SMITHSONIAN MISCELLANEOUS COLLECTIONS
VOLUME 122, NUMBER 7

Charles D. and Mary Vaux Walcott
Research Fund

THE GEOLOGY OF CHACO CANYON NEW MEXICO

IN RELATION TO THE LIFE AND REMAINS OF THE PREHISTORIC PEOPLES OF PUEBLO BONITO

(WITH 11 PLATES)

BY
KIRK BRYAN

(PUBLICATION 4140)

CITY OF WASHINGTON
PUBLISHED BY THE SMITHSONIAN INSTITUTION
FEBRUARY 2, 1954

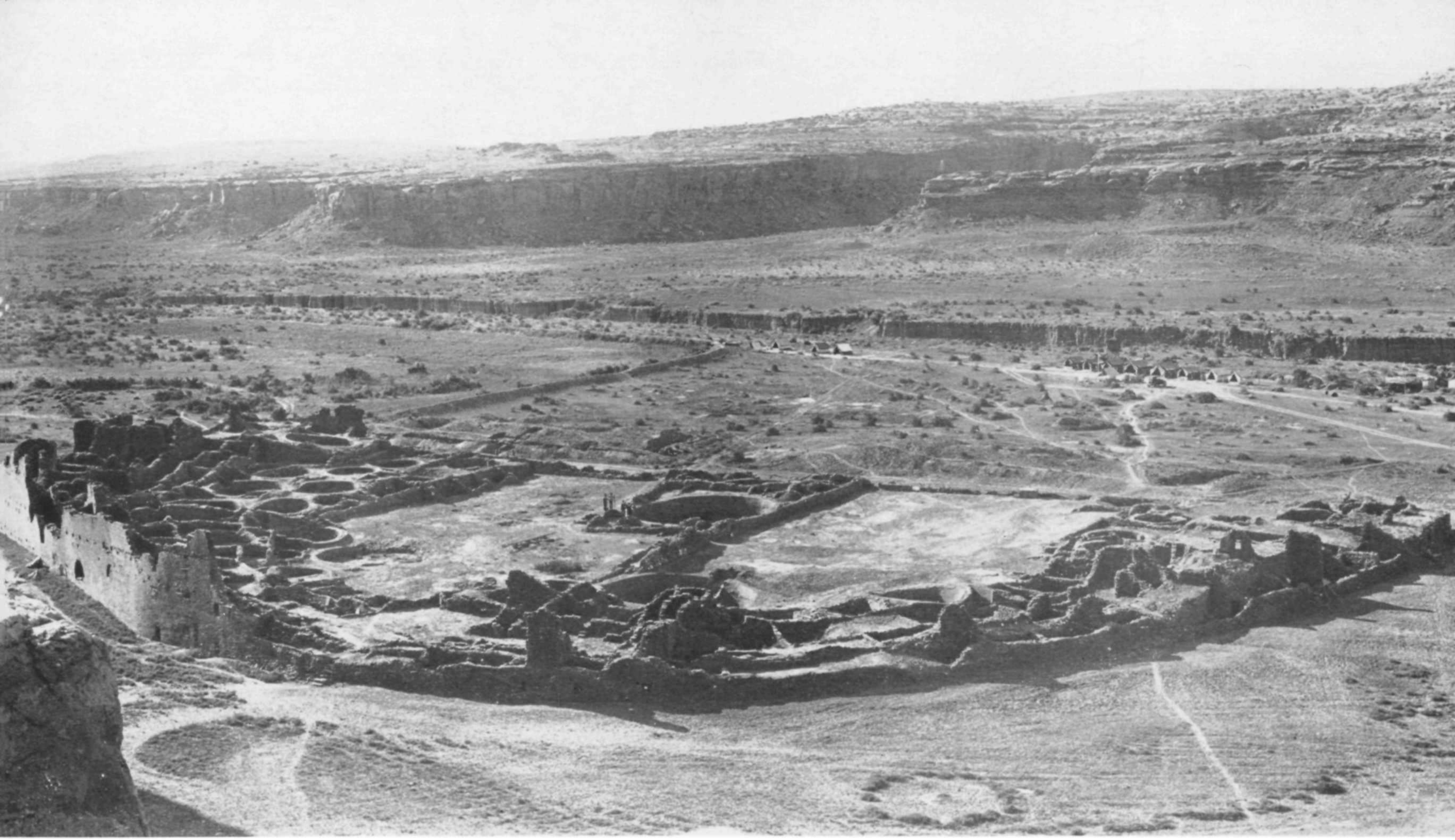

PLATE I

Pueblo Bonito from the north cliff. The east and west refuse mounds lie close beyond the ruin. At the left, the embankment of Wetherill's reservoir; at the right, midway between ruin and camp, a ring of dirt marks pit No. 3. (Photograph by O. C. Havens, 1924.)

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FOREWORD

The geology of Chaco Canyon in relation to its prehistoric inhabitants was a subject that greatly interested Kirk Bryan. Born and schooled in New Mexico, he had seen hundreds of ruined Pueblo villages, mostly abandoned before advent of the Spaniards in 1540, and had given much thought to the reasons behind their desertion. Warfare may have been one cause but it obviously was not the only one.

A geologist with the United States Geological Survey and engaged primarily in a study of groundwater resources of the Southwest, Dr. Bryan seemed to us especially qualified to seek out the factors that had invited, and then repelled, colonization of Chaco Canyon in the days of Pueblo Bonito. He accepted with enthusiasm our invitation to undertake this study but was able to devote only two brief vacation periods to field work, in the midsummers of 1924 and 1925. His observations in Chaco Canyon, admittedly incomplete, prompted like inquiries in other valleys during the decade that followed.

In 1926 Dr. Bryan left the Geological Survey to accept a call from Harvard University, and thereafter academic commitments and summers in the field allowed him but little leisure. In consequence, he never found an opportunity to finish this report on his Chaco Canyon researches. A first draft, dated March 1925, and written before his second visit to the canyon, was repeatedly revised and expanded as his continuing investigations annually provided new data. He appears to have made no change in the text after 1940. For these several reasons some sections of the report lack references to the more recent literature.

Following Dr. Bryan's untimely death in the summer of 1950, his unfinished manuscript was forwarded to me by Mrs. Bryan. I have undertaken to arrange its several parts in conformity with his original table of contents and to eliminate repetitions of subject matter and phraseology. The various stratigraphic columns Bryan examined and the course he plotted for an arroyo more or less contemporary with the decline of Pueblo Bonito are shown on the accompanying map of Chaco Canyon. Stratigraphic sections 10 to 23 were studied in 1925, but we have descriptions for numbers 15 and 17 only, and a third, without number but adequately located in relation to the expedition's camp.

Test pit No. 3, about midway between camp and the west refuse mound, was among those I had caused to be dug in 1922 in connection with an analysis of Chaco Canyon soils. When it was deepened three years later at Bryan's request and was found to penetrate the buried channel he was then trying to isolate, a common impulse was to extend the exploratory trench we had previously dug through the west refuse mound and thus reveal the original surface between buried channel and the old village dump. Pit No. 4, dug expressly for Dr. Bryan, was so named because of its proximity to his section 4, where the buried channel stood exposed near the southeast corner of Pueblo del Arroyo. Thus test pits 3 and 4 and the extended west-mound trench enabled Bryan to plot the course of that prehistoric arroyo as it passed Pueblo Bonito, and led to his search for traces of it as far east as Pueblo Wejegi. The extent of this ancient channel, together with evidence of alternating periods of erosion and sedimentation, formed the basis for Bryan's growing conviction that a slight change in climate was the most likely cause for disruption and dispersal of the Chaco Canyon population in the early twelfth century. His conclusion is certain to exert a profound influence upon future interpretation of past history in the Southwest.

I gladly acknowledge our obligation to Mrs. Kirk Bryan and to two of Dr. Bryan's former students, Dr. John T. Hack and Dr. Luna B. Leopold, both of the United States Geological Survey, for their cooperation in the preparation of this report. Two members of my Pueblo Bonito staff, O. C. Havens and Lynn C. Hammond, and several of our Zuñi workmen assisted Dr. Bryan in Chaco Canyon. The illustrations are mostly from photographs by Mr. Havens.

It was originally intended that this paper appear as fourth in the series reporting the results of the National Geographic Society's Pueblo Bonito Expeditions. But the series was discontinued after the first number, "Dating Pueblo Bonito and Other Ruins of the Southwest," by Dr. A. E. Douglass (1935). Early in 1953 the Society made the present manuscript available to the Smithsonian Institution, which proposed to publish it under the Charles D. and Mary Vaux Walcott Research Fund.

The life and achievements of Dr. Kirk Bryan are briefly reviewed by Frederick Johnson in American Antiquity, vol. 13, No. 3, p. 253, January 1951.

Neil M. Judd.
Leader of the National Geographic Society's Pueblo Bonito Expeditions.

Washington, D. C.
June 1953.

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THE GEOLOGY OF CHACO CANYON NEW MEXICO

IN RELATION TO THE LIFE AND REMAINS OF THE PREHISTORIC PEOPLES OF PUEBLO BONITO

By KIRK BRYAN[1]

(With 11 Plates)

INTRODUCTION

On the initiative of Neil M. Judd, leader of the National Geographic Society's Pueblo Bonito Expeditions, and on the recommendation of Dr. John C. Merriam, then president of the Carnegie Institution of Washington, the present writer was selected to undertake an inquiry into the geologic history of Chaco Canyon. Two brief periods were devoted to field work: July 28 to August 9, 1924, and July 10 to August 1, 1925. In the well-ordered camp of the expedition he was received with gracious hospitality, and to all members of the staff he owes much in kindness. Mr. Judd placed every facility at his disposal including a number of excavations especially designed to bring to light geologic facts and thus expedite the investigation.

Application of the stratigraphic methods of geology to archeological problems is no longer new, and knowledge of these methods forms a part of the equipment of every modern archeologist. Our inquiry into Chaco Canyon geology has proved (1) that the alluvial deposits of the canyon carry various relics of prehistoric peoples and (2) that the deposits can be separated into divisions of differing age. In recent years knowledge of these generalizations has become widespread and additional data have been gathered. It appears that we are now on the brink of establishing in the Southwest an alluvial chronology based on a sequence of episodes of erosion and alluviation. This sequence of geologic events gives a key to the fluctuations of climate of late geologic time and yields a proximate cause for the sudden decay of the great Pueblo communities of the San Juan country. (Bryan, 1941.)

[1] Dr. Bryan died on August 23, 1950.

Previous work on the general geology of this region is referred to hereinafter. During the summers of 1899 and 1901, Prof. Richard E. Dodge made a geological survey of Chaco Canyon as part of the extensive plans for the Hyde Exploring Expedition. His work was done after archeological excavation had ceased, and, unfortunately, his results were published only in skeleton outline in the report of the expedition (Pepper, 1920, pp. 23-25) and in three abstracts (Dodge, 1902a, 1902b, 1910). Even so, these brief sketches record a number of observations of interest that are referred to in the following pages. They indicate that Professor Dodge was on the verge of discovery and, with more archeological help, the geological theory herein set forth would doubtless have been advanced by him 20 years earlier. The 1877 observations of W. H. Jackson (1878) were keen and penetrating, and from exposures no longer visible he made the original discovery of the buried channel whose description and interpretation form such a large part of this report.

The long delay between initiation of this study and its publication has not been without advantage. During the interval we have learned that the geologic history of Chaco Canyon is not unique. Other valleys have similar histories, as will appear from the data on these other valleys summarized hereinafter. Generalizations on the cause of the alternations from erosion to alluviation and on the effect of these events on human affairs now rest upon a foundation of fact much larger than would have been possible in 1924 and 1925.

PLAN OF THE REPORT

This Chaco Canyon study was begun as an isolated project. It was an attempt to relate recent geology to the life of prehistoric peoples in the area. The results proved so successful, however, that other studies were subsequently undertaken. The alternate periods of alluviation and erosion discovered in Chaco Canyon and related to the tree-ring dates of Douglass (1935) have been found in other localities. The periods of alluviation are, so far as evidence now exists, nearly synchronous over the whole Southwest. Thus there has been developed an alluvial chronology still imperfect but valuable as a measure of time in the dating of archeological events. It is presumably still more valuable as a measure of alternating periods favorable or unfavorable to floodwater farming, an important method of agriculture in the area. Still more important are the inferences on fluctuations in climate parallel with alternations in the regime of streams.

