigation here described is a finished one. There are radical differences of opinion on some of the questions discussed

[1] Chamberlin, T. C., Cong. géol. internat. Compte Rendu XII, Ges. Canada, p. 551, 1914.

and there is seeming conflict of evidence. Different classes of data now seem to lead to contradictory conclusions. Conflict of evidence is only another expression for misinterpretation of evidence. There is no conflict when all facts are known, and I am convinced that physiographic principles can be used to great advantage in correlating some of the unfossiliferous sedimentary rocks in the mountain region.

A PRELIMINARY SUMMARY

The succession of events outlined in this paper begins with a time in the Carboniferous period when the sea covered the region where the Southern Rocky Mountains now stand. This sea was expelled and the ancestors of the present Rocky Mountains arose in its place. For long ages these mountains withstood the elements but were finally torn down and swept away. Before they had entirely disappeared other lands were elevated farther west and on them mountains were thrown up. Probably these new mountains were high, for a desert developed east of them, perhaps for the same reason that desert conditions prevail now east of the high mountains of California. The moisture from the Pacific was precipitated on these mountains and the streams carried the rock waste out into the desert, where the winds reworked it, piling the sand into dunes, which are now recognizable in their fossil state.

A broad depression or valley somewhat similar to Mississippi Valley, except that it drained northward, developed between the new mountains and the ancestral Rockies. In the western part of this valley the dune sand accumulated to great depths and graded off toward the east, covering the lower parts of the older, deeply eroded mountain area, but leaving the hilly parts uncovered. After the sands had accumulated in eastern Utah and neighboring regions to a depth of nearly 3,000 feet, the sea advanced in late Jurassic time up the old valley, across British Columbia and the Mountain States as far south as northern New Mexico and Arizona. Much of the submerged area was nearly flat and the sea was shallow in most places. Around it, especially in Utah, New Mexico, and Colorado, were shallow, partly inclosed bays where gypsum was precipitated by evaporation of the sea water. Extensive beds of gypsum have been found in many places which mark the location of these ancient evaporation pans.

The sea was short-lived, and as it retreated, sand drifted over the abandoned areas, covering in some places, but not in all, the gypsum, the fossiliferous limestone, and other beds which had formed in the sea and near it. The correlation of the fossiliferous marine beds with the gypsiferous strata is regarded as the chief contribution offered in this paper, for by this means a narrow zone of rocks, whose age is determined by means of fossils of marine organisms, may be followed far beyond the limits of the fossiliferous beds into unfossiliferous sedimentaries whose age has been in doubt. The area in which these beds are exposed is large and difficult to traverse. It may be many years before this tracing is done and until it is done physiographic data seem to furnish the best available means of correlating the unfossiliferous beds from place to place.

The events following the withdrawal of the Jurassic sea are better known than the preceding events. In the epoch next following this withdrawal, the final stages of planation of the Rocky Mountain region were accomplished and on the extensive plain the sluggish streams formed bayous, swamps, and temporary lakes, and spread out the sediments of the Morrison formation, building up a plain which seems to have been almost perfectly graded from New Mexico to Montana, and from central Utah to eastern Kansas. Over this graded plain advanced the waters of the Lower Cretaceous sea and later those of the great submergence in Upper Cretaceous time, which covered the site of the Rocky Mountains and buried their roots beneath its sediments, where they remained dormant until stirred to life by the post-Cretaceous or post-Laramie movement, when the present Rocky Mountains began to rise.

PRE-MESOZOIC PHYSIOGRAPHY

PENNSYLVANIAN SUBMERGENCE

It is not my purpose to consider the geographic conditions of the Rocky Mountain region, prior to the Mesozoic era, further than is necessary for a proper understanding of Mesozoic physiography. During much of the Carboniferous period sea water covered large portions of the area now occupied by the mountains. Marine limestone of Pennsylvanian age is abundant in central and northern New Mexico and in central and western Colorado. It has been the belief of many geologists that open sea conditions prevailed in western America during the time that the coal measures were forming in the eastern and central parts of the continent. Statements are frequently made that "in the western part of the United States there are no coal accumulations of this age (Pennsylvanian)."[1] There is unques-

[1] Schuchert, Chas., Textbook, p. 745.

tionably a large amount of limestone of marine origin in the rocks of Pennsylvanian age in the Southern Rocky Mountain Province, but there are also thin beds of coal and plant-bearing sedimentary rocks which indicate lowlands and coastal swamps in Pennsylvanian time. These have been found in New Mexico, near Socorro; in the mountains east of Albuquerque; near Santa Fe on the western slope of the main range; in the Pecos Valley between the mountain ranges; east of the main ranges near Las Vegas; and farther to the north in Moreno Valley. Thin beds of coal of Pennsylvanian age have been reported from many places in central and western Colorado and in eastern Utah, both north and south of the Uinta Range. These coal beds are not thick enough to be of commercial value, but they prove that the physiographic conditions of the Rocky Mountain region during the early part of the Pennsylvanian epoch were not so different from those in eastern and central North America as many geologists have supposed. However, later in the epoch these coals were covered by the sea in which was formed the massive limestone of Pennsylvanian age in New Mexico and Southern Colorado, which seems to indicate clear water and open sea conditions. I call attention to these facts because it was in the midst of this sea that the ancient Rocky Mountains were elevated. This is particularly significant, for we shall see later that this process was repeated when the site of the mountains was covered by the sea in the Upper Cretaceous epoch; and in the midst of this sea were formed the present Southern Rocky Mountains.

RISE OF ANCESTRAL ROCKY MOUNTAINS

Some time late in the Carboniferous period these coal-bearing rocks and the marine limestone of Pennsylvanian age were upturned and there followed a period during which the elevated lands furnished red sediment to the neighboring lowlands and seas. Some of these "Red Beds" belong in the Triassic system; others are certainly of Permian age; and still others, such as the Manzano group, have been classed as Pennsylvanian[1] on the basis of the fossil invertebrates, although there is a growing tendency to regard them as Permian. The fossil plants and vertebrates recently discovered in some of the older "Red Beds" tend to establish their Permian age. The subdivision and classification of the "Red Beds" present problems which are not likely to be solved for a long time to come.

[1] Lee, W. T., and Girty, G. H., U. S. Geol. Survey Bull., 389, 1909.

Many geologists believe that the red color of sedimentary rocks denotes cold, arid climate, and the suggestion has been made that the "Red Beds" of the Rocky Mountain region may denote a glacial epoch. No indication of the presence of glaciers has yet been found in these beds, but they seem to be of about the same age as the extensive glacial deposits in India, Australia, and South Africa.[1] If it is true that glacial epochs follow periods of general diastrophism and are caused by changes in oceanic and atmospheric circulation, brought about by earth movements, it seems reasonable to associate these red rocks with glacial conditions and to correlate them with the beds of Permian age in other parts of the world, some of which are known to be of glacial origin. Furthermore, it seems reasonable to assign the elevation of the ancient Rocky Mountains to the period of general diastrophism usually called the Appalachian Revolution, which wrought world-wide changes in climate, geography, and biology.

In this connection it seems not out of place to suggest a line of study that is well worth following, namely, the determination of the date of this ancient uplift of the Rocky Mountains and its relation to this revolution.

Conspicuous evidences of diastrophism are found between Pennsylvanian and Permian, in the restricted area occupied by the Arbuckle Mountains in southern Oklahoma, where the older rocks were uplifted, sharply folded, and eroded so that the beds of Permian age lie across the eroded edges of several thousand feet of strata which range in age from Ordovician to Pennsylvanian. In several places in the Rocky Mountain region an unconformity separates rocks of unquestioned Pennsylvanian age from overlying rocks which may be Permian. However, in some places the Pennsylvanian age of some of the "Red Beds" has never been questioned. Although the indications are that this uplift affected the whole Rocky Mountain region and resulted in a general unconformity between these two series of rocks,[2] the problem has not yet been worked out.

Although much remains to be learned about the time of this uplift and its results, it seems obvious that the sea of Pennsylvanian time was expelled from the Southern Rocky Mountain region and that mountains were raised in its place previous to the time of the principal red-bed accumulation. For our present purpose it is of secondary importance whether these red rocks are of Pennsylvanian

[1] Chamberlin, T. C., and Salisbury, R. D., Textbook III, pp. 632-636, 1906.
[2] Lee, W. T., Geol. Soc. America, Bull., vol. 5, p. 169, 1917.

or of Permian age, but it is of primary importance that highlands were formed where the open sea had been, and that south and east of these highlands lay shallow basins in some of which beds of salt and gypsum were formed. In other places continental deposits accumulated. These consist chiefly of coarse sand with conglomerate in many places. Obviously a large proportion of the red sediments were derived from highlands situated essentially where the Rocky Mountains now stand. These gypsiferous "Red Beds" (the Manzano) of New Mexico and beds of the same age elsewhere, are here regarded as Permian, and the question naturally arises: Are these beds correctly included in the Carboniferous system or should they constitute a separate system? On the principle that the first well-defined movement in a major orogenic disturbance opens a new geologic period and inaugurates a new system, this question becomes pertinent, for there is little doubt that a notable orogenic movement preceded the formation of the Permian "Red Beds." This question appears all the more pertinent when we reflect that in few places in the Rocky Mountain region can a line of separation be drawn between Permian and Triassic rocks. Even in places like the Grand Canyon region, where marine invertebrates occur, the fossils once described as Permian are now said to indicate Triassic age. In brief, so far as now known, there is a much greater break in sedimentation between the Pennsylvanian limestone and the Permian "Red Beds" than there is between the latter and the rocks now classed as Triassic.

TRIASSIC PHYSIOGRAPHY

UPLIFT AND EROSION

Whatever may be the final answers to the questions just raised, it is obvious that previous to the formation of rocks now called Triassic, there were highlands in the Southern Rocky Mountain region, although their original volume had been greatly reduced by the removal from them of great quantities of the detritus which constitutes the older "Red Beds." Also, the greater part of the North American continent was above sea-level, for only small parts of it are now occupied by Triassic rocks of marine origin.

The sedimentary rocks of Triassic age in some parts of the Southern Rocky Mountains have not been differentiated from the older rocks. But those of undoubted Triassic age are non-marine and are classed as Upper Triassic, such as the Shinarump conglomerate and Chinle formations of northern Arizona, and their equivalents in neighboring regions. The land from which the sediments were derived seems to have been relatively high, but the character of the rocks indicates that the mountains were lower than they had been in Permian time. It is important in our present study to note that the mountains had been reduced to such a condition that they furnished little coarse material for the beds to the east, although in western Colorado, eastern Utah and elsewhere they are conglomeratic. It is not certain, however, that the material of the Shinarump conglomerate came from the ancient Rocky Mountains. It may have come from lands farther to the west or south. The sedimentary rocks are relatively thin and probably represent only a small part of the Triassic system. The period seems to have been chiefly one of erosion, not only in the mountain region, but over most of the North American continent.

More is known of the Triassic rocks west of the Rocky Mountains than east of them and these have a significant bearing both on the Triassic physiography of the mountain region and on the changes which closed the Triassic period. These rocks, 1,700 feet thick in western Colorado (Dolores formation), thin to 1,000 feet or less in northern Arizona (Chinle formation), and still farther to the west the Upper Triassic (equivalents of Chinle formation) are only a few hundred feet thick. (See fig. 2, p. 13.) Although the differences in thickness may be due in some measure to post-Triassic erosion, the differences in thickness suggest derivation of the sediments from the east. Also the occurrence of marine Triassic rocks farther to the west and north (Moenkopi formation, classed by some as Permian (?)), seems to strengthen the belief that a large volume of Triassic sediments moved in late Triassic time from the Southern Rocky Mountain region westward to the sea across a low-lying plain on which the sand and gravel of the Shinarump conglomerate, and Chinle formation were laid down.