The report begins with a general consideration of the area and its

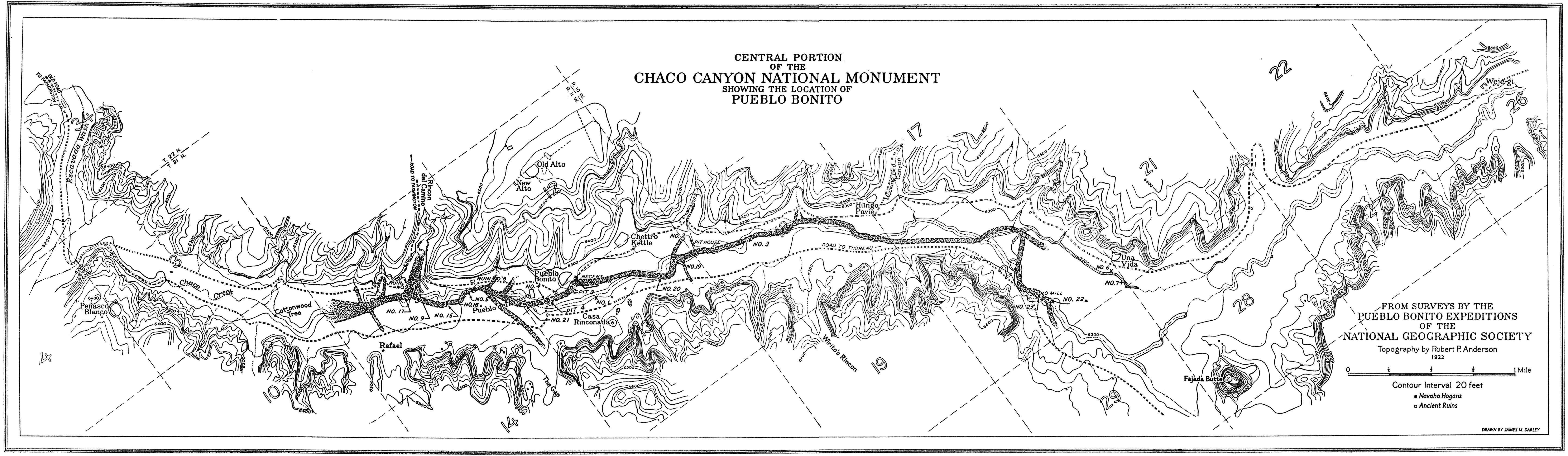


Fig. 1.—The buried, or post-Bonito, channel in relation to the present arroyo in Chaco Canyon.

climate, with such information as is available on the age of the present arroyo in Chaco Canyon, with rather detailed studies of geologic processes now current there, and a description of the alluvium of the valley floor. It then presents evidence that this alluvium is divisible into three parts: the terrace, the main valley fill, and the post-Bonito channel. The antiquity of these divisions and their correlation with similar alluvial formations elsewhere are also considered. The importance of floodwater farming in the Southwest and the effect of the recent epicycle of erosion on this type of agriculture are next set forth.

The cause of the alternation from alluviation to erosion in southwestern valleys is next discussed and the argument advanced that simultaneous alternations in the regimes of widely separated streams must be due to synchronous climatic changes. The concurrent effects of climatic change and change in stream regime throughout the known human history of the Southwest affords a clue to fluctuations in human culture otherwise unattainable.

PHYSIOGRAPHY OF CHACO CANYON

GENERAL RELATIONS

Chaco Canyon lies in northwestern New Mexico on the upper reaches of Chaco River, a tributary of San Juan River (fig. 1). Chaco River, about 100 miles long, is an ephemeral stream such as is characteristic of arid regions. Its sandy bed throughout the greater part of the year is dry and the stream is dignified by the name of river only because of its considerable length and the violence of its floods. The stream begins in the high plains country north of Chacra Mesa at an altitude of 6,900 feet and flows a little north of west for 68 miles. Here the course changes sharply to the north and the river flows nearly parallel to, and on the east side of, the ridge known as the Grand Hogback for 26 miles and thence, breaking through the Hogback in a narrow canyon, it reaches San Juan River in 7 miles. The total length of the stream is thus about 100 miles, of which, however, only 15 or 20 miles of the upper course lies in a canyon worthy of the name. About 12 miles of this canyon, the portion with which we are concerned, is shown on the accompanying map (fig. 1).

Chaco Canyon lies in the southwestern part of the great Plateau province which occupies northwestern New Mexico, northern Arizona, western Colorado, and eastern Utah. The province is noted for its extensive flat surfaces, long lines of cliffs, and deep canyons. The flat surfaces are in part developed on the more resistant beds of nearly horizontal sedimentary rocks, although in part they consist of large outflows of lava, and in part they are the remnants of extensive plains of erosion. In northwestern New Mexico the largest unit of the Plateau province is the San Juan Basin, a vast area in which the rocks dip gently from the periphery toward the center. Chaco Canyon lies near the southern part of this area with a dip of about 2° to the north and east.

Sandstone and shale are the characteristic rocks. The shale is eroded into broad, flat surfaces or gently sloping valleys; the sandstone stands out as ridges or plateaus, bounded, especially on the south, by cliffs. The order and succession of these rocks have been studied by a number of geologists [2] interested primarily in the occurrence of coal or of vertebrate fossils.

Chaco Canyon is cut in the Cliff House sandstone, the upper member of the Mesaverde group. This sandstone member is 369 feet thick as measured by Reeside on Meyers Creek, a few miles northwest of Pueblo Bonito. It is underlain by dark shale containing thin sandstone and coal (Menefee formation) which crops out in the cliffs on the south side of Chaco Canyon and in a few places on the north side. The Mesaverde group is overlain by the Lewis shale which forms the plain north of Pueblo Alto and has a thickness of about 70 feet. Above the Lewis shale lie the Pictured Cliff sandstone and higher formations.

The Cliff House sandstone consists of two massive sandstones separated by relatively thin bedded sandstone. Consequently, weathering tends to produce two cliffs separated by a bench of gentler slope. The lower of these two massive sandstones is buff-colored and about 140 feet thick. The cliffs which make the northern wall of Chaco Canyon are carved from this rock by processes considered more in detail on pages 18-20.

CLIMATIC CONDITIONS AFFECTING GEOLOGIC PROCESSES

The climate of the Chaco country is arid, but such a simple statement does not adequately summarize the effect of climate on the geologic processes. Aridity has many gradations from the almost total lack of rainfall characteristic of parts of the Libyan desert of Africa, and of certain areas on the west coast of Peru, to the tempered aridity of California where trees and grass thrive in areas having relatively low rainfall. Aridity is thus an inclusive term embracing climates having varying amounts of precipitation up to a quantity fixed arbi-

[2] Holmes, 1877; Endlich, 1877; Schrader, 1906; Shaler, 1907; Gardner, 1909; Sinclair and Granger, 1914; Matthew, 1897; Brown, 1910; Bauer, 1917; Bauer and Reeside, 1921; Reeside, 1924.

trarily around 20 inches of rainfall a year. The many shadings and gradations of aridity are dependent on such factors as the proportion of the precipitation that may occur as rain or as snow, on the distribution of precipitation throughout the year, and on the incidence of rainfall whether in hard showers or gentle drizzles. Similarly the daily or seasonal range of temperature and the extremes of heat and cold with their incidence and duration are all factors in aridity.

Climatic elements directly affect various subprocesses involved in the weathering of rocks and indirectly influence the nature of streams which act as the agents of removal and of transportation of weathered rock. Slight differences in degree of aridity often have marked influence in the growth of a vegetative cover, one of the greatest single factors influencing and delimiting erosive and sedimentary processes. In the account of these processes given hereinafter it will be seen that the scant vegetation of an arid region is a necessary prerequisite to the relative intensity of action, or even the existence, of many of the subprocesses. It follows, therefore, that any past or anticipated climatic change, provided it is sufficient to alter the existing vegetation, may have relatively large effect on geologic processes.

The available rainfall records of the Navaho Country up to the end of 1913 were collected by Gregory (1916, pp. 51-59) and the factors of climate in Chaco Canyon are now being recorded by the National Park Service. Herein only such general elements of climate are described as seem necessary for the purpose of defining climate in respect to geologic processes.

The climate of the Plateau province may be considered moderately arid. On the higher portion, between the valleys of San Juan River and the Little Colorado, there is greater precipitation than in the lowlands. In the mountains doubtless as much as 20 inches may fall each year, but current rainfall stations are all on lower ground. St. Michaels, Ariz., altitude about 6,950 feet, has a mean of 13.72 inches based on records for 29 years out of a period of 68 years; Crownpoint, altitude 6,800 feet, has 10.93 inches, based on an incomplete record extending over 11 years. At lower elevations, especially to the north and south of Chaco Canyon, the precipitation is less. Holbrook, Ariz., altitude 5,069 feet, has 9.38 inches with 25 years of record out of a total of 33 years. Places in the San Juan Valley have a lower rainfall: Fruitland, N. Mex., altitude 4,800 feet, 6.38 inches with 7 years of record; Farmington, N. Mex., altitude 5,220 feet, 9.23 inches with 7 years of record; Aneth, Utah, altitude about 4,700 feet, 4.96 inches. It seems likely the Chaco Canyon district has a precipitation similar to that at Crownpoint with a little less rainfall on the floor of the canyon which is 300 to 400 feet lower than the adjacent cliffs. For the purpose of this study it will be assumed that Chaco Canyon has a mean of about 10 inches.

A large part of this precipitation falls during the so-called summer rainy season in July and August. This period is characterized by sharp local or general rains from cumulus clouds or thunderheads. The rate of rainfall is high but the storms seldom last long. The incidence of the rains is also variable in time and space. Small areas are deluged and adjacent areas are left dry. The rains may come as early as June or as late as September, or may be inconsiderable in amount for a whole summer.

Gregory (1916, p. 63) summarizes many observations as follows:

> The area covered by a shower is frequently only a few square miles, and on two occasions showers of 20 to 30 minutes' duration resulted in wetting less than 300 acres. Many of the showers result in a heavy downpour, and the total precipitation for a month is not infrequently the result of a single shower. . . . Generally the intense heat preceding a shower is reestablished within an hour or two after rain has ceased, especially at elevations below 6,000 feet. . . . Lightning is the almost invariable accompaniment of summer showers and constitutes a real danger to travel. . . . My records of thunderstorms for the Navaho Reservation during the field seasons 1909, 1910, 1911, and 1913 are 38, 26, 33, and 23, respectively, and it is believed that the annual number exceeds 40.

The winter precipitation falls gently and is likely to be widely spaced in time, but on the average totals nearly as much as the summer rainfall. At elevations above 6,000 feet there are 17 to 25 inches of snow, and at lower elevations some snow is possible each winter.

The distribution of precipitation throughout the year and its effect on agriculture is best expressed in the following table compiled by Gregory and amplified in a quotation also from him (ibid., pp. 61-62):

Season	Months	Precipitation in percent of mean rainfall
Summer	July, August, September	37
Early winter	October, November, December	25
Later winter	January, February, March	26
Spring	April, May, June	12

> It will be noted that the season of least rainfall, April to June, is the growing season for most crops, and that therefore the seasonal distribution of rain is unfavorable for agriculture or for the vigorous reproduction of many grasses. Half an inch of rain per month for the period April, May, and June is an unusually large precipitation for most parts of the reservation, and during many years the combined precipitation of these three months is less than one-half inch. Moreover, plants obtained only a portion of this meager supply, for evaporation

is most effective during the clear, dry, hot days of early summer. The moisture in the ground, supplied by the rains of winter supplemented by the scattered showers of spring, is sufficient to allow seeds to germinate and to send their stalks above ground, but is insufficient to bring a crop to maturity. The rainfall of July becomes therefore the critical factor in the life of the Navaho. If his prayers to the rain gods are answered his corn crop is assured, and grass springs up from the desert floors; if his prayer is denied the crop is a failure. . . . For a large part of the reservation corn, without irrigation, fails to mature every second or fourth year.

The variation in rainfall from year to year is of the greatest importance. The amount ranges between half the normal and twice the normal. For the 29 years of record at Fort Defiance and St. Michaels the year of greatest rainfall was 1854 with 22.44 inches; the year of lowest rainfall was 1900 with 6.52 inches. It is obvious that in years of severe drought like 1900 almost nothing grows. Such years are periods of starvation for a population dependent on agriculture or on the pasturage of animals.

Similarly the native vegetation must be able to resist these extremes of drought and precipitation. In general, sagebrush and scattering grass grow in the dryer areas, and perennial grasses where precipitation is more generous. With a slight additional increase of rainfall, cedar (juniper) forms sparse groves and a total precipitation of 15 to 20 inches is adequate for the open pine forests of mountain areas. These vegetative zones are, however, not strictly bounded by lines of equal rainfall because slope, exposure, and soil are all factors in the growth of plants. Near Chaco Canyon the flat parts of the plateau are generally underlain by clayey soils derived from shale or by loams formed by the admixture of sand from the sandstone beds with clay from the shale areas. These soils, under the influence of the local climate, support a fairly continuous cover of perennial grasses. The outcrops of sandstone have a rough and broken topography without soil or with only a thin sandy soil. Here grow scattered cedars, occasional woody bushes, and patches of "sand grass" but large portions of such areas are bare rock. The floor of Chaco Canyon supports a growth of greasewood (chico) with, in areas overflowed by storm water, a fair growth of perennial grass. A few cottonwood trees have survived from the period when the stream bed was shallow and are evidence that, with a slightly higher water table or less interference by man, domestic animals, and floods, many of these trees would again grow in the valley.