A search through geologic literature shows that Triassic rocks have been found in relatively few places in North America. Areas occupied by sedimentary rocks of this age are found only along the Pacific Coast and in the western interior of the continent. An inspection of existing maps and descriptions shows that certain "Red Beds" in the mountain region are regarded as Triassic by some geologists and as Permian or Pennsylvanian by others. The scarcity of fossils in the "Red Beds" renders it difficult in many places to distinguish between Triassic and older rocks. In large part, at least, the Triassic sedimentaries of the mountain region represent upland accumulation. Some of the beds east of the mountains which have been referred to the Triassic system contain salt, gypsum, and other evidences of sea connection. It may not be out of place here to question whether these beds do not really belong in some other system. Similar deposits occur in this region in the Permian series and accumulated at a time when marine waters had access freely to the Southern Rocky Mountain Province. Also, it will be shown later that certain younger beds of gypsum are probably Jurassic in age and were derived from sea water late in Jurassic time.

Inasmuch as the greater part of the continent was above sea-level in Triassic time, it is not easy to understand how marine waters could reach the Southern Rocky Mountain region and deposit the gypsum. The reference of the gypsiferous beds to the Triassic in the vicinity of the mountains does not harmonize with the evidence which tends to prove that this region was one of erosion and of the accumulation of sediments of continental type during the latter part of the Triassic period. At present we are confronted with seeming conflict of evidence. Apparently the Triassic rocks consist of débris which came from the mountains situated in the midst of this region of sedimentation; that is, the site of the present Rocky Mountains. Until more convincing evidence is brought forward than I have found thus far, I prefer to think of the older salt and gypsum beds as belonging in the Permian series of the Carboniferous system with the other beds of marine origin, and of the younger gypsum as part of the Jurassic system. (The gypsiferous Moenkopi formation is not known to extend eastward to the mountains proper.) If this relationship can be established, there is nothing that I know of in the Rocky Mountain region to negative an orderly succession of events such as follows: (1) The low-lying flats and shallow seas of Pennsylvanian time were disturbed by the uplift of mountains which rose in the region of the present Southern Rocky Mountains. (2) There followed a time in the Permian epoch during which detrital matter from the newly formed mountains gathered in the neighboring shallow seas and on gypsum flats and salt marshes. In many places it gathered as upland deposits on the plains which sloped away from the mountains, just as detrital matter is accumulating now in the western interior in places which are thousands of feet above sea-level. (3) There followed a time not well recorded in the mountain region during which many events of importance occurred farther west. An arm of the Pacific extended eastward into Colorado and New Mexico in late Permian or early Triassic time; was later expelled; the rocks which formed in it (Moenkopi formation) exposed to erosion; and some change in the relation of highlands and lowlands effected, which caused the streams to spread out, over a wide area, the sand, gravel and mud of the Shinarump conglomerate and other rocks of late Triassic age, both west and east of the mountains. (4) The period was brought to a close by the rise of a land mass of continental proportion in the Pacific Coast region, which persisted through all of Jurassic and Cretaceous time and furnished the enormous quantities of fragmental rocks which make up these two systems. This rise seems to have affected the Rocky Mountain region but little, for erosion continued there until stopped by the accumulation of younger sediments on the peneplain.

CLOSE OF TRIASSIC PERIOD

There is little known from the Southern Rocky Mountain region to indicate the events which closed the Triassic period, for this region was one of erosion during most of Triassic and Jurassic time. For evidence of these events we must look farther west, and here also much of the record has been destroyed by later erosion. However, an examination of the Jurassic formations described later indicates that the vast quantities of material composing them came from the west (see accompanying sections); hence it seems certain that the sea which had extended from the Pacific Ocean eastward into Nevada and Utah was blotted out and a land mass of great magnitude formed in its place. Further, the physical characteristics of the sedimentary rocks of the La Plata group indicate accumulation under desert conditions. It seems probable that the mountains of this western continent were high enough to precipitate the moisture from the westerly winds, just as the Sierra Nevada does at the present time, and that the streams thus formed washed rock débris into the Jurassic desert where it was reworked by the winds. This elevation of land to the west seems to have formed a broad valley similar to the Mississippi Valley between the ancient Rocky Mountains, now greatly reduced, and the new western highlands. It was in this valley that the desert sands accumulated and were later covered by the Jurassic sea, hence it is with this valley and its filling that we are much concerned in working out the physiographic history of the Jurassic period.

JURASSIC PHYSIOGRAPHY

INTRODUCTORY STATEMENTS

With the Jurassic we approach the main subject of this paper. The evidence from the sedimentary rocks is still meager, but enough to make some of the history of the period plain. The ancient Rocky

Mountain region was still a highland, but was reduced before the close of the Jurassic to a peneplain, and thin deposits of sediment accumulated on it toward the close of the period. But the interpreta-

FIG. 1.—Sketch map of area occupied by sedimentary rocks of Jurassic age. (The numerals 1-33 denote location of sections used in figures 2-6.)

tion of Jurassic events is based chiefly on a study of the deposits in the old valley.[1]

In order to determine the physiographic conditions under which the stratified rocks were formed, it is necessary to observe their litho-

[1] In order to make the study complete the entire filling of the valley should be considered. But as this paper deals chiefly with the Rocky Mountain region, little is said of the principal deposits of the La Plata group, which are situated in the western part of the old valley.

logic character and their stratigraphic relations over an area of considerable size, where the rocks can be traced at the outcrop or where exposures are so close together that correlation by lithology or otherwise is satisfactory. From these observed relations the governing physiographic conditions may be judged. If judged correctly, the physiographic criteria help in correlating the rocks in a field examined later or perhaps in correcting the correlations made without their help. To apply this principle in the present study, it is necessary to review the information relating to the La Plata sandstone and its age equivalents and to test by the new criterion the correlations which have been made from time to time.

In the accompanying groups of sections I have indicated by means of the names attached to some of them the correlations which have been made in the published descriptions. The symbols and connecting lines indicate my personal inclinations as to correlation which in several instances differs from that made by the different authors. The data presented have been gleaned chiefly from the literature, but much unpublished information is used which has been gathered in part by myself and in part by several of my associates on the United States Geological Survey, who have freely contributed from unpublished manuscripts and notes. The most that can be claimed for the grouping is that it represents possible relations. The implied correlations should be tested rigorously by observations in the field and modified as newly established relationships are determined. Most of the sections have been grouped with reference to the top of the Morrison as a datum plane. This plane was close to sea-level and formed the floor on which the Dakota sandstone was deposited.

COMPARISON OF SECTIONS

ARIZONA TO NORTHERN UTAH AND EASTERN WYOMING

The La Plata sandstone described by Cross[1] in southwestern Colorado has been traced by Gregory[2] southward into Arizona, where the upper sandstone is called Navajo, the lower sandstone Wingate, and the beds separating the two Todilto. These subdivisions have not been carried far to the north in the walls of the canyon of the Colorado River, but it seems probable that the Gray Cliff and Vermilion Cliff sandstones in the region of Henry Moun-

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[1] Cross, Whitman, U. S. Geol. Survey Geol. Atlas. La Plata folio (No. 60), 1899.

[2] Gregory, H. E., U. S. Geol. Survey Prof. Paper 93, 1917.

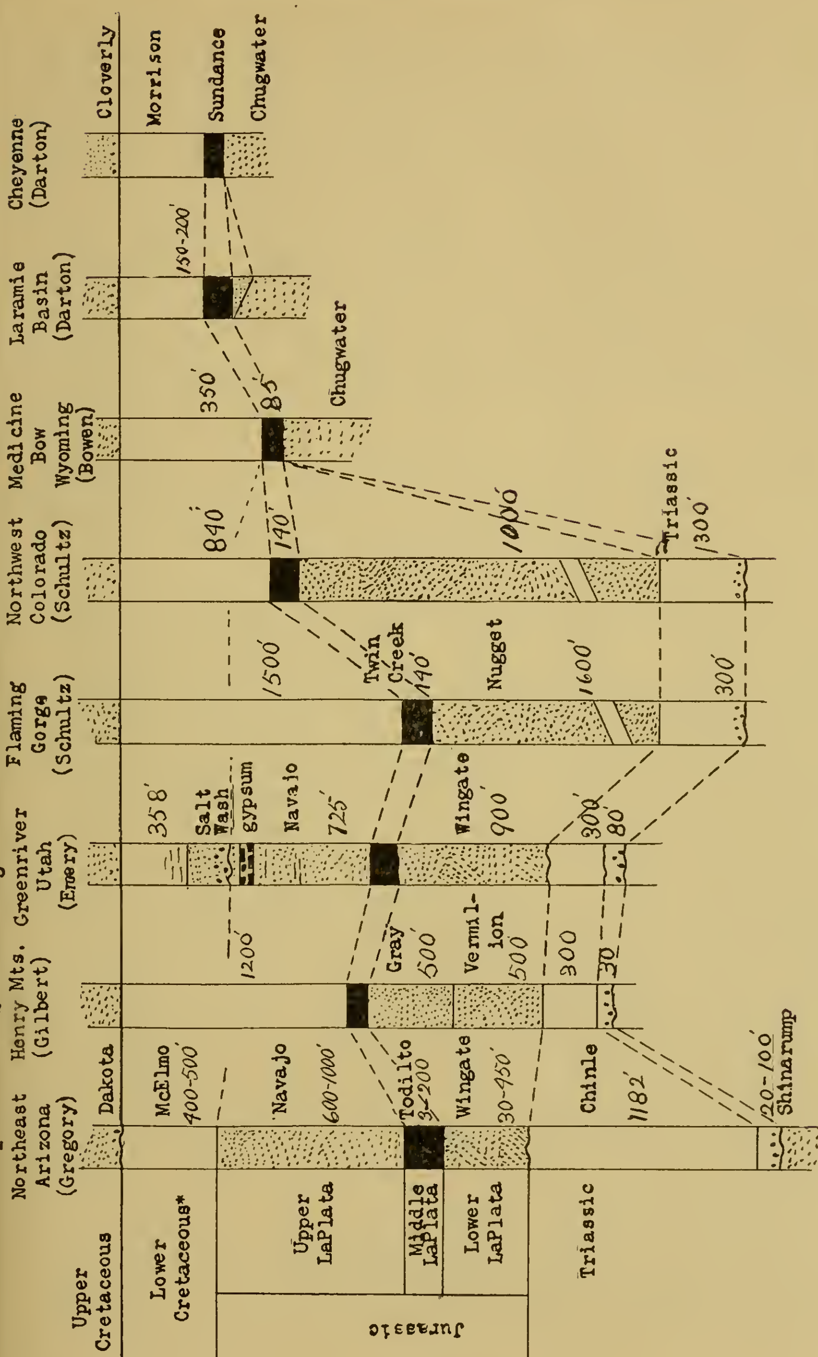

FIG. 2.—Group of columnar sections from Arizona to eastern Wyoming, showing correlations of sedimentary formations ranging in age from Triassic to Upper Cretaceous.

* The Morrison and McElmo formations are classed by the U. S. Geological Survey as Cretaceous (?).

tains, described by G. K. Gilbert, may correspond to the Wingate or Lower La Plata and the limestone above the Gray Cliff to the Todilto on the one hand and the marine Jurassic on the other. Equivalents of other formations seem to occur here, as shown in figure 2. They are described by Powell, Dutton, and others, as exposed continuously in the canyon walls northward as far as the Uinta Mountains.