The temperatures of the region are, when expressed in yearly or monthly means, those of a temperate region. Yearly means range from 47.6° F. to 60.6° according to the altitude of the station. The annual and daily ranges in temperature are, however, very great. The maximum range recorded for various stations in the region is as follows: Fort Defiance–St. Michaels, 122° (98° to –24°); Fruitland, 124° (110° to –14°); Holbrook, 127° (106° to –21°); Crownpoint, 103° (98° to –5°). Temperatures exceeding 100° normally occur for 10 to 20 days each summer and 5 to 6 days of below-zero weather are likely each winter. The daily ranges in temperatures may amount to as much as 40° to 50° and, although doubtless effective in producing the disruption of rocks, are somewhat mitigated in their effect on man and beast by the low humidity of the air.

The growing season, or number of days between the last killing frost of spring and the first killing frost of autumn, ranges at various stations from 89 days to 161 days. In general, localities of lowest altitude have the longest growing season but there is at all stations a variability from year to year in the length of the growing season that may be shorter than the mean by as much as a month. Fort Defiance, at an altitude of 7,000 feet, has experienced killing frost in every month of the year except August. Obviously these variations in the length of the growing season add an additional hazard to agriculture in a region where rainfall is scant and also highly variable in incidence and amount. The data also give an index of the probability of changes in temperature that cross the frost line and these changes are the ones effective in the disruption of rock by frost action.

EXCAVATION OF CHACO CANYON

One who climbs the north wall of Chaco Canyon to Pueblo Alto is rewarded by magnificent views of a region that appears to be flat on all sides. To the south, beyond the canyon, he sees a vast plain from which rise a few low hills and, far to the southwest, high mesas that close in the horizon south of Crownpoint. To the north, the valley of Escavada Wash is a prominent feature bordered by ragged bluffs, but beyond lies a plain similar to the one on which he stands. This high level plain occurs generally on the more elevated parts of the San Juan Basin and is more or less independent of the hardness of the underlying rock. Canyons divide this plain into several parts that are obviously remnants of a once continuous erosion surface that formerly extended over the entire region. The plain has been too little studied to warrant strict definition or to hazard correlation with the Mojave peneplain which Robinson (1907) believes to have existed over the whole of northwestern New Mexico and northeastern Arizona.

Bryan and McCann (1936) imply that this surface is older than the

Ortiz surface and other surfaces which, in the drainage of the Rio Puerco (of the East), are graded to the Rio Grande.

From the evidence near Chaco Canyon it seems possible to postulate two or more erosion cycles during each of which the region was reduced to very low relief. Whether a single peneplain or a more com-

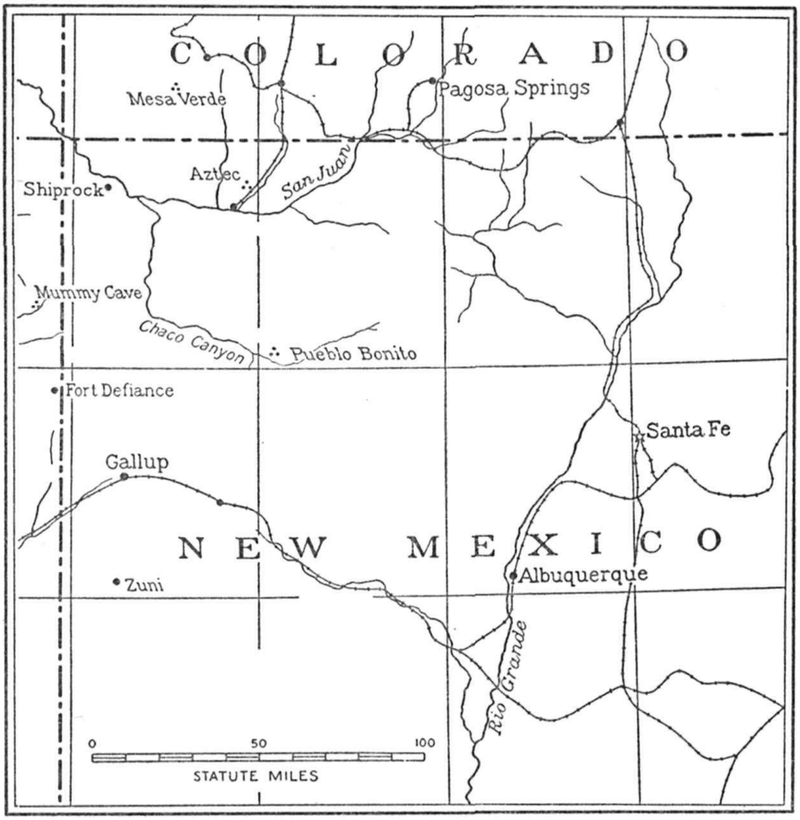


FIG. 2.—Northwestern New Mexico showing the location of Chaco Canyon and Pueblo Bonito.

plex series of erosion cycles will be demonstrated by further work in the area, Chaco River and the adjacent streams gained their courses in a region of such moderate relief that the direction of flow was more or less independent of the distribution of hard and soft rocks. After a general uplift of the Plateau country, the "Canyon Cycle of Erosion" was initiated and the great canyons of the Colorado River system were cut.

Chaco River, a distant and rather feeble tributary of the Colorado, also lowered its bed. In some places it excavated canyons and in others fairly broad valleys. That its canyon cutting was not continuous is evidenced by a well-marked erosional terrace near the mouth of Escavada Wash, a terrace capped by gravel largely derived from the local rocks and lying at an elevation about 150 feet above Chaco River. How important or general this pause may have been awaits field work over a larger area.

The general course of the river appears to have been controlled by undiscovered factors on the ancient plain already mentioned, but details of the carving of the rocks within Chaco Canyon, as we see it, result from the interaction of forces of erosion normal to the climate and the structure of the rocks.

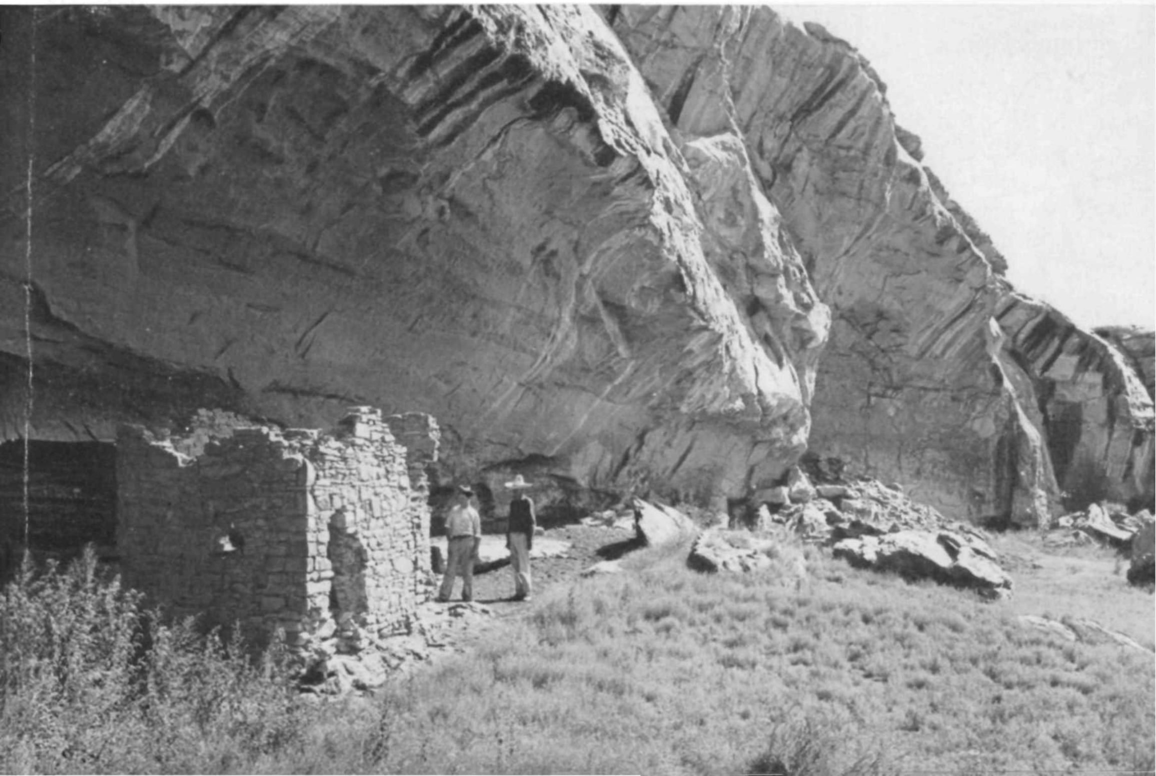
The most notable feature of the canyon is its asymmetry. The north, or rather northeast, wall is steep and but little indented; the south or southwest wall is gentler and broken by branching canyons. Asymmetry is not an uncommon feature of valleys and canyons in New Mexico that have an east-west trend. For example, the relatively smooth, boulder-strewn slope of the south wall of Canyon del Rito de los Frijoles, near Santa Fe, contrasts strongly with the sheer cliffs of its north wall, in which Indians carved caves for occupancy in pre-Spanish times. Yet this canyon, cut in lava and tuffs having a slight dip downstream, is essentially alike in the two walls. The south side, however, is shaded for much of the day, a condition that leads to lower evaporation both of rain and snow, and consequently plants thrive. Small bodies of soil are held in place by grass and bushes; chemical erosion is promoted; talus heaps become overgrown with trees and mantle the rock slopes. In contrast, the north wall with its slope exposed to the sun is relatively dry. The mechanical forces of erosion are in full swing here and debris once loosened from the wall falls clear from rock surfaces which are thereby again exposed to the weather.

Chaco Canyon also has an almost east-west course and is subject to the same influences. A more important factor in creating a difference in the slopes of the canyon walls is, however, a northeasterly dip of the rocks. This inclination varies from 1 to 2 degrees with the result that the base of the Cliff House sandstone lies at or below the floor of the canyon on the north side, whereas it is from 50 to 100 feet above on the opposite side. In consequence the south cliff is undermined with relative ease by sapping of the underlying soft sandstone and shale. The fall of blocks is also assisted by a slight inclination of the bedding planes. Consequently, numerous and relatively large branch canyons

PLATE 2

Upper: Fajada Butte from Pueblo Una Vida, with the present arroyo dimly seen beyond the ruin, and, at the right, the treeless plateau extending southward toward Crownpoint. (Photograph by Neil M. Judd, 1920.)

Lower: A small ruin in a northern branch of Chaco Canyon between Una Vida and Wejegi. Seepage has deposited an incrustation of gypsum along the rear wall of the cave. (Photograph by Neil M. Judd, 1926.)



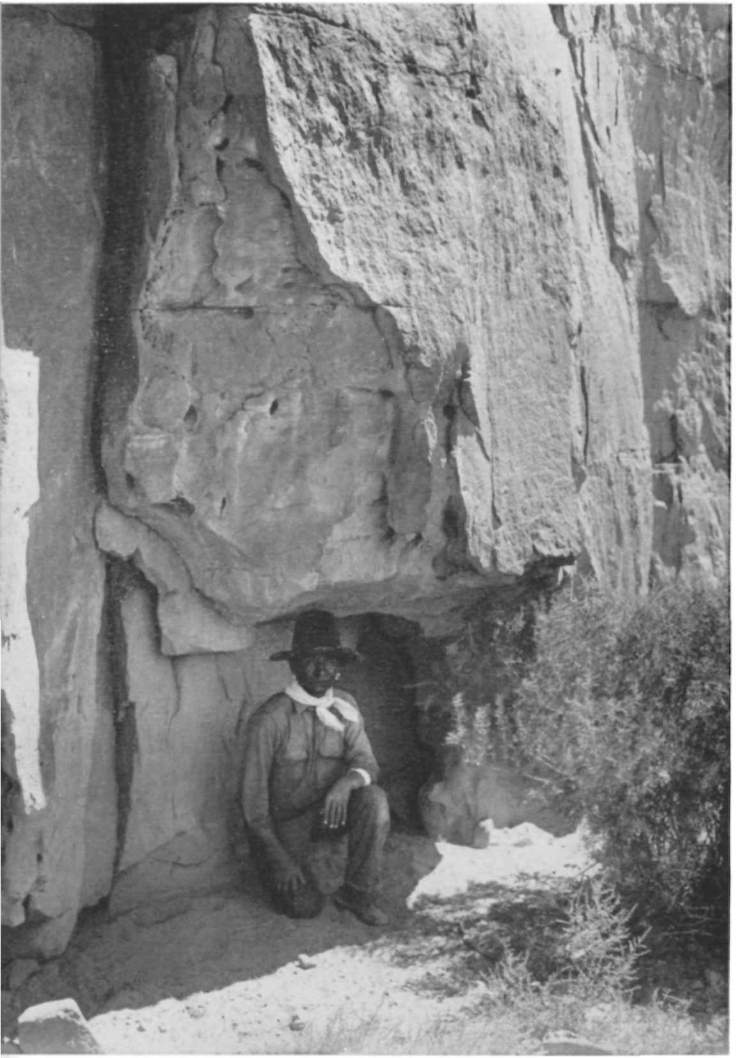


PLATE 3

Left: Carved by wind and water, this niche reveals the characteristic cleavage planes of the lower Cliff House sandstone in the north wall of Chaco Canyon.

Right: A feature at section 5 was this slab-sided Pueblo III fireplace 5 feet below the present surface.

(Photographs by O. C. Havens, 1924.)

PLATE 4

Upper: Near the mouth of the Escavada Wash the lower Cliff House sandstone in the north wall of Chaco Canyon has been scoured and blasted by wind-driven sand. Dunes have blocked the old road to Farmington.

Lower: Rainwater percolating through sandstone often results in a type of weathering called "stonelace." On the rock in the background water issuing from holes has left vertical streaks.

(Photographs by O. C. Havens, 1924.)

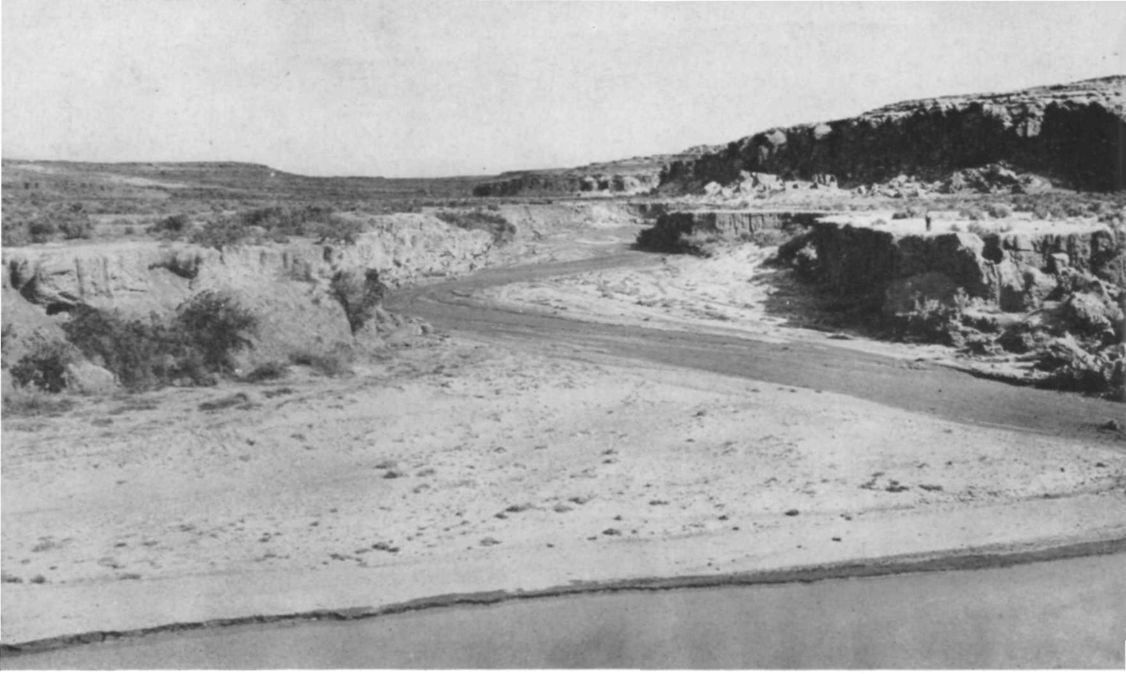


PLATE 5

Upper: Looking down Chaco Canyon from Pueblo del Arroyo. The irregular mass of Peñasco Blanco is seen on the horizon at left center. At the right a sunlit cliff in the middle distance marks the mouth of Rincon del Camino; between it and the standing figure are the broken walls of Ruin No. 8.

Lower: A newly fallen section of bank immediately west of Pueblo del Arroyo.

(Photographs by O. C. Havens, 1925.)

have developed. In the vicinity of Fajada Butte a large tributary drainage has completely destroyed the south canyon wall and enters through a valley broader than that of Chaco River (pl. 2, upper).

On the north side of the Chaco the base of the Cliff House sandstone lies below the canyon floor from Escavada Wash to Mockingbird Canyon. This part of the escarpment is characterized by having a sheer cliff surmounted by a bench and a more gentle cliff above. Its tributary canyons are generally less than half a mile in length and many are mere indentations in the cliff, of the type commonly called "rincons." From Mockingbird Canyon upstream the base of the sandstone lies above the valley floor and the lower cliff is benched rather than sheer, the tributaries are longer and the aspect of the canyon wall is more like that of the southwest wall.

Excavation of the canyon is a process long since interrupted, for the main stream nowhere runs on rock today, nor is it cutting laterally against the walls of the canyon. The process of canyon cutting was succeeded by a period of alluviation resulting in deposition of a valley fill to the level of the present valley floor (see below). Filling of the canyon has also been interrupted by formation of the present arroyo (p. 35).

ALLUVIATION OF THE CANYON FLOOR

After cutting Chaco Canyon to a depth somewhat greater than at present, the stream changed its habit and began to deposit more material than it removed. The gradual character of this filling and details of the process are here recounted at some length. This change from erosion to sedimentation was not confined to Chaco Canyon. Other canyons of the Plateau province and other streams throughout the Southwest were also filled and alluviation was the characteristic process up to a time within the memory of man. The isolation of Chaco Canyon has prevented the accumulation of definite historical data on characteristics of the canyon during this recent period of alluviation. However, canyons of adjacent parts of the Plateau province furnish reliable and analogous data since they lie at similar elevation, and are cut in like rocks under similar conditions of climate and settlement.

During the surveys of Powell and Dutton in 1878-1880, the canyons were undergoing alluviation as attested by the following statement (Dutton, 1882, pp. 228-229):

> Most of these lateral canyons . . . are slowly filling up with alluvium at the present time, but very plainly they were much deeper at no remote epoch in the past. The lower talus in some of them is completely buried and the alluvium

mounts up on the breasts of the perpendicular scarps. In some cases a smooth floor of alluvium extends from side to side of what was originally a canyon valley.

Such conditions no longer exist and had, even in Dutton's time, ceased in certain parts of the San Juan drainage. At present every main canyon in the area is occupied by an arroyo with vertical banks from 10 to 100 feet high. The streams now run at a level lower than the flat floors Dutton described by an amount equal to the height of their banks. These arroyos began at or near the lower end of canyons and progressed headward by a receding fall. The upper (or falls) portion of an arroyo is ordinarily marked by a vertical bank or a chaos of jagged, vertical banks and great blocks of detached alluvium. In many canyons the head of the arroyo has not yet completed its advance and, generally, only in the lower and larger tributaries have branch arroyos been formed.

In the undissected parts of canyons and in minor tributaries there can still be seen at work the processes by which their flood plains were built up during the period of alluviation that has so recently been brought to a close. The flat floor of such a canyon slopes downstream at a grade dependent on the ratio of the volume of water in floods to the supply of sediment carried. In general there is no well-marked central channel, but numerous small discontinuous and branching channels mark the central part of the canyon floor. Low alluvial fans consisting of sediment carried in from minor tributaries diversify the plain. Some of these fans are so large they have partly dammed flood waters of the main canyon and thus created temporary lakes or leveled broad stretches of the canyon floor. In such places perennial grasses may grow in quantities great enough to be cut for hay. However, the features of these canyon floors constantly change, since floods vary in volume, in quantity of material carried, and in the time of their occurrence in the annual cycle. Obviously a flood that occurs after a long dry season during which vegetation has been reduced to a minimum by the dryness of the soil will readily change the minor features of the plain over which it flows. However, generally speaking, the parched soil will absorb so much that only when it is present in large volume will floodwater be able to run the full length of a canyon. On the other hand, a heavy rain and small flood in early summer may produce such a rapid growth of vegetation that the plain will, for the rest of the summer, be protected against erosion by much greater floods.

Obviously, also, floods down the axis of a canyon tend to produce a slope more or less uniform at any locality but of decreasing declivity—the so-called graded slope of a stream. Floods in the tributaries, however, tend to dump material on the floor of the main canyon and interrupt this "graded slope." Opposite the fan of a tributary, therefore, the main stream may have a marked channel that is constantly renewed and shifted in position. Such discontinuous channels must be sharply differentiated from the arroyos characteristic of dissection.

Discrimination of these minor channels from continuous channels that indicate a new cycle of erosion is not always easy. Both are commonly described in the Southwest as arroyos. The character of discontinuous channels can best be explained by an example. The Cañada del Magre, located about 90 miles southeast of Pueblo Bonito, is a narrow, flat-floored canyon tributary to the Rio Puerco (of the East). Its walls are of buff Cretaceous sandstone similar in color, massiveness, and porosity to the Cliff House sandstone. A tributary, the Cañada de Bernardo, is similar. In 1909 a steep-walled gully about 25 feet deep extended from the arroyo of the Rio Puerco across the abandoned flood plain of that stream and a quarter of a mile within the Cañada del Magre where it ended in a chaos of blocks of alluvium and an intricate dry falls. This was the head of the new arroyo representing the readjustment of grade of the Rio Puerco—a readjustment gradually affecting all its tributaries. Upstream from this arroyo head the floor of Cañada del Magre was a grassy flat for a distance of about half a mile. There the center of the flat became sandy and this sandy stretch was enclosed in low banks which gradually increased upstream until they were about 6 feet high and which closed in from the sides until they were only 10 feet or so apart. Here there was another dry falls, more or less grassed over. Some grass also grew on the floor of the arroyo. Above this latter falls was another grassy flat, succeeded at irregular distances by similar gullies and similar grassy flats. It is evident that these discontinuous channels are merely a phase in the process of transportation and deposition on the floor of such a valley. If the grade is locally out of adjustment but the grass cover prevents the easy removal of a thin sheet of alluvium over the whole floor, more sand and clay become lodged in the grass. Alluvium thus continues to be deposited even though the floor is above grade. Finally the strong currents of an exceptional flood break through the grass cover and initiate a gully which then increases headward rather easily. The overpour at the head of the gully so increases the ability of floods to erode that the gully is carried deeper than necessary and its lower end begins to fill with coarser sediment derived from the upper end. The manner in which these gullies disappear can only be inferred from the characteristics of certain ones which are very broad and low-banked at the downstream end and shallow and almost obliterated by the growth of grass at the upper end. Evidently lateral erosion in the lower and middle parts of a gully removes material lying above normal grade, and since the head of the gully stands below this grade it is, with the help of vegetation, gradually filled in.

That such discontinuous gullies existed during the alluviation of Chaco Canyon there seems no reason to doubt. The kind of sediment in the floor and the nature of rocks in the drainage area are so similar to those of the Cañada del Magre and other canyons of the Rio Puerco drainage as to preclude the possibility that dissimilar conditions existed. Cross sections of the valley fill exposed in the banks of the modern arroyo show numerous irregularly placed channel deposits from 10 to 40 feet wide and 2 to 10 feet deep that may well have been deposited in discontinuous gullies.

The existence of channels of this type adds much uncertainty to the usefulness of the accounts of travelers in dating the initiation of modern arroyo systems. Thus Simpson (1850) states that in 1849 the banks of the Rio Puerco were 10 feet high and had to be cut down to allow the passage of artillery at a point 7 miles above Cabezon. Banks of similar height at the crossing of Arroyo Torrejon (Torreones) and the Arroyo Cedro are also recorded. Yet even in 1926 the upper portions of the Cañada (en) Medio, a tributary of the Torrejon, and the Cañada de Piedra Lumbre were undissected and their flat floors were farmed by Navaho Indians. A recent investigation (Bryan, 1928a) has, however, shown that the early discontinuous channels of the Rio Puerco were relatively shallow and narrow compared to the existing arroyo which was initiated between 1885 and 1890.

These minor features of the canyon floor, though constantly changing, doubtless had a marked similarity from year to year for there is a balance between the forces involved that could only have changed gradually with the progressive fill of sediment. The experienced observer can easily predict what areas of such a canyon floor will be gently flooded and what areas will be scored and eroded by tumultuous waters. Only gently flooded areas will be suitable for floodwater farming.

The process of filling Chaco and other canyons was doubtless a slow one and for each foot of material permanently added many feet were deposited temporarily and later shifted downstream. The irregularities in bedding produced by this process preclude an estimation of the time involved in deposition by any method now known.

At various places wind is effective in shifting material and thereby adding complexity to minor features of a canyon floor. Much of the material dropped by floods adjacent to channels of greatest flow is incoherent and sandy. It is easily picked up by the wind and piled in low mounds or dunes. Such material is often in motion within an hour after recession of a flood. Nevertheless, these piles of sand are often effective in changing the courses of channels and in spreading floods. Areas so affected are small and usually are confined to three locations, here listed in the order of their relative importance: 1, Adjacent to channels; 2, on alluvial fans of tributaries carrying sandy debris; 3, outcrops of sandstone.

The work of winds in the vicinity of human habitations is notable and is described on pages 21-22.