Emery[1] recognized these subdivisions near Greenriver, Utah, where he correlates the marine Jurassic rocks with Todilto and the overlying sandstone with Gregory's Navajo and the upper sandstone of Cross' La Plata. These beds were both included in the McElmo by Lupton.[2] Still higher in the section is the conglomeratic Salt Wash member and overlying variegated beds. These contain fossil dinosaurs which seem to correlate them with the Morrison formation.

The occurrence of gypsum in this region above the supposed equivalent of the Navajo (see also the Castle Valley section, fig. 4, p. 17) is not easily explained unless there were two incursions of the Jurassic sea (see p. 27).

In northwestern Colorado, south of the Uinta Mountains, a similar section has been described by Gale,[3] who correlated the rocks below the variegated beds with La Plata and with White Cliff,[4] describing them as consisting, like the original La Plata, of two sandstones of equal thickness separated by shale. Marine fossils were found within the upper sandstone and also above it. The variegated beds are presumably the same as those from which the collectors for the Carnegie Museum secured dinosaurs of the Morrison type.

Schultz[5] has more recently examined the sedimentary rocks upturned around the Uinta Mountains, including those formerly examined by Gale. He measured a section near Flaming Gorge north of the mountains, and one at the eastern end of the Uintas in northwest Colorado. In both of these sections there are beds equivalent in character and position to the Morrison. Also in both there are beds several hundred feet thick between the Morrison and the marine Jurassic (Twin Creek) which may correspond to the Upper sandstone of the La Plata group. The cross-bedded sandstone (Nugget) below the Twin Creek obviously corresponds to Gale's White Cliff

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[1] Emery, W. B., Paper in preparation.
[2] Lupton, C. T., U. S. Geol. Survey Bull. 541, pp. 115-133, 1914.
[3] Gale, H. S., U. S. Geol. Survey Bull. 340, 1908.
[4] Gale, H. S., U. S. Geol. Survey Bull. 415, p. 51, 1910.
[5] Schultz, A. R., Unpublished manuscript.

and to lower La Plata. Still lower in the sections are beds lithologically like the Shinarump conglomerate and the Chinle formation.

East of the Uinta Mountains the rocks of Jurassic age are covered for many miles. But near Medicine Bow, Wyo., the variegated beds (Morrison) lie with apparent conformity on marine Jurassic (here called Sundance), and this in turn on Chugwater or typical "Red Beds." Apparently the La Plata group has no representative here unless the Sundance be included in that group.

In the Laramie Basin, Wyo., Morrison and Sundance are present. The Sundance is described as resting in some places on typical Chugwater, but in other places on beds which, although included in the Chugwater formation, are described[1] as not like Chugwater. Special attention is called to these because similar beds in several places farther south will be compared with them.

The section east of the mountains, near Cheyenne, differs from the Laramie Basin section only in the apparent absence of the beds between Sundance and Chugwater.

NORTHWEST COLORADO TO NORTHEAST COLORADO

Attention is next directed to a group of sections a few miles south of those last described, starting with northwest Colorado. Farther east, near Meeker, the variegated beds, which are doubtless equivalent to the Morrison, are separated from the typical "Red Beds" by sandstones, which Gale[2] regards as probably equivalent to his White Cliff (Nugget of Schultz), but no marine beds of Jurassic age were found.

In the vicinity of Encampment, Wyo.,[3] and a little farther south, near Hahns Peak, Colo. (Encampment section), the Sundance lies between Morrison and typical "Red Beds." There seems to be no representative of the La Plata sandstone. Still farther to the east in North Park, Colo., no representative of the Sundance was found, but a sandstone of variable thickness, which corresponds in character with the La Plata sandstone and with the unnamed beds between Sundance and Chugwater in the Laramie Basin section, occurs near the base of what Beekly[4] classed as Morrison. In the foothills

[1] Darton, N. H., *et al.*, U. S. Geol. Survey Geol. Atlas, Laramie-Sherman folio (No. 173), 1910.

[2] Gale, H. S., U. S. Geol. Survey Bull. 340, 1908.

[3] Spencer, A. C., U. S. Geol. Survey Prof. Paper 25, 1904.

[4] Beekly, A. L., U. S. Geol. Survey Bull. 596, 1915.

region east of the mountains yellow and pink sandstone, having a maximum thickness of 150 feet, occurs between the Morrison and the typical "Red Beds" at the horizon of the Sundance or near it, and Butler,[1] suggests that it may belong to that formation. In view of the relation of the La Plata sandstone to the marine beds as determined west of the mountains, it seems more probable that this sand-

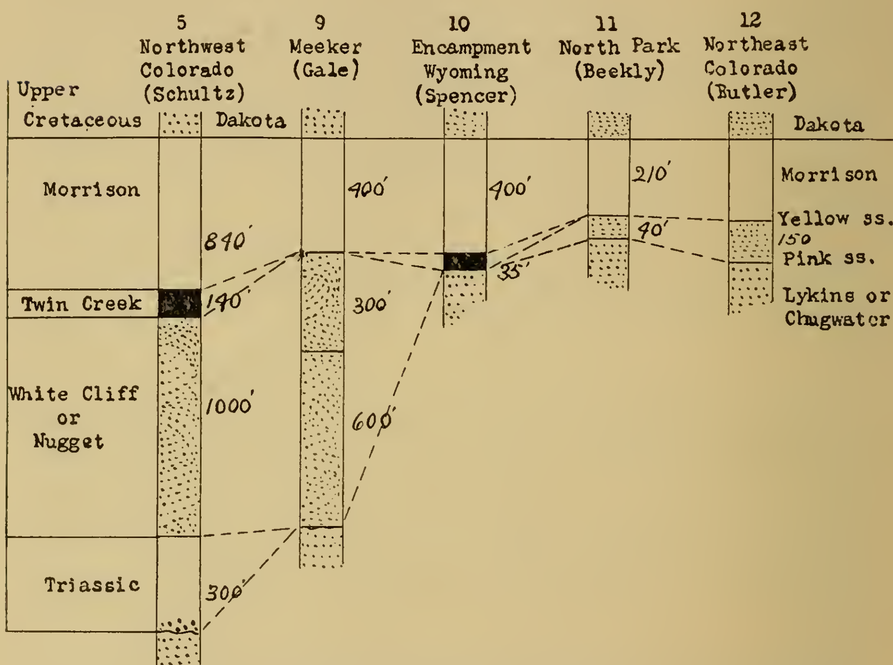

FIG. 3.—Group of columnar sections from northwestern Colorado to northeastern Colorado, showing the correlations of formations ranging in age from Triassic to Upper Cretaceous. (For location of sections see fig. 1, p. 11.)

stone is equivalent to the unnamed sandstone of the Laramie Basin section lying below the Sundance and to some part of the La Plata sandstone.

CENTRAL UTAH TO DENVER, COLORADO

A series of sections from central Utah eastward to Denver, Colo., shows relationships somewhat similar to those just described but differing from them in some ways which are significant. The section in Castle Valley differs from that near Greenriver only in the greater

[1] Butler, G. M., Colorado Geol. Survey Bull. 8, 1914.

thickness of the formations. Similar formations have been observed from place to place between Greenriver, Utah, and Grand Junction,

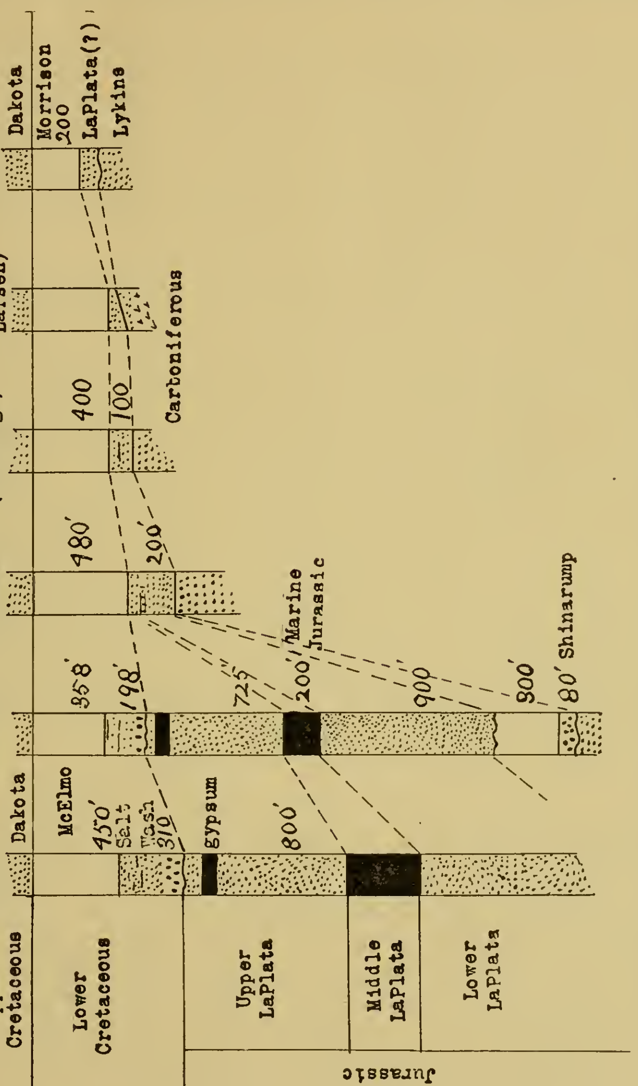

FIG. 4.—Group of geologic sections from eastern Utah to eastern Colorado, showing correlation of formations ranging from Triassic to Upper Cretaceous. (For location of sections see fig. 1, p. 11.)

Colo., where they constitute the Gunnison formation.[1] The upper part of the Gunnison consists of variegated beds similar to the Morrison, and by means of dinosaurs found in these upper beds near

[1] Lee, W. T., U. S. Geol. Survey Bull. 510, 1912.

Fruita, Colo., they have been correlated with the Morrison. The lower part of the Gunnison near Grand Junction consists of flaggy sandstones with a few layers of limestone, and rests unconformably on "Red Beds" supposed to be of Carboniferous age. This lower part of the Gunnison is doubtless equivalent to some part of the La Plata group. Farther to the east, near Crested Butte, a white sandstone near the base of the rocks there classed as Gunnison probably represents the La Plata, for in the same general region Cross and Larsen,[1] the former of whom originally named and described the La Plata, recognized it east of the town of Gunnison, where it overlaps the older sedimentary rocks onto the Archean.

The Dakota and Morrison formations are present in the intermontane basins, such as Middle Park and South Park, although little is definitely known about their relations there. But east of the mountains, at Morrison, Colo., is the type locality of the Morrison formation. Between this formation and the underlying "Red Beds" (Lykins), formerly called "Upper Wyoming," there are beds of sandstone and limestone which have been included in the Morrison, but which are lithologically different. Butler[2] has suggested that these may represent the sandstones farther north (northeast Colorado section), which he correlates with the Sundance. I am inclined to regard them as the attenuated edge of the Nugget or lower La Plata sandstone. It seems probable that the limestone and gypsum at or near this horizon farther south[3] may represent the extension of the Jurassic sea beyond the localities where its waters were suitable for the support of marine organisms.

NORTHERN ARIZONA TO SOUTHEAST COLORADO

Relations still farther to the south are shown by sections situated along a broken line extending from northern Arizona eastward to Purgatoire Canyon in southeast Colorado. The Rico and Ouray sections are essentially the same as the La Plata section at the type locality of the La Plata sandstone. A significant feature in this southwestern area is the limestone and calcareous shale of the middle of the La Plata group. Near Telluride,[4] situated between Rico and

[1] Cross, Whitman, and Larsen, E. S., Washington Acad. Sci. Jour. vol. 4, p. 237, 1914.

[2] Butler, G. M., Colorado Geol. Survey Bull. 8, 1914.

[3] Richardson, G. B., U. S. Geol. Survey Geol. Atlas, Castle Rock folio (No. 198), 1915.

[4] Cross, Whitman, U. S. Geol. Survey Geol. Atlas, Telluride folio (No. 57), 1899.

Ouray, the limestone is described as 6 to 16 feet thick and varies in character from black and massive to thin-bedded and shaly. Near Placerville, situated in this same general region, the limestone between the two sandstones of the La Plata is described orally by Frank L. Hess, who has examined it, as consisting of small masses which seem to occupy channels eroded after the lower La Plata sandstone was formed. Still farther to the north, according to members of the Colorado Survey (personal communication), the upper sandstone of the La Plata group is absent in some places. The formations included in these sections have been identified by Gregory in Arizona, as shown by the lines connecting the Arizona and Rico sections in figure 5, and Cross and Larsen have traced them eastward to the base of the Rocky Mountains. In Piedra Valley in southern Colorado [1] these observers recognized the two sandstones of the La Plata group, separated by dark-colored thin-bedded bituminous limestone having a maximum thickness of 30 feet. In some places this limestone is distinctly brecciated. The lower La Plata is normal in thickness and character and overlaps older sedimentary beds onto the Archean. The upper sandstone of the La Plata group is absent in some places.

Still farther to the southeast, on Chama River, N. Mex., the upper La Plata seems to be represented by 75 feet of sandstone, the middle La Plata by a bed of gypsum, and the lower La Plata by the Wingate sandstone.[2] This section may be regarded as characteristic of the western foothills region of southern Colorado and northern New Mexico. Similar beds outcrop in the foothills east of these mountains. In the Pueblo section, which has been selected to represent this eastern region, all rocks between the Purgatoire and the underlying " Red Beds " were formerly classed as Morrison.[3] However, beds of gypsum in the lower part of these rocks may represent the marine Jurassic to the north and the middle La Plata to the west. If the stratigraphic relations have been correctly interpreted here, the Morrison of the Pueblo region overlaps Carboniferous beds (Fountain) onto the Archean.

In Purgatoire Canyon in southeast Colorado the Morrison is present and in some places, but not in all, there are thick beds of gypsum between it and the typical " Red Beds." I described this gypsum

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[1] Cross, Whitman, and Larsen, E. S., Washington Acad. Sci. Jour. vol. 4, p. 237, 1914.

[2] Darton, N. H., Unpublished manuscript.

[3] Gilbert, G. K., U. S. Geol. Survey Geol. Atlas, Pueblo folio (No. 36), 1897.

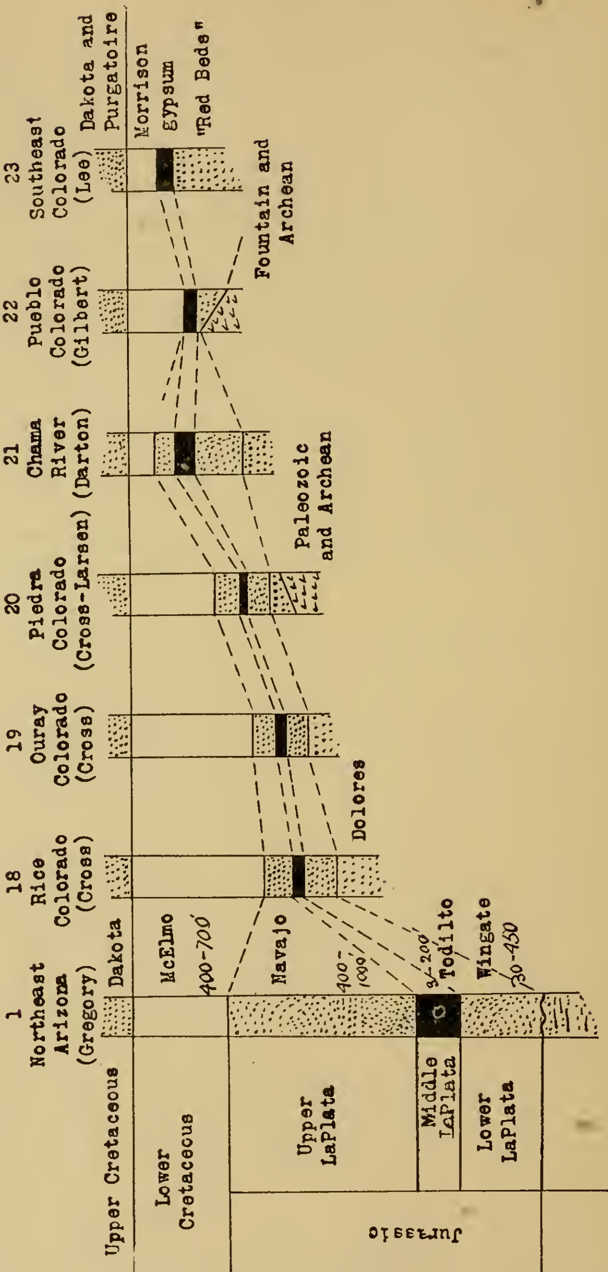

FIG. 5.—Group of geologic sections from northeastern Arizona to eastern Colorado, showing the correlations of formations ranging in age from Triassic to Upper Cretaceous. (For location of sections see fig. 1, p. 11.)

several years ago[1] as a part of the "Red Beds," but on further study I am inclined to believe rather that the gypsum is of the same age as that which occurs in the middle of the La Plata group in many places in southwestern Colorado and northern New Mexico.

SOUTHERN UTAH TO NORTHEASTERN NEW MEXICO

The southernmost group of sections here described extends from northern Arizona, where Gregory has correlated the formations with those of the type locality of the La Plata, westward through Utah and eastward through New Mexico. The Shinarump conglomerate is a persistent and easily recognized stratum and forms a convenient datum plane for grouping the sections of Utah and Arizona. The overlying beds of Triassic age (Chinle) were eroded and later covered with the sands of Vermilion Cliff and White Cliff. These sandstones have been supposed to constitute two separate formations, the older one of Triassic and the younger of Jurassic age. They are separated in some places, but not in all, by shaly beds, but the horizon of the shaly parting seems to vary from place to place. Also the color of the sandstone is variable, the white of the upper sandstone disappearing entirely in some places where the brilliant colors of the Vermilion Cliff extend to the top of the sandstone. Gregory[2] correlates the Todilto of northwest Arizona with the shaly beds which separate the Vermilion Cliff from the White Cliff in the canyon walls along Colorado River. On the other hand, Emery recognizes the marine Jurassic of the Greenriver region, which is above the White Cliff sandstone as probably the Todilto of the Arizona section. But the marine Jurassic of southern Utah is also above the White Cliff, hence the question arises again, Are there two marine Jurassic horizons or is the Todilto of Arizona to be correlated with the marine beds of Utah, as indicated in figure 6, rather than with the shaly beds lower in the sections.

Less uncertainty exists in the correlation of the Arizona section with those of northern New Mexico and southern Colorado. According to Gregory the tripartite division of the La Plata group is even more conspicuous in Arizona than it is in southern Colorado. The Wingate sandstone is traceable eastward to Thoreau in New Mexico, and the Navajo is probably equivalent to the two sandstones, 290 feet thick, of the Thoreau section which underlie the variegated beds.

[1] Lee, W. T., Jour. Geol., vol. 9, pp. 343-352, 1901.

[2] Gregory, H. E., U. S. Geol. Survey Prof. Paper 93, 1917.

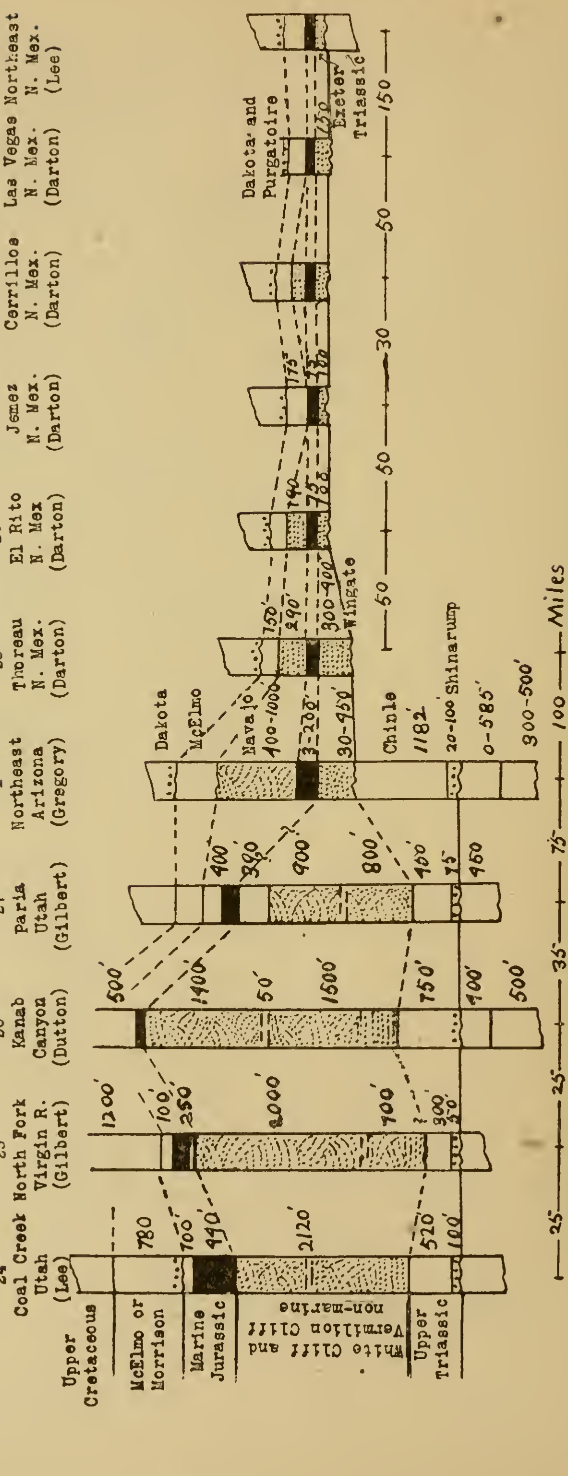

FIG. 6.—Group of geologic sections from southern Utah to northeastern New Mexico, showing the correlation of formations ranging in age from Triassic to Upper Cretaceous. (For location of sections see fig. 1, p. 11.)

The Todilto is represented in western New Mexico by a thin limestone which is described as appearing "singularly out of place" between two massive sandstones.

Farther to the east this limestone is recognized as the peculiar bituminous shaly limestone which underlies the gypsum of the El Rito section, with typical Wingate sandstone below it and another sandstone above.

Still farther east, near Jemez, N. Mex.,[1] the limestone and gypsum appear above the Wingate, but no equivalent of the Navajo is found unless it is included in the lower part of the beds here classed as McElmo. However, near Cerrillos, south of Santa Fe, and also in the Sandia Mountains, east of Albuquerque, the gypsum, limestone, and Wingate sandstone are typically developed, according to Darton, and between the gypsum and the overlying variegated beds are rocks composed chiefly of pink and yellow sandstone which may represent upper La Plata. These beds east of the Rio Grande are separated from those farther to the west by a covering of younger rocks, and the correlations must be made chiefly on lithologic similarity of beds and on sequence of formations.