DATE OF RECENT STREAM TRENCHING

Historical records at Chaco Canyon are meager, and it is impossible to fix precisely the beginning of its present arroyo. That this is recent and that the process is still continuing is self-evident. Many of the tributary canyons, such as Mockingbird, were yet undissected in 1925, although a falls that receded each year marked the head of their respective arroyos. Since 1925, extension of these gullies probably has destroyed the alluvial plains in the tributaries. That the main Chaco arroyo has increased since early expeditions to the canyon was recognized by Dodge (1910) and the evidence is here reviewed. Not only are its physical features recent but they resemble in every detail those of other arroyos in the Southwest whose date has been fixed with some assurance (Bryan, 1925a, 1928a). It seems reasonable to assume, therefore, that the trenching of Chaco Canyon took place at about the same time as the trenching of other valleys.

During a military expedition against the Navahos in 1849 under command of Col., afterward Gen., John M. Washington, Chaco Canyon was visited and a description of its ruins recorded by Lt. J. H. Simpson. According to this account (Simpson, 1850, p. 78), the "Rio Chaco" had, on August 27, 1849, a width of 8 feet and a depth of 1½ feet at the expedition's camp near Una Vida. It is evident that this description applies to the muddy water then flowing. No mention is made of a gully although Simpson described the steep-walled arroyos of three other streams that were crossed on the way to Chaco Canyon.

Lt. C. C. Morrison (1879, p. 367) visited the Canyon in 1875 but does not mention an arroyo. Oscar Loew (1879) was there about the same time, but his description of the topography of the canyon is too vague to be of value.

William H. Jackson, whose pioneer archeological work in the Southwest is of great accuracy as to detail, spent five days in Chaco Canyon in 1877. Five or six miles above Pueblo Pintado the arroyo was so shallow that Navahos had formed "water pockets" (reservoirs) by obstructing the channel; nearer Pintado the arroyo was 10 or 12 feet deep (Jackson, 1878, p. 433). Between Pueblo Pintado and Wejegi the depth of the arroyo almost entirely cut off communication from one side of the canyon to the other. Numerous small cottonwoods grew along the bank. Near Una Vida Jackson noted that the arroyo was dry where Lt. Simpson had found running water in 1849 and explains that his own visit was made in the spring, when floods are rare, whereas Simpson was there in August when floods are more common (ibid., pp. 436-437). At Pueblo del Arroyo the arroyo was 16 feet deep and 40 to 60 feet wide, as stated and also shown by his sketch map (ibid., p. 443 and pl. 59); 250 yards below this ruin there were shallow pools of stagnant water and here Jackson camped. New grass among young willows and cottonwoods in the bed of the arroyo extended for half a mile up and down stream (ibid., p. 446). The rapidity with which this channel has developed may be judged from the fact that, at Pueblo del Arroyo where Jackson recorded a depth of 16 feet and a width of 60 feet, the arroyo is now (1925) 30 feet deep and 150 to 300 feet wide.

Mr. Judd has diligently collected local traditions on past conditions in Chaco Canyon. Jack Martin, a long-time freighter in the region, said that between 1890 and 1900 the arroyo was so shallow most freight wagons could be hauled across without doubling the teams. The favored crossing was just south of Pueblo del Arroyo and part of the dugway down the north bank is still recognizable. In 1925 Padilla, an old Navaho who lives 7 or 8 miles west of Pueblo Bonito, stated to Mr. Judd and also to me that in his boyhood the arroyo was an "arroyito" not more than breast deep (about 5 feet) and that along it grew cottonwoods and willows. Since his boyhood it has continually widened and deepened.

Later the same year Wello, a Navaho thought to be about 75 years old, told Mr. Judd that Chaco River had no channel when he was a boy; that there were cottonwood and willow trees on the flat opposite Pueblo Bonito and grass was knee high. Water was close to the surface of the ground. Padilla was present at this interview and agreed that these things were so. He may be 5 to 10 years younger than Wello and doubtless based his agreement on knowledge gained from older men, but he still insisted on the truth of his previous statement that, in his boyhood, the "arroyito" was only breast high. If we can accept 1860 as the period to which these elders referred then we have an approximate date for the beginning of the Chaco arroyo. It was 5 feet deep when Padilla was a boy; about 10 years earlier there was no channel at all, according to Wello. Simpson did not mention an arroyo because such a feature did not exist in 1849.

The original notes and maps of the townships surveyed under contract for the U. S. Land Office Survey in the early 1880's have been inspected. These records contain gross errors, and some of the township surveys appear to be entirely fictitious. Hence no useful information was obtained from them.

In attempting to determine a proper date for the beginning of arroyo cutting in Chaco Canyon, the problem is to decide whether the arroyo described by Jackson in 1877 is a portion of a through-going and complete arroyo system. It may have been merely a discontinuous arroyo with a head in the broad areas of the valley near Fajada Butte and a fan near the entrance of Escavada Wash downstream. Our information refers only to this part of the river and we have no data on conditions farther down the Chaco. It seems necessary, therefore, to assume that the arroyo of 1877 was the headward portion of a new system and that the present arroyo is its successor.

The year 1877 cannot be the beginning of this arroyo and allowance must be made for growth of the one described by Jackson. Some weight must also be given to statements of the two Navahos, Padilla and Wello. If Padilla is 70 years old he cannot remember farther back than 1860 to 1865. Wello, an older man, remembers, or remembers statements by others, that there was once no arroyo. Balancing these considerations, it seems that 1860 is as early a date as is possible since it affords 17 years for cutting the arroyo Jackson saw and is consistent with the stories of the two old Indians. The date must be considered as an arbitrary choice, however, and not very precise.

Elsewhere in the Southwest existing evidence indicates that the phenomenon of arroyo cutting began at slightly different times, stream to stream. A considerable period elapsed between initiation of a given channel and its completion throughout the length of its valley floor. The date of beginning is apparently earlier in southern Colorado, northern New Mexico, and northern Arizona than elsewhere, and may easily fall in the decade 1860 to 1870. On Rio Puerco, however, a nearby and similar stream, the date has been satisfactorily placed within the years 1885 to 1890, and in the Hopi country, arroyos were not cut until after 1900.

The effect of arroyo cutting on native vegetation and on habitability of the area affected is very considerable. In southern Arizona, meadows of coarse-top sacaton with groves of cottonwood and walnut have been drained by arroyos, and dense forests of mesquite have since sprung up. On the Rio Puerco, natural hay fields of fine-top sacaton and other grasses once naturally irrigated have dried up and the deep-rooted chamiso, "wafer sage," has replaced the grasses. Areas near San Ignacio and San Francisco that were once irrigated by use of crude ditches or by natural flooding are now 30 feet above the stream bed. Since these areas can no longer be farmed, the towns have been abandoned.

Instances of similar change in native vegetation and of the abandonment of fields could be multiplied (see references given in Bryan, 1925a, 1928b). The present lack is a quantitative estimate of the decrease in vegetation and consequent lessened opportunity for man under the changed conditions. Primitive man, without domestic animals, would not suffer from decrease in forage or from loss of hay fields but, to the extent that he was dependent on floodwater farming, might have his very existence jeopardized by these changes. On the other hand entrenchment of Moenkopi Wash, near Tuba City, Ariz., has, according to Gregory (1915), increased the low water flow of the stream and thereby provided more water for irrigation during the critical period of plant growth. An old Hopi farming village here, after long abandonment, was reoccupied in 1880 and is now a thriving community of about 300 people.

PRESENT GEOLOGIC PROCESSES

WEATHERING AND EROSION OF THE CLIFFS

The asymmetric form of Chaco Canyon is due to its east-west course and to the prevailing dip of the rocks, as explained on pages 10-11. The processes now at work on the cliffs differ from those of the past only because of two factors: (1) The relatively recent valley fill which covers the lower part of certain cliffs; (2) the possible differences between present and past climates. The first factor can have little effect on the nature of the processes; the second affects only the rate of erosion, as the probable changes in climate do not involve a change to a strictly humid climate. When past climates were wetter than the present but still relatively arid, cliff recession was doubtless accelerated; when the climate was drier, the process was slowed down.

Chaco cliffs can be divided into two sorts in two locations: The lower division of the Cliff House sandstone generally forms vertical cliffs but these differ in detail according to whether the base of the sandstone lies below or above the level of the alluvial plain. The upper division has domelike forms and generally produces low cliffs either stepped or rounded where the base is above the alluvium. In lateral canyons the base of this upper member falls below the level of the alluvium and here crenulated and rounded cliffs occur.

Erosion of the lower part of the Cliff House sandstone is largely due to differential sapping at its base. Rainwater entering the sandstone above emerges below. If the base is above the level of the flood plain, the water emerges at the top of the friable sandstones, coal, or shale of the somewhat variable underlying Menefee formation. This material is decomposed and carried away partly by this seepage water and partly by direct rainwash. As a result the cliff is undermined and blocks break off along characteristic joint planes. Perhaps because the edge of the cliff settles and these joints are open some distance back from the face, the cliffs of these localities are less sheer than those of the same rock where the base of the sandstone is below the level of the alluvial plain, as in the north wall of the canyon near Pueblo Bonito. Here water absorbed by the overlying sandstone emerges at or near the level of the alluvial plain. It dissolves the cement of the rock and appears as an efflorescence of a white salt. The sandstone becomes friable and grains are loosened from the surface. These grains fall by gravity, especially during windstorms, or are loosened and carried off by the sheet of water that covers the face of the rock in rains. Thus cavities or niches (Bryan, 1928c) are formed like the one shown in plate 3, left. With the formation of these cavities the rock splits on its characteristic vertical joints; as loosened blocks fall, the vertical face of the cliff is renewed. Narrow slabs several hundred feet long, partly loosened, are fairly common features, and one directly back of Pueblo Bonito has excited much interest because massive masonry below it shows that the prehistoric peoples attempted to brace the slab against falling. [It actually did fall, on January 22, 1941.—N. M. J.]

The upper member of the Cliff House sandstone tends to weather in domal forms. Widely spaced vertical joints more or less at right angles to each other afford points of attack for the weather and the resulting, nearly cubical blocks are then rounded on the corners. The process of sapping takes place in this sandstone also. There is, however, a relatively irregular zone of slabby and shaly sandstone below, at which the water may emerge. On the double cliffs back of Pueblo Bonito the sapping takes place over such a thick and irregular zone that the upper cliff is discontinuous and in many places is replaced by a series of benches. In canyons and rincons that enter Chaco Canyon from the north, this contact passes below the level of the alluvium and the zone of seepage emergence is more or less confined. The rounded bosses are undercut. Where temporary waterfalls cascade over the cliffs during rains, niches are formed.[3]

Such a niche, in Rincon del Camino, is notable because water emerges under the overhang throughout the year and in sufficient quantity to constitute a spring. Other niches may have only enough seepage to support a few green bushes or there may be merely a damp place on the rock. It requires, however, no stretch of the imagination to perceive that with a slightly greater rainfall springs would exist in these and similar situations.

The rate at which cliffs recede according to the processes just reviewed is necessarily slow. That parts of some cliffs are newer than others is attested by their bright, unstained surfaces and the lack of talus. Other parts have relatively ancient, iron-stained surfaces and have shed no fragments since completion of the alluvial plain which laps their bases. Some cliff faces are marked by carvings or pictographs; others have had holes cut in them to support the roof timbers of abutting dwellings. Often blocks at the foot of a cliff are so like the cliff face in color they must be of equal age. In general it can be said that, except for fall of a few blocks here or a mass of debris there, the Chaco cliffs are essentially the same as they were when the canyon was inhabited by prehistoric peoples.

The blocks of sandstone that fall at the foot of a cliff also slowly weather and disappear. There are relatively few such occurrences in Chaco Canyon; rarely are the blocks numerous enough to form a heap or talus. The lack of talus may usually be explained as owing to burial of all blocks formed previous to alluviation of the valley floor. Exposed blocks are mostly recent falls and some of them are so little weathered that they can easily be correlated with scars they left on the cliffs. Others are much weathered and disintegrated. The principal process of weathering appears to be the solution of cement by rainwater that percolates through the blocks and emerges on the side or near the base. Numerous fantastically shaped holes are thus produced, as illustrated in plate 4, lower. The movement of water through such rocks was particularly observed on August 3 and 4, 1924. A sharp shower occurred about 2 p.m. August 3 in which 0.14 inch of rain fell. After the shower several rocks of this type were examined. The exposed portions were wet, and part of the dust under the larger overhang was eroded by the splash of falling rain, but the cavities were dry. Next morning parts wet the day before were dry but the cavities

[3] Bryan's negatives were not found, but those he intended to use here are reproduced in Zeitschrift für Geomorphologie, 1928, pl. 3, A, B.

were damp, and some were almost wet. Evidently within 12 hours water absorbed at the top had percolated through the rock. In rainstorms of greater duration water must pour out of such cavities in considerable volume and carry with it sand grains resulting from previous solution of the cement.