About 25 miles east of the point where the Cerrillos section was measured, and a few miles south of Lamy, N. Mex., a sandstone between typical "Red Beds" and typical Morrison (pl. 2, fig. 1) is regarded as Wingate by Darton, although no gypsum has been found above it. However, still farther to the east, near Las Vegas, N. Mex., the sandstone which holds the same relative position has a thin limestone above it, which is described as being the same as that which caps the Wingate sandstone of localities farther to the west. This limestone separates the sandstone from the Morrison and there seems to be no room here for an equivalent of the upper La Plata sandstone. Darton regards the sandstone as equivalent to the Wingate, although in the Santa Fe guidebook[2] it is labeled Triassic (?). On the other hand, I became convinced some years ago, while working in that part of the country, that this sandstone is the same as the Exeter sandstone (pl. 3, fig. 1) of northeastern New Mexico which I then referred with the query to the Triassic.[3] Like the Wingate, this sandstone is overlain at its type locality by limestone and gypsum, but unlike the Wingate it is variable in thickness and is entirely absent in some

[1] Darton, N. H., Manuscript in preparation.

[2] Darton, N. H., U. S. Geol. Survey Bull. 613, fig. 13, 1915.

[3] Lee, W. T., U. S. Geol. Survey Bull. 389, 1909.

places. In the canyon of the Dry Cimarron, in northeastern New Mexico, it rests with angular unconformity on the older "Red Beds." Inasmuch as recent investigations tend to show that the Exeter may be equivalent to the Wingate, it seems advisable to class it as Jurassic, rather than Triassic.

In brief, the Wingate of Arizona and New Mexico seems to be the southward extension of the lower sandstone of the La Plata group, and this sandstone is traceable eastward to the Rio Grande. East of that river and on both sides of the Rocky Mountain axis a sandstone of similar character and holding the same stratigraphic position seems to be equivalent to typical Wingate and lower La Plata. It occurs in many places, but not in all, as far east as Oklahoma.

The middle La Plata or Todilto is traceable by means of the limestone and gypsum eastward to the Rio Grande and is recognizable by peculiar lithologic characters in many places farther east. It seems probable that the limestone and gypsum east of the mountains above the Exeter sandstone denotes the same horizon. The gypsum is not continuous for great distances. It occurs in more or less restricted lenses. The thin limestone underlying it is more persistent and occurs in places where there is no gypsum.

The upper La Plata (Navajo) seems to be less persistent than the lower formations of the group. It thins out in some places in the Zuni Mountain region of western New Mexico and has not been found near Jemez. It seems to have a representative in the Cerrillos section, but has not been reported from localities farther east.

PREPARATION FOR JURASSIC SEDIMENTATION

The reduction of the ancient Rocky Mountains, which had been in progress during much of Permian and all of Triassic time, seems to have reached a stage of advanced peneplaination by the opening of the Jurassic period. However, the region was still above sea-level, and erosion continued during a long interval which, with minor interruptions, lasted through Jurassic and Lower Cretaceous time. During all of this time the greater part of the North American continent was above sea-level and exposed to erosion.

It seems desirable in this connection to attempt to picture the physiographic conditions in the Southern Rocky Mountain Province previous to Jurassic time. In my opinion, it is necessary occasionally, in order to obtain the best results, to stand off at a distance from a problem and take a comprehensive view of it in its relation to other problems. The constant tendency of the investigator is to confine attention to the minutiæ of his problem until he grows scientifically nearsighted and fails to see that some line of evidence other than his own may have an important bearing on his problem.

The meager information as to physiographic events in the Rocky Mountain region in late Triassic time is widely scattered through geologic literature. A brief summary is probably all that the present discussion calls for. Sedimentation which had been in progress both east and west of the mountains was terminated at the end of the period for some reason not now known and the Triassic rocks subjected to erosion. Before sedimentation was renewed in the Jurassic period this erosion appears to have reduced large parts of the region to a nearly level plain. It cut away the mountains, truncated domes and anticlines, and removed such large parts of the older sedimentary rocks that the sediments of the La Plata group were spread out on a floor consisting of all the older rocks of the region from Triassic down to Archean. This plain, completed over a vast area in early Jurassic time, may be called the *La Plata peneplain,* for on it the sediments of the La Plata group were laid down.

The peneplaination continued throughout Jurassic and Lower Cretaceous times in areas not covered by La Plata, the central portions of Colorado being the last of the uplands in the Southern Rocky Mountain Province to disappear. It was on the lowest parts of this peneplain that sediments began again to accumulate in late Jurassic time.

Farther west, Jurassic sedimentation began earlier, possibly at the beginning of the period, when the sands of the Vermilion Cliff began to accumulate in the old valley. By the time the accumulations had pushed across the valley to the present mountainous region of Colorado, the Jurassic period was well advanced, and only thin, isolated representatives of the La Plata sandstone were formed there.

JURASSIC DEPOSITS

Years ago the marine sedimentary rocks of late Jurassic age were regarded as the oldest representatives of the Jurassic system in the Rocky Mountain region, the underlying " Red Beds " being referred to the Triassic. But for several years there has been a growing tendency to include in the Jurassic system some of these unfossiliferous older rocks. In some places in the mountain region these are thin; in other places they are absent. But west of the mountains, rocks which seem to be the age equivalents of these thin beds are very thick and persistent over a large area. For this reason they must be considered in connection with those of the mountains proper. They constitute what is here called the La Plata group (see pl. 2, fig. 2). They occur principally in Colorado, eastern Utah, northern New Mexico and Arizona. The group takes its name from southwestern Colorado, where Cross[1] first studied and described the deposits as the La Plata sandstone. The original La Plata and its approximate age equivalents cover some such areas as that shown in the accompanying figure 1, page 11. It includes the White Cliff and Vermilion Cliff sandstones of Utah; the Navajo, Todilto, and Wingate of Arizona; the Wingate and other formations in western New Mexico; the Exeter sandstone of eastern New Mexico, and rocks in other places which have been grouped by some geologists with the underlying Triassic and by others with the overlying Morrison, but which are here regarded as being of essentially the same age.

The La Plata sandstone and the formations believed to be its age equivalents consist chiefly of massive cross-bedded, cliff-forming sandstone (see pl. 1). They contain a subordinate amount of shale, and in some places there are thin limestones which contain a few shells of fresh-water invertebrates. In the southern part of the area occupied by these deposits gypsum is abundant in the center of the group. The typical La Plata is prevailingly light-colored, but in northeastern Arizona and northwestern New Mexico its equivalent formations are red, and in northeastern New Mexico they are pink to buff-colored. In lithologic character and stratigraphic position the White Cliff and Vermilion Cliff sandstones correspond closely with lower La Plata, but there seems to be lack of general agreement as to their exact correlation. Some facts seem to indicate that these correspond to the two sandstones of the La Plata group; others, that they represent only the lower sandstone, and are together equivalent to the Wingate—a view which I am inclined to advocate after seeing them in southern Utah. There is further disagreement as to the relations in northern Colorado and Utah, some geologists correlating the cliff-making sandstone (White Cliff of that region which some call Nugget) with La Plata as a whole, others with lower La Plata only. The correlation embodied in figure 2, page 13, harmonizes with the known facts.

Emery,[2] who is familiar with the formations in the Navajo country in Arizona and who has recently (1917) examined the similar forma-

[1] Cross, Whitman, U. S. Geol. Survey Geol. Atlas, La Plata folio (No. 60), 1899.

[2] Emery, Wilson B., Manuscript in preparation.

tions in eastern Utah recognizes near Greenriver the equivalent of the Wingate—called White Cliff in this region by some geologists and La Plata by others; the Todilto, which is here gypsiferous and contains marine Jurassic invertebrates; and an equivalent of the Navajo, formerly included in the McElmo of this region. My own observations in southern Utah in 1917 convinced me that the Vermilion Cliff and White Cliff sandstones are essentially one great formation. There is little difference between them except in color, and this distinction sometimes fails, for in some places the sandstone is all red. Also, while there is often a shaly division, it is not obvious that the shale is at the same horizon in all places. Furthermore, the fossiliferous marine Jurassic limestone and associated gypsum is above the White Cliff sandstone of southern and eastern Utah.

The possible correlation of Todilto with the marine Jurassic, as indicated in figures 2 and 6, is made on the assumption that there was only one invasion by the Jurassic sea. A suspicion has been entertained by some geologists that there were two invasions by this sea, separated by a relatively short interval of time. The Ellis formation in Montana has been regarded as the time equivalent of the Sundance in Wyoming. Recently some of the fossils from these formations have been critically examined by John B. Reeside, Jr., who has kindly permitted me to examine his manuscript. He concludes that the Ellis is older than the Sundance, the former corresponding to the Lower Oxfordian and the latter to the Upper Oxfordian of Haug.[1] Another suggestion of two separate invasions is derived from the descriptions by Mansfield and Roundy,[2] who find in southeast Idaho marine Jurassic fossils at two horizons separated by an unconformity and by more than 1,000 feet of unfossiliferous sandstone.

It seems fairly certain that the limestone and gypsum in northern New Mexico which are correlated with the Todilto formation were deposited in sea water. If Gregory's correlation of the Navajo and Grand Canyon sections is correct, these beds (Todilto) are represented by shaly beds about 1,000 feet below the marine Jurassic of the canyon region. If, on the other hand, there was only one incursion of the Jurassic sea it seems probable that the Todilto is equivalent to the marine Jurassic beds which overlie the White Cliff, and that the correlation shown in figure 6, page 22, is correct.

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[1] Haug, Emil, Text, p. 998.

[2] Mansfield, G. R., and Roundy, P. V., U. S. Geol. Survey Prof. Paper 98, p. 81, 1917.

All things considered, it seems probable that in spite of the great difference in thickness the Vermilion Cliff-White Cliff sandstone is equivalent to Wingate or lower La Plata; the marine Jurassic to Todilto; while the upper La Plata has been included in McElmo in some places and was eroded away in other places before McElmo time.

Much might be said of the rocks in other places, which are here included in the La Plata group. But in this paper a tedious review may be omitted, with the statement that I have consulted every available source of information and embodied the results in the correlations shown in the accompanying figures. In brief, the sedimentary rocks of Jurassic age are very thick in the plateau region of Utah and thin eastward. The evidence tending to prove that the sandstones originated largely as wind-blown deposits is in harmony with the supposition that the material came from the newly formed mountains to the west and gradually thinned toward the east.

SIGNIFICANCE OF LOWER LA PLATA CONTACT

In southwestern Colorado the La Plata sandstone rests unconformably on the Dolores formation which is classed as Triassic and which has a known range in thickness from something more than 1,700 feet to 100 feet or less. Similar relations obtain in northeastern Utah, but in southern Wyoming (fig. 2) marine Jurassic rocks rest unconformably on Chugwater, which is classed by some geologists as Triassic and by others as Permian. In northern, central and southern Colorado west of the Rocky Mountains, rocks correlated with the La Plata rest unconformably on "Red Beds" and overlap these onto the Archean. Also east of the mountains, sandstones which may be age equivalents of the La Plata overlap Triassic and older rocks down to the Archean. It is obvious therefore that there is a broad, well-defined plain of unconformity here called the La Plata peneplain separating the La Plata group from older formations.

It is further obvious that the few feet of Jurassic strata in the Rocky Mountain region cannot represent the entire time required for the accumulation of the deposits of this age in Utah which are more than 3,000 feet thick (fig. 6, p. 22). The thinning of the rocks eastward points to a western source of the sediments, and the fossils of the marine beds above the White Cliff denote late Jurassic time. It is therefore probable that the upland deposits—such as the sand of the Vermilion Cliff and White Cliff sandstones—accumulated in early or middle Jurassic time, while the areas farther east were still undergoing erosion, and that the deposits spread eastward as time went on until this upland deposition was interrupted by the invasion of the sea. There is reason, therefore, for correlating the Wingate sandstone with both the White Cliff and Vermilion Cliff sandstones. There is equally good reason for believing that the unconformity at the base of Vermilion Cliff, the only obvious unconformity between the rocks of undoubted Triassic age and the marine Jurassic in Utah, is the westward extension of the great unconformity now well known at the base of the La Plata group in Arizona, New Mexico, and Colorado.

If the correlations as outlined are correct, it seems probable that most of the material constituting the La Plata group was derived from the highlands in western Arizona, Nevada, and neighboring regions. The thinning of the La Plata where it overlaps onto the Archean in the Rocky Mountain region in central Colorado seems to prove that such lands as existed there at that time were so low that they furnished little sediment. It follows that the mountains in Colorado which had furnished the great quantities of coarse material for the older "Red Beds" had been reduced to a peneplain before La Plata time.

The old valley in which the sediments of the La Plata group accumulated was partly filled with sand and depressed so that the surface was near sea-level in late Jurassic time and may or may not have been occupied by a trunk stream. It lay so low that a slight rise of water level caused the marine waters to spread out in it as a broad, shallow sea. It is not known how far this ancient valley-plain extended southward and eastward, but the great length of time that the western interior had been subjected to erosion was sufficient for the reduction to a low-lying plain of any mountains which may have existed.

I picture the physiographic conditions at the opening of La Plata time something as follows: The broad valley had developed during the early part of the Jurassic period between the ancient mountains of Colorado and the newly formed continental land mass farther west, somewhat similar to the Mississippi Valley of the present day. It may have been formed partly by subsidence, but it seems probable that it was an area cut off from the ocean by uplift to the west and later shaped by erosion. In few places unusual thicknesses of the sedimentary rocks seem to denote local basins caused by downwarping. But the uniform thickness of the sediments which were spread out over extensive areas on this plain proves that a large part of it was practically unaffected by warping during the deposition of the Jurassic sediments.

The old valley seems to have been so near sea-level that a slight land movement would shift the courses of the streams or even reverse the direction of their flow, much the same as a relatively slight movement now in central North America would modify the drainage between the Hudson Bay and the Gulf of Mexico. Except in a few localities where the sedimentary rocks of Jurassic age are thick, as previously noted, the uniform thinness of the marine Jurassic rocks (Sundance) indicates that the waters of the Jurassic sea spread out over a nearly level floor.

If the red color of sedimentary rocks and the occurrence of gypsum are sufficient indications of aridity, southwestern America had not recovered in La Plata time from the arid conditions that seem to have prevailed there in Permian and Triassic time. Indeed the strong colors of the Vermilion Cliff seem to have been responsible for the early reference of this sandstone to the Triassic system. It seems probable, however, that the arid conditions under which the sediments of the La Plata group gathered (pl. 1) were caused by the western mountains, as already suggested. For some reason not all of the sediments brought into this old valley in La Plata time were carried away. The physiographic conditions there may have been such as would obtain in the Mississippi Valley should the climate for any reason become so arid that the Mississippi River and its tributaries would be unable to transport the material delivered to them. The streams would then bring débris from the highlands and spread it out over the lowlands, there to be reworked by the winds and the local streams on a large scale. In this way relatively coarse débris is now being spread out in the bolsons of the semiarid southwest and in the "dead" valleys of the Great Basin. Perhaps still better illustrations of these conditions are to be found in the great deserts of North Africa, Asia Minor, and central Australia. To complete the picture the desert should be practically at sea-level and the water have easy access to it so that a slight subsidence of land or a rise of water level would shift the strand line far up the valley.

PROJECTION OF THE MARINE HORIZON BEYOND THE LIMITS OF THE FOSSILIFEROUS BEDS

Gypsum is commonly derived from sea water, and its occurrence in fossiliferous marine Jurassic rocks proves that conditions were favorable for the deposition of gypsum around the Jurassic sea. The gypsum in the unfossiliferous rocks is so near the same horizon as to render it probable that water from the Jurassic sea had access to localities beyond those where marine fossils have been found. Where tracing of the beds is possible, ultimtae correlations naturally will depend on detailed work. But in many places such tracing will not be accomplished for many years to come. Also there are places where tracing is impossible because of erosion or because of cover by younger rocks, and other methods must be employed. As gypsum is derived chiefly from sea water, it is difficult to understand where the gypsum which occurs above the White Cliff sandstone in Utah and above the Wingate sandstone in New Mexico came from if not from the waters of the Jurassic sea. The correlation of the gypsum beds above the Wingate sandstone in northwestern New Mexico and above the Exeter sandstone in northeastern New Mexico with the marine Jurassic beds is in harmony with the correlation of these two sandstones with sandstone below the marine beds in Utah and elsewhere. Also, by means of the gypsum below the Morrison, the correlation may be carried northward through regions east of the mountains where the Exeter is not known, to southern Wyoming, there to connect again with the marine Jurassic (Sundance). Gypsum occurs in many places east of the mountains in Colorado at or near the same horizon and so near the line of separation between the Morrison and the older formations that in the supposed absence of an intermediate division it seems to have been chiefly a matter of personal judgment whether it should be classed with the beds above it or with those below. The correlations here suggested indicate that the gypsum and associated rocks may be of Jurassic age and represent a distinct stratigraphic horizon between the Morrison and the underlying " Red Beds."

Throughout the region here described, the gypsum classed as middle La Plata occurs in relatively isolated bodies, as if it had been deposited in separate basins. There are several possible explanations for this manner of occurrence, four of which are suggested below.

(1) A continuous bed or series of overlapping beds of gypsum may have been formed and later cut away in some places by erosion. The lack of evidence of such erosion renders this explanation improbable.

(2) Gypsum derived from upland sources, as, for example, from the erosion or solution of older deposits, may have accumulated in inclosed basins in some such manner as gypsum beds are forming now in the vicinity of Alamogordo, N. Mex., where the gypsum is derived from older gypsiferous beds in the surrounding hills. The

extremely low relief of the region in Jurassic time renders this explanation improbable.

(3) Water of the Jurassic sea may have found its way into the lowest places on the partly submerged peneplain by more or less circuitous routes, and because of poor connection or perhaps because of intermittent connection with the sea, evaporated and deposited gypsum. Some of these partly inclosed arms of the sea must have received enough fresh water from the drainage of the surrounding country to prevent precipitation of gypsum, or even to keep the water essentially fresh, hence the occurrence of fresh-water limestone and non-gypsiferous clastic sediments in some places at a horizon which seems to be the same as that of the gypsum beds. The absence of salt from the gypsiferous middle La Plata indicates that concentration in the arms of the sea did not reach so advanced a stage as it did in the older seas in this region. In this connection it may be pointed out that some of these arms should have contained water suitable for the marine life that flourished in the main body of the sea. Doubtless the boundary of this sea, shown in figure 1, p. 11, will be extended as new information is obtained, and it is possible that careful examination will disclose the presence of marine fossils where they have not yet been found.

(4) The gypsum deposits, although at nearly the same horizon, may differ slightly in age, and the several deposits represent temporary basins partly or wholly cut off from the broad but very shallow sea. Such basins would be formed readily on the partly submerged peneplain by slight warping of the surface; by sand bars; by vegetable growth; or in other ways.

Little need be said in this connection of the occurrence of limestone where marine fossils are found nor of the ordinary fresh-water limestone which occurs in thin beds in the La Plata group and in the McElmo formation. But there are some limestones which are quite different from the others, in that they are dark-colored and bituminous, and which by reason of their peculiar nature are easily recognized. They seem to be confined to a very narrow zone and hence are valuable horizon markers. The dark-colored limestone and limy shale occur in the middle of the La Plata group in southwest Colorado and are described as being easily recognized by their lithologic character. At the same horizon in southern Colorado, in Piedra Valley, this limestone is dark-colored and bituminous, and is shaly in some places and brecciated in others. Farther south in New Mexico a thin, dark-colored, bituminous, shaly limestone underlies the gypsum beds in many places, but occurs at some localities where the gypsum is absent. Darton found this limestone so persistent and its peculiar character so constant that it proved valuable in tracing the formations over wide areas. He describes its occurrence as far east as Las Vegas, N. Mex.[1] An impure limestone of somewhat different character occurs near the gypsum in northeast New Mexico.[2] Although this was examined long before there was any suspicion that special significance might be attached to it, it was found to be enough different from the limestones of the overlying Morrison to attract attention. It seems probable that by reexamination of sections described years ago, this limestone and gypsum horizon in eastern New Mexico and Colorado may be identified as middle La Plata in age.

INVASION OF JURASSIC SEA

EXTENT AS DETERMINED BY FOSSILS

The sea water entered the interior of the North American continent in late Jurassic time, submerging a large part of the Northern Rocky Mountain Province and extending southward through Utah to Arizona. The waters of this sea apparently represent the maximum submergence of land during the Jurassic period. It is possible, of course, that this advance of the sea water may have been due to a subsidence of land, but it is equally possible, and in my opinion more probable, that the submergence was due to a rise of sea-level and that the water flowed over the lower parts of the old valley in much the same way that a rise at the present time would cause the Gulf waters to submerge the lower part of Mississippi Valley.

The area covered by this Jurassic sea has been outlined by W. N. Logan[3] (fig. 1, p. 11) to include all localities where marine Jurassic fossils have been found. There is a tendency to assume that the boundary line marks the maximum extent of the sea, whereas in reality it denotes only the extent of fossiliferous strata. Sediments were probably accumulating under conditions which were not favorable for marine life, over a much larger area.

Relatively little can be learned now of the physiographic conditions west of this sea because of erosion since Jurassic time, but in the southern and eastern parts of the area occupied by it there is abundant evidence that the water spread out in a thin sheet over

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[1] Personal communication.

[2] Lee, W. T., Jour. Geol., vol. 10, p. 46, 1902.

[3] Logan, W. N., Jour. Geol., vol. 8, pp. 241-273, 1900.

a plain which was nearly level. The fossiliferous beds deposited in this sea in eastern Wyoming constitute the Sundance formation. These beds are uniformly thin over a large area. Even where the Sundance has not been clearly differentiated from the rocks above and below it there is little room for variation in its thickness within the region represented by the sections here described. There are many critical places for which no convincing descriptions are obtainable. Perhaps the most confusing of these are in eastern Utah, where gypsum occurs at two horizons nearly 1,000 feet apart. As the rocks of the lower horizon contain marine Jurassic fossils, they have been correlated with the fossiliferous and gypsiferous rocks elsewhere. But there remains the possibility that some of these beds elsewhere may represent the upper, rather than the lower, gypsiferous horizon.

It is possible, as already suggested (p. 27), that the difficulties in correlating these rocks with those of other regions may be due to the presence of marine Jurassic rocks at two horizons, whereas only one has been recognized.