WIND WORK

In various places on the cliffs, especially on the bench between the upper and lower sandstones, there are patches of windblown sand. This sand, evidently derived from disintegration of the nearby sandstone, accumulates in places more or less sheltered from the wind. Some heaps are fixed in position by the growth of grass. That such heaps accumulate is proof that a much greater quantity of sand is moved by the wind and either blown off the cliff altogether or into position where it is carried away by rainwater. How much the movement of this sand scours the rock is difficult to evaluate. It seems likely that the scouring effect is small, for the rock at the surface is soft and crumbly. At the mouth of Escavada Wash, where the Farmington road left the Chaco prior to 1920, the wind has heaped up sand out of the wash to form a group of dunes that encroaches on cliffs similar to those upcanyon (Bryan, 1928c). Here the sandstone has the same domes, niches, pinnacles, and other characteristic details, yet the surface is hard and firm (pl. 4, upper). Tiny iron concretions stand above the surface like collar buttons. The surface is continuously scoured by sand and is in marked contrast, by reason of its firm texture, to the soft and crumbly surfaces seen elsewhere. Nevertheless, the total erosion is obviously less than it seems, for otherwise the domes, niches, etc., would disappear and be replaced by new details equally dependent for their shapes on the process of wind scour.

Near Pueblo Bonito, dust is easily raised on any windy day and windblown sand accumulates, as it has in the past, in every sheltered nook and cranny. Between the ruin and the cliff sand had collected to a depth of 4 to 6 feet between 1900, when the Hyde Exploring Expedition concluded its excavations, and 1921, when the National Geographic Society inaugurated its researches. Similarly, windblown sand near other ruins of the region evidences more wind work than appears at places of otherwise similar location.

These conditions are easily understood when the activity of man and his domestic animals is considered. Near his habitations man and his animals continually disturb the surface soil and thus make the work of wind easy. In addition the soil is made pulverant by abnormal quantities of organic matter consisting of the excrement of men and animals, the debris of crops gathered and brought in, the refuse of building materials and fuel, and litter of all sorts swept up and carried out of houses. These organic substances added to the surface soil serve to make it friable in the same way that manure improves the tilth of a field. The soil, when wet, is no longer a gummy mass that becomes pavement-hard on drying. It is less muddy when wet, and when dry is loose and friable and thus easily picked up and transported by the wind.

With only dogs and turkeys to help in the processes just described, prehistoric peoples probably did not create as much dusty ground as the same number would today. Yet their refuse mounds testify to an enormous quantity of rubbish discarded systematically and enable one to picture the proportion of such litter that must have been scattered about the inhabited areas. The quantity of windblown sand and wind-reworked material found buried in the refuse heaps of Pueblo Bonito evidences a considerable amount of wind work in prehistoric time that, on the grounds set forth above, may be considered as influenced by the habits of prehistoric man.

ALLUVIAL FANS

At the foot of the cliffs, and particularly at every indentation in them, alluvial fans are now forming. These are composed largely of buff and yellow sand derived from disintegration of the sandstone of the cliffs and talus blocks. During every rain, sheets and streams of water pour over the cliffs; the largest flows naturally occur at the indentations. Alluvial fans deposited by these streams are more or less proportional in size to the indentation and, by inference, to the area of surface drained. In a few places the sand of alluvial fans is picked up by the winds and formed into low heaps, but, as was pointed out above, currently there is more wind-moved material in and around the various ruins than at other places in Chaco Canyon.

The soil of these alluvial fans is loose and sandy and doubtless formed the best agricultural land in prehistoric time. During and after rains, waters that pour from recesses in the cliff could easily be directed over the fans. The problem of directing and spreading such runoff so it will wet without gullying the land is a difficult one which must have taxed the ingenuity of the prehistoric farmer. It is possible, but by no means certain, that part of these floodwaters were directed over the more clayey areas in the middle of the valley not only for the purpose of irrigation but also to mix water-borne sand with the less tractable clay.

ADOBE FLATS

Adobe flats still constitute a large part of the floor of Chaco Canyon and are added to each season by storm waters draining from adjacent areas. They are, however, no longer built up by the marginal waters of main stream floods or by deposition in temporary lakes. Progressive cutting of the arroyo has left these flats mere relics of past conditions, but the method by which they were formed can be interpreted from observations in such undissected tributaries as Mockingbird Canyon.

EROSION IN THE ARROYO

The initiation of dissection and the formation of arroyos has already been discussed (pp. 12-13). The present (1925) arroyo varies in width from 150 to 500 feet, and in depth from 10 feet near Escavada Wash to 30 feet at Pueblo Bonito. Upstream, however, the height of the bank again decreases to about 20 feet near Wejegi.

The vertical walls are formed by undermining the alluvium which then breaks off in blocks parallel to an obscure jointing. Undermining is largely due to the lateral cutting of floods in swirls and eddies on the outside of bends. It seems probable, however, that water absorbed in the alluvial plain seeps into the arroyo at the base of these banks, softening and helping to undermine them. The rate of such lateral cutting is rapid, and significant changes may occur in a single year (pl. 5, upper and lower).

THE VALLEY ALLUVIUM

MATERIALS OF THE FILL

The alluvial fill of Chaco Canyon consists largely of sand, yet so much of its surface is covered by a layer of dark sandy clay (locally called "adobe"), that the true character of the fill is not evident except where exposed in the arroyo. Even there the degree of sandiness can be detected only by close inspection, for rains wash mud down over the vertical walls and this, like a film of plaster, conceals the sand and gives the impression that the whole bank is made of clay. The relative quantities of sand and clay will appear from the measured sections on pages 51 to 59; in the following paragraphs, each class of material is described separately.

Small discontinuous bodies and lenses of gravel occur sparingly. The gravels contain much fine sand and mud and are thus similar to the small bodies of gravel found in the present arroyo bed. Like the latter they are obviously the deposits of tumultuous and muddy floods.

The pebbles are mostly partly rounded fragments of sandstone and of limy concretions derived from the Mesaverde and Pictured Cliffs sandstone, but there are also a few water-worn pebbles secondarily derived from the Tertiary rocks. These pebbles may vary in diameter from half an inch to 2 inches, but angular stones up to 6 or 8 inches in diameter are also found.

The sands are of several types not wholly distinct in character that grade into one another even in the same bed. Some sands have almost no bedding or lamination and consist of yellowish, rusty grains such as result from disintegration of the sandstone of the canyon walls. These accumulations seem to have been deposited by outwash and are parts of ancient fans similar to those now being formed at the foot of the cliffs. Lenses of clean white sand, laminated and crossbedded, were laid down by the stream of the main canyon, just as like lenses are being deposited today. Somewhat similar but generally finer-grained sands may have very minute and irregular crossbedding that is a remnant of wind-made ripples. Such beds clearly have been subject to wind action but it seems likely that the sand was first deposited by water and subsequently reworked by the wind. The very same process may be seen today when sand recently deposited in the channel by a flood is reworked by wind shortly afterward.

Gray or brown silt in beds that are minutely though irregularly laminated make up a considerable part of the alluvium. Ripple marks, current marks, and mud cracks are common on the surface of the laminae; a few rusty streaks, some parallel and some at large angles to the laminae, are doubtless the impressions of stems and roots. In many places the silt beds are 2 to 4 feet thick, but in others silt occurs as thin layers in sand or clay. Obviously it was deposited in outer portions of the channel by the main stream or in nearby parts of the flooded area.

The clay of the valley fill locally known as adobe is mostly gray or brown and contains appreciable amounts of sand and silt. A more realistic name would be "sandy or silty clay" or "clayey fine sand." The usual clay bed is from 6 inches to 3 feet thick and is nearly uniform in color and texture. Lamination is not always apparent to the unaided eye but it probably is a constant feature since it has been detected under the microscope and doubtless would be readily visible were it not for vertical jointing and a tendency to "check."

Well-laminated, less sandy clays occur in discontinuous lenses a few feet long and varying from 2 to 12 inches in thickness. These lenses appear to have been deposited by floodwater that was ponded in abandoned and shallow channels. In contrast, the more abundant sandy clay is the result of sheetlike overflows of the main stream and of its tributaries. These overflows formed flats or meadows of alkali sacaton grass. The imperfect lamination and reticulated structure are probably to be accounted for by successive drying of the mud on exposure after each overflow and by the influence of grass roots. The dark color is due to finely divided organic matter incorporated in the clay. In such flats the rate of soil formation is rapid and the reticulated (chernozem) soil structure is quickly attained.

ARRANGEMENT OF THE MATERIALS

The walls of Chaco arroyo and its various branches afford ample exposure in which the several sorts of material just described are displayed. The dominant characteristic is lack of continuity. No bed, however uniform over a short distance, extends very far, nor does a like sequence of beds occur in the wall of the arroyo at any two places.

In general clay beds are the most continuous and some of them have a length of nearly a quarter mile. Such beds rest on, and in turn are covered by, essentially parallel beds of different composition from place to place. These changes in lithology imply that there are many minor unconformities between beds. In some places sharp and definite erosion surfaces cut clay beds which are overlain by sand deposited in the channel responsible for the erosion. Less definite evidences of erosion contemporary with deposition occur, but no one of these episodes of erosion within the formation has any time value, for such irregularities are to be expected in the deposits of ephemeral streams. Each large flood forms new channels of flow and destroys in part the work of its predecessor. In such localities the measure of erosion or sedimentation is the algebraic sum of the erosion and deposition of successive floods.

In several places a cross section of a much older channel is exposed in the wall of the arroyo. These exposures generally show a round-bottomed channel, filled with crossbedded sand to a depth of 2 to 10 feet, and the lenticular character of adjacent clay beds. Such channels are evidently interformational for they are shallow, occur at all levels, and are covered by beds that are conformable with others, adjacent and contemporaneous. Evidently these channels are of the discontinuous type described on pages 13-14 and are to be distinguished from the relatively recent, buried channel discussed on pages 32-37.

DEPTH OF THE ALLUVIUM

Tangible evidence on the total depth of the valley fill is wanting in Chaco Canyon. The well at the Society's Pueblo Bonito camp was dug

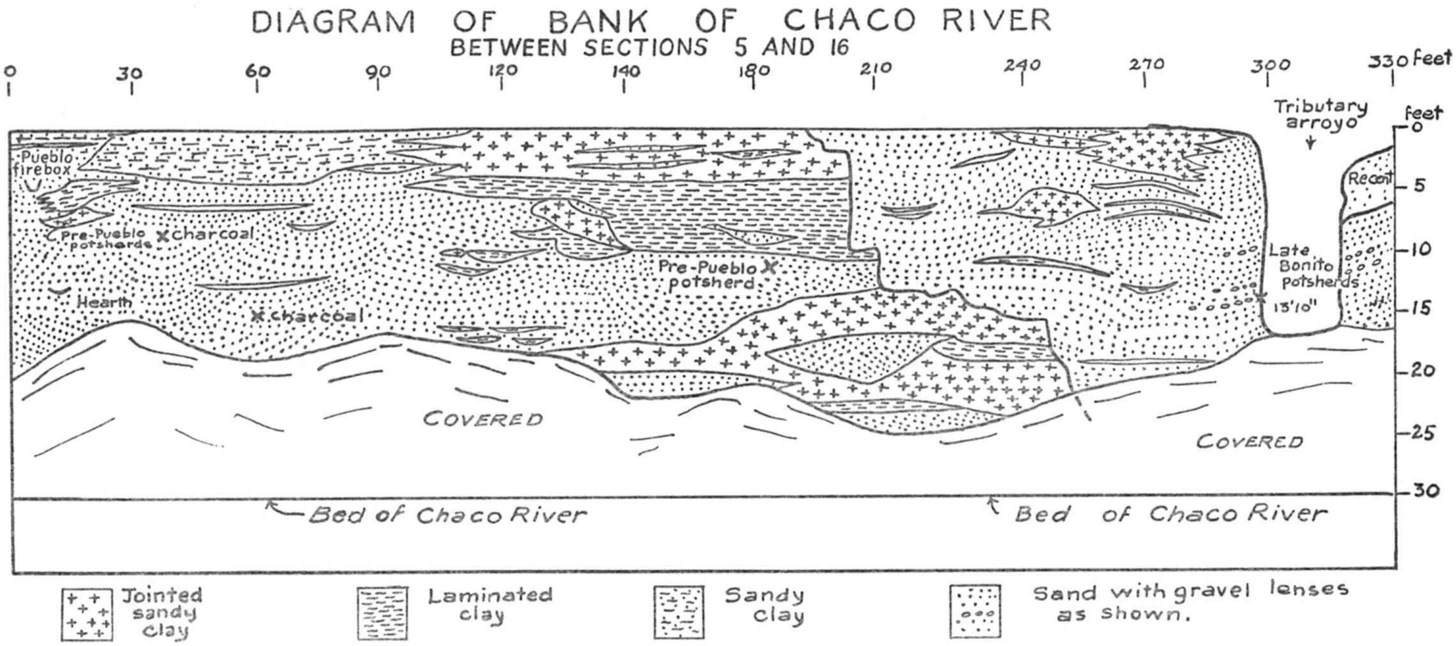


FIG. 3.—Diagrammatic sketch of the valley fill between sections 5 and 16.

PLATE 6

Upper: Annually since 1877 Chaco floods gnawed at this small Pueblo III ruin until the last vestige of it disappeared in 1948. Pueblo del Arroyo stands at the right, beyond the sheds. (Photograph by Charles Martin, 1920.)