DETERMINATION OF AGE

The Sundance fauna is described as similar to the Oxfordian fauna of Europe. On this basis the Sundance formation has been correlated with the Oxford, which in Europe represents a stage referred by some geologists to the base of the upper third of the Jurassic system and by others to Middle Jurassic. It has been said, therefore, that the Sundance belongs in the lower part of the Upper Jurassic or the upper part of the Middle Jurassic. If this correlation is correct and if the overlying or Morrison beds are Lower Cretaceous in age, as many geologists believe, evidence of a hiatus should be found at the top of the Sundance. But little evidence of such hiatus has yet been found unless the absence of certain beds, as indicated by the groups of sections, be accepted as evidence. The structural relations are such as would be expected if the Sundance were late Jurassic, formed near the close of the period. On the other hand, if the Sundance is represented by the beds in the middle of the La Plata group, and if any considerable part of the upper La Plata sediments accumulated after the retreat of the sea, the time of this accumulation must be represented by a hiatus at the top of the Sundance where upper La Plata is not represented.

In considering the evidence of a lapse of time between the Sundance and the overlying Morrison, the physical conditions of this region in late Jurassic time must be taken into account. From all that I have been able to learn the whole region was so near sea-level that an easily recognizable unconformity is not to be expected.

The fact that little evidence of a hiatus has been found between Sundance and Morrison is not proof either that there is or is not a hiatus. The problem must be solved on such broader considerations as change in general physiographic conditions, and their causes; changes resulting in differences in lithology, and in distribution of the formations; in overlap relations and in the presence of interwedging formations.

On the principle that a period ends with a maximum retreat of the sea, the Sundance of the Rocky Mountain region should hold a position in the time scale slightly below the theoretical upper limit of the Jurassic system, and there should be found evidence of a slight hiatus corresponding in time to the wedge of upper La Plata sandstone. This naturally raises a question as to the basis of correlation.

Comparison with formations previously described and classified calls up the question: What weight should be given in intercontinental correlation to similar fossil forms and to similar faunas; to identical species and identical faunas? The question is an old one and will probably never be answered to the satisfaction of all geologists. The uses and perhaps also some of the misuses of such data are familiar. One geologist places great weight on similarity of faunas, and another places little weight on this similarity. Some geologists maintain that the similarity of the Sundance fauna to the Oxfordian fauna is sufficient to fix the position of the Sundance in the time scale at the base of the upper third of the Jurassic system. Others admit that so far as the fossil evidence at present available is concerned, the Sundance might as reasonably be placed near the end as near the middle of the system; and that the two faunas are separated by such distances that differences in environmental conditions and barriers to migration might readily negative close correlation on the basis of fossils alone.

This naturally suggests the query, Can we find criteria for correlation that are more reliable than those derived from the fossils? One method has been proposed which seems attractive, but which in the opinion of many geologists has not yet been adequately tested. It is based on the well-known principle that a movement of any considerable part of the mass of the earth is likely to change the capacity of the ocean basins and therefore to shift the strand line. A disturbance in the solid mass of the globe in one place, such as the settling of an oceanic sector, will cause internal readjustments which will manifest themselves in one way or another at the surface in other places. The greater disturbances, which are appropriately recognized as introducing and terminating periods and systems, are likely to cause the most obvious movements of the strand line. It seems possible that a downward mass-movement may be compensated in part by the rise of a neighboring mass, but it seems improbable that such compensating movements would be so nearly equal that the strand line would remain unaffected. Inasmuch as the constant tendency of rock masses under the influence of gravity is downward toward the center of the earth, it is difficult to conceive of the actual (as distinct from apparent) upward movement of any great mass of the globe except as a result of some still greater mass-movement downward.

This is not the place to enter into a discussion of diastrophism. But there are some questions which refer to the cause of diastrophic movements and which bear so directly on the problems connected with the Jurassic marine invasion that it seems advisable to at least ask them, even though they cannot be answered. Were the great disturbances which caused the major fluctuations of sea-level, movements constantly in progress, or were they relatively short interruptions of a state of general repose in the mass of the earth? Locally applied, was the advance of the water into the Jurassic sea caused by subsidence in western North America, or was it caused by a decrease in the capacity of the ocean basins, due perhaps to submarine vulcanism or the discharge of sediments into the sea? Was the drainage of the sea due to a rise in western North America of the land which had previously subsided, or was it caused by an increase in the capacity of the oceans, due perhaps to subsidence of some part of an ocean bed? Are great land masses as fickle as some geologists are wont to suppose, rising and falling frequently, or are many of the supposed movements of land only apparent because of movements of sea-level? Was the Jurassic sea drained quickly, or did the retreat of its waters occupy an appreciable length of geologic time? To be still more explicit, was the sea advancing during all of lower La Plata time and retreating during all of upper La Plata time?

The Jurassic sea apparently represents the maximum advance of sea water over the North American continent and therefore the maximum rise of sea-level during the Jurassic period. But inasmuch as only small parts of the continent were covered, the transgression seems to have been a relatively small one. On the principle of wide uniformity of action, apparently necessary if diastrophic principles are to be of material use in long-distance correlation, a similar advance of the sea over the other continents should be found. The great development of the Jurassic system in Europe shows that large parts of that continent were under water during much of the period, but the greatest submergence seems to have been in late Jurassic time. E. W. Berry, who has recently reviewed the conditions in Europe during this time, is of the opinion[1] that the transgression of the Jurassic sea, which commenced at about the close of the middle Jurassic, reached its maximum extent in the Upper Jurassic (Kimeridgian stage), and that its subsequent withdrawal, which marks the close of the Jurassic period, was probably contemporaneous with the similar withdrawal of the Jurassic sea in western North America, and both series of events may have been the result of a common cause. In other parts of the world relatively small areas comparable in size with the Jurassic areas of North America were submerged also in late Jurassic time. (See fig. 341 of Haug's textbook.)

Also, attention may be called to the fact that the Jurassic seems to have been a period of general continental stability. There were land movements in places and some of these movements attained considerable importance, but the continents were chiefly above sea-level and subjected to erosion throughout the period. The Jurassic has been termed a period of repose in contrast to the Cretaceous, which as a whole was a period of diastrophic activity. If the continents were really as stable as they seem to have been, the marine invasion may have been due to a rise of sea-level. It seems reasonable to attribute this rise to the discharge into the basins of sediments derived from long erosion of the lands. It has been shown that the volume of land now above sea-level is sufficient to raise the level of the sea 650 feet. If the Jurassic was a period of world-wide continental repose, we may reasonably attribute the submergence of low-lying areas to a general rise of sea-level. Also, we may reasonably assume that aside from the effect of local warping of the surface, maximum submergence at widely separated localities denotes equivalency in time.

DRAINAGE OF JURASSIC SEA

Following this hypothesis still further, if the Jurassic submergence was due to transfer of rock waste from the land to the sea, with resulting rise of sea-level, what was the cause of the withdrawal of

[1] Berry, E. W., Personal communication.

the water? Also, did this withdrawal occur within the period or at its close? At this point a definite answer is needed to the question previously asked, Was the sea drained quickly or slowly? If the Jurassic was a period of continental repose, it would seem appropriate to regard any diastrophic movement which had sufficient magnitude to cause the drainage of the submerged portions of the continents, as appropriately marking the close of the period. It seems probable that the draining of the sea was due to the first or introductory movement—perhaps a relatively slight one—of the diastrophism which characterized the Cretaceous period.

In western North America the Jurassic period was closed by crustal movements called the Sierra Nevada disturbance by Schuchert; the Sierra Nevada movement by Whitney; the Nevadian movement by Blackwelder; and the Cordilleran revolution by Smith. It seems probable that the Jurassic movement to which S. F. Emmons[1] ascribed the expulsion of the Jurassic sea from the Rocky Mountain region was part of this diastrophic movement which closed the period; for there seems to be good reason for doubting that this so-called Jurassic movement was a local movement of land in the Southern Rocky Mountain Province. The draining of the sea may have been due to a general lowering of sea-level, caused perhaps by the sinking of some part of an ocean basin. And it seems reasonable to believe that this movement was a part of the diastrophic disturbance which terminated the long period of continental repose and introduced the equally long period of diastrophic activity which followed. If the land in the Southern Rocky Mountain Province was elevated at all, the elevation must have been slight. The sediments of the Morrison formation were spread out over a nearly level plain only slightly above sea-level and nearly 1,000 miles long and 500 miles wide. It is inconceivable that the nearly base-leveled area covered by the Jurassic sea could have been elevated to any great extent and then have settled back to form the extremely regular surface on which the Morrison sediments were deposited. Such a plain could have been formed only under the gradational processes of standing or running water. In this, as in the maximum advance of the sea, there seems to be an analogy between America and Europe, for in Europe the period is described as closing with a retreat of the sea from the continent without notable disturbance of land.

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[1] Emmons, S. F., U. S. Geol. Survey Mon. 27, p. 21, 1896.

SUMMARY OF PHYSIOGRAPHIC CONDITIONS IN LATE JURASSIC TIME

I picture the physiographic conditions of this time something as follows: The Rocky Mountain region had become degraded in late Jurassic time to a peneplain so low that it furnished little sediment. West of the present mountain system the broad valley previously developed had been filled chiefly with sand (lower La Plata) and graded so that its surface was a continuation of the peneplain. This sand brought from the western mountains thinned out toward the east, where it accumulated only locally in the low-lying portions of the Southern Rocky Mountain Province, the beds thinning out in some places on the slopes of the higher portions.

These deposits now constitute the lower sandstone of the La Plata group—that is, the Vermilion Cliff, White Cliff, Wingate, Exeter, and possibly other sandstones of the eastern foothills region, which have been included by some geologists in the "Red Beds," and by others in the Morrison. These continental deposits seem not to have extended northward far into Wyoming.

At a slightly later date, if not during the time these continental deposits were accumulating, the marine waters entered the old valley from the north and spread over the lowest portions of the area formerly occupied by the ancient Rocky Mountains. In Wyoming the sea covered the eroded surface of the older "Red Beds," but in Utah and western Colorado it covered the older non-marine deposits of Jurassic age. Water suitable for the support of marine animals probably extended southward as far as Arizona and spread over some such area as that shown in figure 1. Sea water, which by evaporation became too saline for these animals, extended farther south and east over the lower parts of the peneplain and gathered in partly inclosed shallow basins or "pocket seas," where they deposited gypsum in much the same way that saline deposits are being formed now in some parts of Great Salt Lake. Doubtless there were many of these pocket-seas formed by local warping of the surface and in other ways, in which concentration of water did not reach the degree at which gypsum may be deposited. In still others the supply of fresh-water was sufficient to expel the marine. In such basins limestone formed. In some places the presence of fossils proves this to be fresh-water limestone, but in most places no fossils of any kind are found in it. It is a matter of observation that at some localities this limestone occurs at the same general horizon as the gypsum. No gypsum is present in the layers with the marine fossils, although these layers may occur below or even be interbedded with the gypsum. Careful observation is needed to determine, first, whether the unfossiliferous limestone is, in fact, of fresh-water origin and, second, whether it is actually at the same horizon as neighboring beds of gypsum. It is conceivable that bodies of fresh water and of salt water existed side by side. It is also conceivable that the bodies of shallow water shifted from place to place as the surface was built up.

If the significance of the gypsum is correctly interpreted, the saline water extended south into New Mexico and east over much of central and eastern Colorado. Because of later erosion, it is not possible now to determine how much of the present mountainous region was covered by it, but the occurrence of the gypsum on both sides of the Rocky Mountains indicates that the marine water may have covered considerable portions of the present mountainous area. The large areas where no La Plata rocks are known render the occurrence of Jurassic " islands " possible. Also, because of erosion, the maximum southern extent of the sea cannot now be determined and because of cover by younger rocks its eastern extent is not known.