Lower: A Pueblo I pit house with roof 6 feet below the valley surface was revealed by caving of the arroyo bank during the 1921 flood season. (Photograph by Neil M. Judd, 1922.)

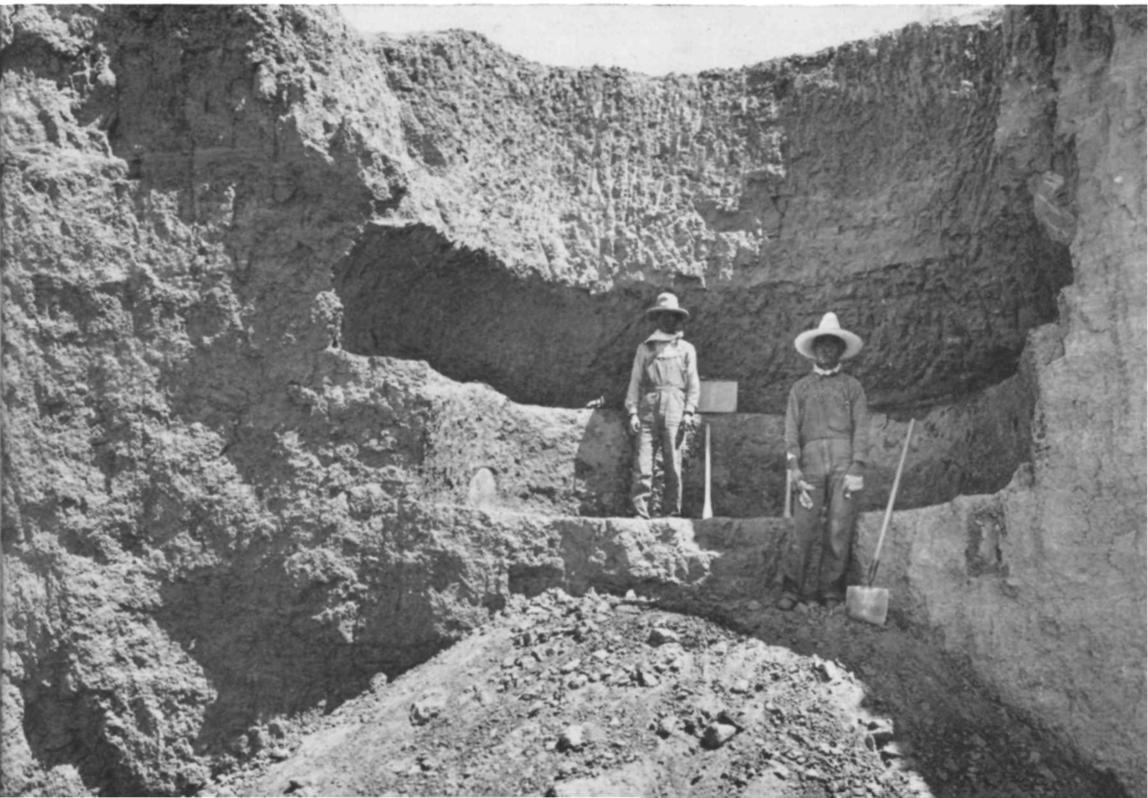


PLATE 7

Upper: The buried channel as exposed at section 16. Here Late Bonitian potsherds were found at a depth of 13 feet 10 inches. (Photograph by O. C. Havens, 1925.)

Lower: The author stands below a cross section of the post-Bonito channel at section 4, near the southeast corner of Pueblo del Arroyo. (Photograph by O. C. Havens, 1924.)

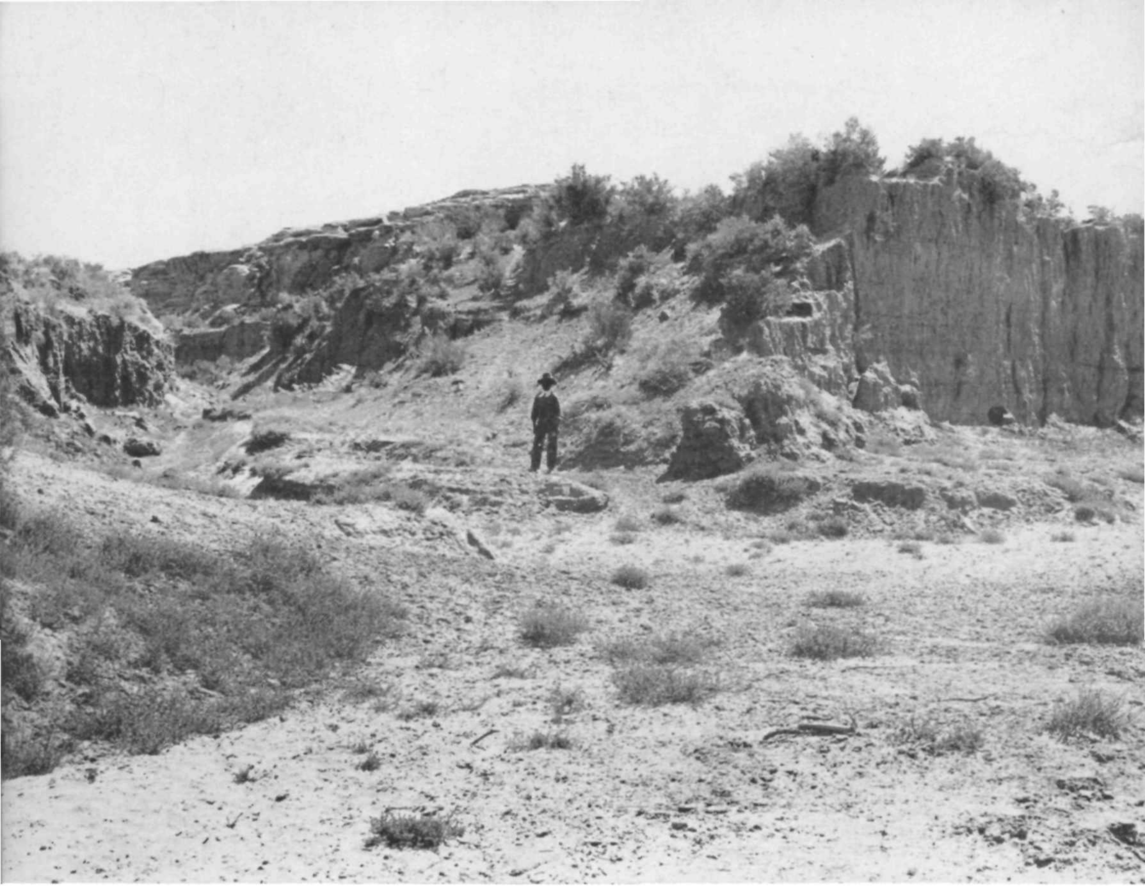


PLATE 8

Upper: As it did in the days of Pueblo Bonito, the Rincon del Camino comes in from the north to join the main Chaco arroyo. (Photograph by O. C. Havens, 1924.)

Lower: Lateral erosion caused by drainage from The Gap. View looking north across the Chaco toward Pueblo del Arroyo in left middle distance. (Photograph by Neil M. Judd, 1929.)

PLATE 9

Upper: About half a mile west of Ruin No. 9 a disarticulated skeleton was found in the arroyo bank 6 feet below the surface.

Lower: Hearth at depth of 12 feet 8 inches, section 9, at mouth of Rincon del Camino.

(Photographs by O. C. Havens, 1925.)

about 10 feet below the level of the stream bed in the arroyo, here 30 feet deep, and thus shows at least 40 feet of alluvium. About 1900 a well said to have been 350 feet deep was drilled between Richard Wetherill's old home and the southwest corner of Pueblo Bonito and was promptly abandoned because the water was brackish. No record of the material passed through is available.

In other, somewhat similar canyons and valleys, the alluvium is known to be relatively shallow. As recorded by Gregory (1916, p. 160), wells at Leupp, in the Little Colorado Valley, northeastern Arizona, and along Oraibi Wash, farther north, show a depth to bedrock ranging from 60 to 80 feet. In the Puerco Valley, 50 to 70 feet of alluvium is found. At Gallup, near the Arizona line in New Mexico, there is 175 feet of alluvium above bedrock.

From these data one may assume that the alluvium in Chaco Canyon probably does not exceed 100 feet in depth. Thus there is exposed only about one-third, or 30 feet, of the total. The generalizations of this paper are based on an examination of this exposed third but we may be sure an equally thorough examination of the lower and unexposed portion would reveal equally interesting and significant information.

HUMAN RELICS IN THE VALLEY FILL

During investigation of the sediments exposed in the walls of Chaco arroyo, relics of man's activity were observed repeatedly. These relics consisted mostly of hearths, charcoal, stones, bone fragments, and potsherds. Remnants of masonry structures were also found, although infrequently. Most of the hearths are not constructed fireplaces but, rather, surfaces more or less blackened or reddened by heat and overlain with charcoal. They are merely places where fires had been built and obviously represent no more than temporary camps. Some may have been used for only a day; others, to judge from the depth of the burnt ground and the amount of charcoal, could have been used for a period of weeks. Some hearths have been buried by sand or clay laid down so gently by running water that the charcoal was not eroded. They are thus good evidences (1) that the contemporary surface at that place was occupied by people during the period of alluviation and (2) that alluviation was accomplished in part by gently moving sheets of water which did not destroy previously existing surfaces.

Scattered charcoal, on the other hand, is not conclusive evidence of the presence of man since it may have been incorporated in the sediments by erosion of areas where the vegetation was burned by fires of natural origin. However, as previously pointed out, the character of the sediments indicates that the region has always been an arid one. In such a region fires of natural origin are, because of the scarcity of burnable vegetation, likely to be small in extent and thus produce small amounts of charcoal. Certainly charcoal is not common in the stream beds of the present time, either in this area or in the Southwest generally. It seems more likely, therefore, that occurrences of scattered charcoal in the Chaco fill are due to the erosion of hearths or refuse dumps. Since charcoal is soft and friable, it cannot be carried far and indicates human occupation at no great distance upstream.

Isolated stones in the fine-grained sediments occur in many places, but, however others may have reached their present positions, those found near hearths were probably brought in by man. Their presence thus tends to confirm such evidence of onetime human occupation as worked flints, stone and bone artifacts, and fragments of pottery.

Bone fragments are not positive proof of man's presence unless showing signs of human workmanship but, like scattered stones, may be confirmatory when in association with man-made objects.

Potsherds are resistant to erosion and provide durable and unquestioned evidence of man's presence in the past. They have such large surfaces in proportion to their weight that they may be carried in currents unable to transport small stones and thus often occur in fine-grained deposits. Generally, however, they are associated with gravels. Some potsherds, found singly in fine-grained beds, may have been dropped on the surface and simply buried by the mud of the next flood. Deposition by floods on uneroded surfaces was doubtless common, as shown by the lack of erosion of charcoal in hearths. Potsherds also have a genuine stratigraphic value because pottery made by prehistoric peoples at different periods differs in texture and decoration and can be identified with some certainty. Thus, if collected systematically, potsherds can be used as fossils are used to identify the age of sediments.

COMPLEX CHARACTER OF THE VALLEY FILL

The nature of the sedimentary deposits comprising the main fill of Chaco Canyon is clearly revealed in the walls of the present arroyo. Here 30 feet and more of successive strata have been laid bare and one has only to read the story they tell.

Before discussing the significance of these exposures and the methods used, some of the difficulties we encountered will be mentioned for the benefit of future workers. Study of arroyo banks involves the tiresome traversing of the stream bed, which is soft and sandy when dry and may be dangerously boggy just after a flood. The banks are a monotonous brown and in many places are covered with a film of mud washed down from above.

Like a coat of calcimine over a fresco, this film obscures the characteristics of the materials of the bank. The freshest exposures are usually on the outside of bends for here the stream cuts laterally with greatest activity. On the inside of bends, temporary bars or heaps of windblown sand accumulate and may cover the bank to half its height. Frequently there has been left adhering to the bank a remnant of such a bar formed at some past time in the process of cutting the arroyo. Occasionally these remnants form little terraces 3 to 20 feet wide and 4 to 6 feet lower than the top of the bank. They consist of Chaco River deposits similar to the rest of the valley fill and are so deceptive in appearance we came to call them "false banks." Sometimes the "false bank" contains sheep dung and recency of deposition is thus definitely established. Elsewhere one must rely upon the form of the bank or some local difference in bedding, in color, or in grain of the clays and sands to distinguish the false from the true bank.

In full sunlight the relatively small variations in color and texture of beds are almost invisible. Therefore each locality was scrutinized at least twice, once in the morning and once in the afternoon so that, as nearly as possible, every part of the exposure could be seen in the shade.

Detailed descriptions of the valley fill at each of the 23 sections examined would merely weary the reader. A number of such descriptions are offered hereinafter (pp. 51-58) for those interested primarily in the geological aspect of this study, but our present purpose will be served by a single example. Typical conditions are shown at a locality on the south bank of Chaco River, opposite Ruin No. 8 and approximately half a mile west of Pueblo Bonito (fig. 1). Our diagram (fig. 3) was constructed by measuring the beds on verticals spaced 10 feet apart and by sketching the form of the several bodies of material in the intervals.