It is not easy to picture the physiographic conditions of the Southern Rocky Mountain Province in late Jurassic time. I doubt if there is an area of any considerable size in the world to-day that exhibits an approximation to them. The whole province seems to have been so far degraded that a change of a few feet in the water level of the sea would have shifted the strand line many miles. An advance of the sea over such a peneplain would produce an intricate pattern of shallow, interlacing channels, bays, lagoons, gypsum pans, and salt marshes.

Continental deposits probably continued to accumulate around the sea during the whole period that it occupied the interior of the continent. Following its retreat they must have still continued to accumulate and to cover the marine beds in some places. These accumulations constitute the upper part of the La Plata group, which seems to form a wedge entering from the west and thinning eastward between marine Jurassic beds and those of the McElmo or Morrison formation. The rocks of this wedge are not as regular in thickness as those of the lower La Plata. They thin out to the south and east and also in some places in the midst of the area where the upper La Plata is typically developed. Where these beds are absent, the Morrison and its age equivalents rest on the marine beds or Sundance wherever this formation is present; on the beds of gypsum which are believed to be the age equivalents of the Sundance; or on still older rocks at localities where the marine Jurassic is not present. It seems reasonable to believe that the waters of the Jurassic sea may have been advancing up the old valley during the time that the sediments of the lower La Plata were accumulating; that the gypsum beds represent maximum extent of the sea water; and that the upper La Plata sediments accumulated as the sea was retreating. Hence the marine Jurassic beds, although relatively thin, may be partly equivalent in age to the sandstones of the La Plata group.

As gauged by the thickness of the sediments deposited in it, the sea occupied the Rocky mountain region only a short time. However, these deposits probably represent a longer time than would the same thicknesses of material deposited in a sea surrounded by higher lands. The country to the east of it seems to have been so near base-level that it furnished little detritus. This may explain in part the fact that the Sundance is all there is along much of the eastern margin of this sea to represent the thick Jurassic sediments which gathered farther west.

It was on the graded plain abandoned by the Jurassic sea and the peneplained area surrounding it that the streams of early Cretaceous time spread out the sediments of the Morrison formation. The story of this formation and its significance is well known [1] and that of the relation of the later Cretaceous formations to the Rocky Mountains has already been presented.[2] The papers describing these Cretaceous events, and the present paper, which should have been published first, give the sequence of events, as I picture them, by which the ancient Rockies were peneplained; submerged by the Cretaceous sea; and buried by its sediments, from which they finally emerged at the close of Cretaceous time.

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[1] See Geol. Soc. America Bull., vol. 26, pp. 295-348, 1915. Mock, Charles C., New York Acad. Sci. Annals, vol. 27, pp. 39-191, 1916.

[2] Lee, W. T., U. S. Geol. Survey Prof. Paper 95-C, 1915.

Wind-blown sand, old and new, near Tuba, Arizona, showing a recent accumulation of dune sand at the right, and at the left sandstone of La Plata group which is composed in part of ancient sand dunes consolidated into rock. Photograph by H. E. Gregory.

FIG. 1.—Wingate sandstone near Lamy, New Mexico. A massive light red sandstone about 100 feet thick, resting on beds of purple sandstone and shale. Photograph by N. H. Darton.

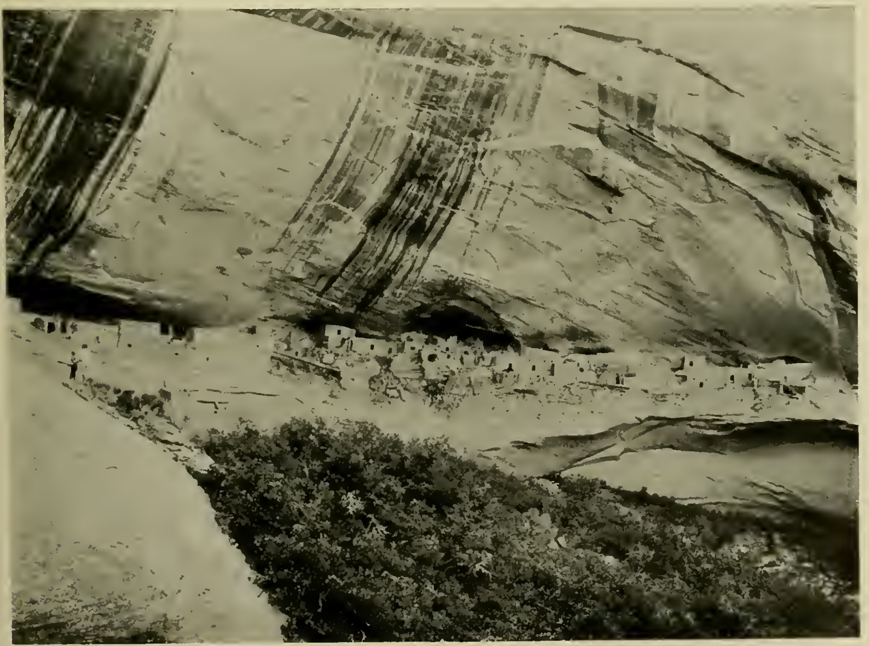


FIG. 2.—Rocks of La Plata group near Segi Mesas, Arizona, showing the Navajo sandstone above, the Wingate sandstone below, and the space from which the softer shaly beds of the Todilto formation has been removed, now occupied by an ancient cliff-dwelling known as the Keet Steel village. Photograph by H. E. Gregory.

FIG. 1.—Exeter sandstone in northeastern New Mexico, the supposed equivalent of the Wingate sandstone exposed in the south wall of the canyon of the Dry Cimarron, overlain by the Morrison and Purgatoire formations and Dakota sandstone. The sharp line at the base of the light-colored ledge is the unconformity separating the Triassic red beds from the Jurassic. Photograph by W. T. Lee.

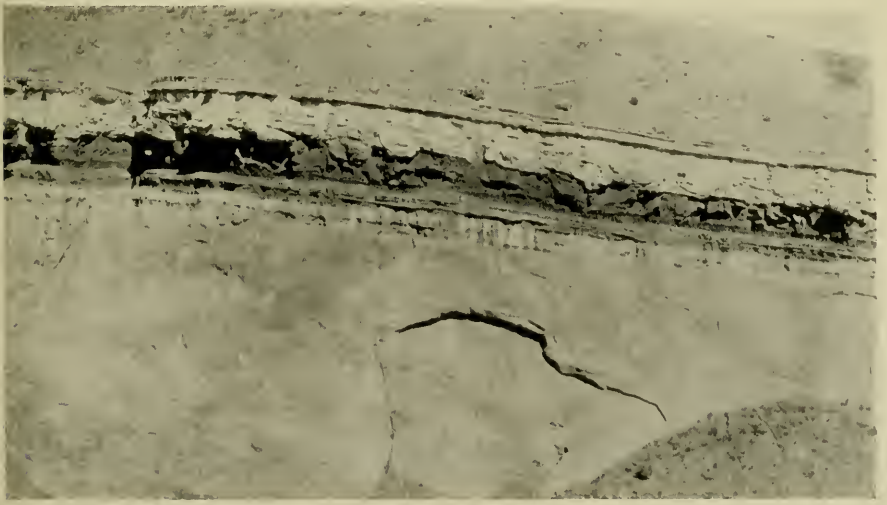
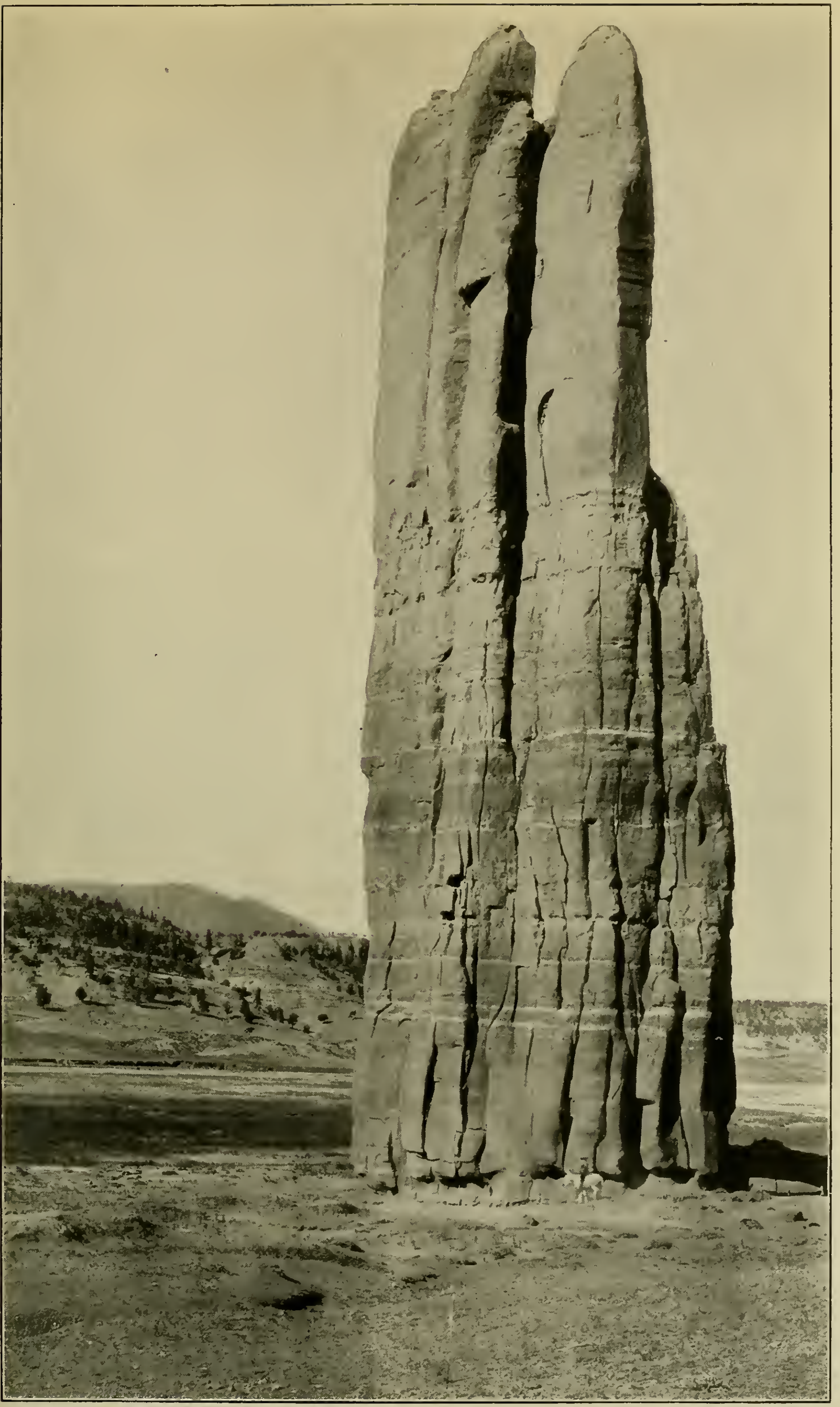


FIG. 2.—The Navajo-McElmo contact in northeastern Arizona, showing the Navajo sandstone below and the McElmo formation above, separated by 3 feet of sandy calcareous shale. Photograph by H. E. Gregory.



Venus Needle, Todilto Park, New Mexico. Column of sandstone of the La Plata group. Height may be judged by comparison with the horse at the base. Photograph by H. E. Gregory.