On the left are shown the irregularly continuous beds of the main valley fill at section No. 5. A conspicuous feature here is a fireplace of nearly vertical stone slabs built when the surface was 5 feet lower than it is now (pl. 3, right). Archeologists consider this type of fireplace characteristic of the period of settlement known as Pueblo III. Nearby, both in the bank and on the surface, are potsherds of that age. A few feet to the west, however, and at a depth of 6 feet 3 inches, sherds of indeterminate age were found. A second hearth at a depth of 12 feet 8 inches, and charcoal at 16 feet 3 inches, are doubtless records of the presence of people earlier than Pueblo III. Near vertical 180 a potsherd of distinctive type attributable to pre-Pueblo (P. I) times was found in a loose block of earth. This block retained the shape of the bank so perfectly there is no doubt the sherd came from a depth of 11 feet 3 inches.

At the right of vertical 180 is represented the coarse, sandy filling of an ancient arroyo at section 16 (pl. 7, upper). In the gravel lenses of this old channel and at a maximum depth of 13 feet 10 inches, potsherds of the type characteristic of the latest phases of Pueblo Bonito were found. The sherd collection here was comparatively large because the gravel lenses could be followed for 50 feet at right angles to the section in the lateral tributary of the modern arroyo.

Generally speaking, material within this ancient arroyo is sandier and more crossbedded than that of the main valley fill. In other sections examined the laminations dip from both sides of the channel toward the middle and at or near the bottom there are one or more lenses of gravel. These lenses are, on the average, 3 to 12 inches thick and 2 to 4 feet long. The gravel is clayey and dirty and similar to gravel beds of the valley fill or those in the present stream bed. However, potsherds are relatively plentiful and most frequently of Pueblo III type. The unusual number of these late potsherds is in itself significant and, so far as my experience goes, an infallible indicator of the presence of the buried channel. Connecting channels of contemporary age are commonly filled with coarser material similar to that in the present tributary arroyos.

Typical conditions are thus recorded in the main valley fill between sections 5 and 16. The current arroyo has exposed its predecessor and bared evidences of human occupation in times past. To depths of 4 feet and more, rarely 6 feet, potsherds of Pueblo III type are fairly common. Below this horizon the sherds are of definitely earlier types or of indeterminate age. Here, as elsewhere, we detect no physical division between the lower and upper sedimentary beds, merely a separation of the early and late pottery fragments found in them.

RELATION OF HUMAN RELICS TO MAIN VALLEY FILL

The various relics of man's activity found exposed in the walls of the modern arroyo indicate that man inhabited Chaco Canyon during the latter part of the period of alluviation. The greatest depth at which potsherds were seen during the course of our investigation was in a bed ranging from 17 feet to 20 feet 6 inches below the surface of the valley floor (section No. 3, fig. 1). At another site, section 8, charcoal was found at a depth of 21 feet. Man may have been present during the earlier phases of sedimentation but his presence during deposition of the last 21 feet of fill is definitely established. It seems a fair inference that in the prehistoric period most streams in this region were building up their flood plains and primitive man witnessed the process.

Chaco Canyon was by no means unique in this respect. Ashes, pottery, artifacts, and like evidences of man have been recovered at various depths in the alluvium of other Southwestern valleys. Published records are not so numerous as might be expected but those available, together with some of the present writer's observations, are tabulated herewith:[4]

Relics of man in the recent alluvium

State	Name of stream valley	Feet below surface	Author	Reference
Arizona	Rio de Flag	9	A. E. Douglass	1924, pp. 238-239
	Santa Cruz	10	E. Huntington	1914, p. 24
	Navaho Country	..	H. E. Gregory	1915
	Navaho Country	..	A. B. Reagan	1924a, pp. 283-285
	Pueblo Colorado Wash	10	A. B. Reagan	1924b, pp. 335-344
Sonora	Sonoita River	12	C. Lumholtz	1912
Colorado	Montezuma Canyon	2	G. O. Williams	1925, pp. 201-202
New Mexico....	Chaco Canyon	17	R. E. Dodge	1920, pp. 23-25
	Chaco Canyon	14	W. H. Jackson	1878, pp. 431-450
	Coyote Canyon, Sandia Mts.	6	Kirk Bryan	1925a
	Rio Puerco	6	Kirk Bryan	1926b
	Nutriosa Creek Zuñi drainage	6	Kirk Bryan	1926b

In Chaco Canyon, potsherds and other artifacts were collected from noteworthy depths at many different places. Generally, sherds from the upper 4 to 6 feet of the valley fill are of relatively late types of pottery (Pueblo III). Earlier types are found at greater depths. From our data it seems clear that the upper 4 to 6 feet of the main valley fill is not only younger than the lower horizons but that the division between the prehistoric periods known as Pueblo II and III lies at the base of this layer.

Two Pueblo I pit houses in Chaco Canyon were excavated and described by Judd (1924). One of them, so far as critical evidence was preserved, may have been built after alluviation had filled the valley

[4] It is to be emphasized that this paper was begun in 1925 and was added to from time to time until 1940, when it was left incomplete. Hence the absence of later references.—N. M. J.

to its present level. It was situated at the base of the talus on the south side of the canyon, opposite Pueblo Bonito. The other and more perfect example, at the locality marked "Pit House" on figure 1, was evidently occupied when the surface of the alluvial plain was 5 feet 11 inches or, in round numbers, 6 feet below the present surface (pl. 6, lower). Because potsherds of precisely the same type as those recovered from these two P. I pit houses have been found repeatedly in the valley fill, one can scarcely avoid the conclusion that during the time when strata at depths of 4 to 21 feet were being deposited, Chaco Canyon was occupied predominantly by people of this cultural stage.

The exact relationship between the Pit House people and later inhabitants of the valley is not wholly clear at this writing. Pottery similar to that from Judd's two pit houses has been found in and below rubbish associated with the older parts of Pueblo Bonito and portions of a slab-lined pit house were encountered 12 feet beneath the west court of the great ruin. I leave solution of this puzzle to the archeologists but, at the moment, it would seem as though the inhabitants of Chaco Canyon had passed rather abruptly from a P. I to a P. III society. So direct a transition in human culture appears physically possible for the valley fill records no break in sedimentation; hence the environment must have been relatively uniform during the change.

As previously stated, numerous relics of the Pueblo III people have been found in the upper 4 feet of the main body of the valley alluvium. Most distinctive of these remains are house walls which, in a number of instances, rest on undisturbed material 3 feet or more below the general surface. There is no better example than the small house on the south bank of the arroyo, opposite Pueblo del Arroyo. Its relationship to the underlying strata is clearly shown in plate 6, upper. One corner had recently been undermined when Jackson first noted its precarious situation in 1877. Since then the little house has paid annual tribute to Chaco floods and its complete destruction is only a matter of time.

Near section No. 2 (p. 53) the foundations of another small building reach a depth below the surface of 8 feet, but this is exceptional. Apparently at this site the alluvial fan of the adjacent tributary has been built up several feet above the normal level.

THE BURIED CHANNEL AND ITS SIGNIFICANCE

One of the notable discoveries of W. H. Jackson during this keen observer's visit in 1877 was a buried channel just south of Pueblo del Arroyo, 14 feet deep and containing numerous potsherds, flint chips, and other human relics (Jackson, 1878, pp. 443-444). Unquestionably this exposure was among those later seen by Prof. Richard E. Dodge and reported in published excerpts from his field notes of 1899 and 1901 (*in* Pepper, 1920, pp. 23-25). It is perhaps only natural, therefore, that the present writer, although these earlier discoveries were unknown to him at the time, should have happened upon the same ancient channel mentioned by Jackson and Dodge.

As shown in plate 7, lower, this buried channel is round-bottomed and crescentic in cross section. Its boundaries are sharp and clearly cut across the horizontal bedding of the older valley fill. The materials within the channel are such as might be expected: gravel and cross-bedded sand 3 to 4 feet thick form the base of the deposit and are succeeded by clay which, in turn, is overlain by successive beds of sand and sandy clay. The first clay bed seems to indicate a ponding of flood-water in this channel while the main floods were diverted into another. A series of sandstone blocks in the clay bed resembles stepping stones placed to provide a passage over the mud but such an explanation of the blocks, though plausible, can scarcely be considered as established.

Buried potsherds, broken bones, and beads were revealed also in a reentrant of the modern arroyo which existed in 1924 and 1925 a few yards from the south wall of Pueblo del Arroyo and a hundred feet, more or less, west of the exposure described above. The potsherds included some of the latest varieties of pottery made in Pueblo Bonito and were, according to Mr. Judd, produced somewhere around A.D. 1100. Although this deposit was visible for about 75 feet its lateral contacts were, at the time of my examination, unfortunately obscured by a small gulley on the east and by unusually severe weathering on the west.

With two exposures in line, extension of this buried channel eastward under the plain before Pueblo Bonito was obvious. To provide a third contact, a test pit (pit No. 4) was dug 60 feet back from the edge of the bank where the channel was first observed. At a depth of 18 feet sherds of the latest Pueblo Bonito pottery were found, proving this pit to be located in the buried channel.

Nearer Pueblo Bonito, Judd's test pit No. 3 was deepened and more late pottery was discovered. Next, a trench previously dug through the west refuse mound as a means of studying its composition was extended out into the flat. In this extension the north bank of the buried channel was clearly profiled. The channel filling, marked by coarser material, rests unconformably on the edge of the old refuse mound and on strata of the main valley fill.

Farther east, an outcropping in the north wall of the present arroyo gave still another point and thus enabled us to indicate the course of the buried channel as it passed Pueblo Bonito. In 1936 Senter (1937) dug pits near Pueblo Chettro Kettle and likewise exposed a buried channel containing potsherds of late date. From the position given, however, I would judge his buried channel to be a branch of the arroyo produced by the stream which drained the reentrant in the cliffs back of Chettro Kettle.

A careful reading of Jackson's account shows that there was in 1877 an abandoned side channel 8 feet deep, or half that of the main arroyo, between the latter and the ruins of Pueblo del Arroyo. This side channel ("old arroyo" of his map) still existed, in part at least, in 1925. It must be distinguished from Jackson's buried channel which he describes as 14 feet deep and marked by "an undulating stratum of broken pottery, flint chippings, and small bones firmly embedded in a coarse gravelly deposit." This stratum he first observed below masonry walls exposed by the side channel above referred to—walls that did not show on the surface. He traced the stratum upstream "several rods" in the vertical north bank of the main arroyo, noted its presence also on the opposite side, and followed it thence farther upstream to the small ruin shown in plate 6, upper. The stratum reached its lowest level 14 feet below the surface, or 2 feet above the bed of the main arroyo, a fact that led to Jackson's conclusion: "Since the desertion of this region the old bed has become filled to the depth of at least 14 feet, and through this the arroyo has made its present channel." (Jackson, 1878, p. 444.)

In 1924 and 1925 the walls of the "side channel" were much weathered and waste from the Society's excavation of Pueblo del Arroyo had been dumped into the main arroyo southeast of the ruin in an effort to check further erosion. The exposures described by Jackson had been destroyed in the widening and deepening of this arroyo but in an excavation made for a storage cellar back of the old Wetherill "hotel," the northern border of a channel containing late Bonito pottery could still be seen.

When considering the significance of the buried channel described above, I have often thought of it as the "post-Bonito channel" because late Bonito potsherds on the bottom of it identify the channel with the final years of Pueblo Bonito or even later. In 1925, by means of test pits in the plain that lies in front of Pueblo Bonito, we traced this old channel eastward from the exposure near Pueblo del Arroyo for more than 1,000 feet. The lenses of clayey gravel and other materials found in those pits were thoroughly characteristic of channel deposits. Late

Bonito pottery fragments were found from 10 to 18 feet below the surface in test pit No. 3 and from 7 to 15 feet below in pit No. 4. Additional exposures enabled us to plot the channel's course with a high degree of accuracy for several miles.

That this buried channel is part of a continuous arroyo once extending the full length of Chaco Canyon seems definitely established. The existence of such a through channel is proof that there intervened during alluviation of the valley a period of arroyo formation and dissection similar to the present. To put it another way, an early period of alluviation, represented by the main valley fill, was followed by a period of dissection that included our post-Bonito channel. After an unknown interval alluviation was again resumed, the arroyo system was filled up and some slight addition made to the valley deposits, and alluviation, or at least a balance between alluviation and erosion, was continued down to the year 1860 to be interrupted in the ensuing decade by formation of the present arroyo.

Such a history appeals to the imagination by reason of its symmetry and because of the nice correlation with human history that can be made, as outlined in a later part of this paper. However, the importance of the issues involved requires that available evidence be examined with care.

The buried channel, as exposed in various places, is round-bottomed although vertical side walls have been detected in a few instances. Vertical walls are to be expected in any through-flowing arroyo. However, as previously pointed out, local conditions often prevented a critical study of side contacts of the old channel. The present arroyo, which coincides very closely with this post-Bonito channel throughout much of the area under examination, has, by reason of its greater width, removed all traces of the buried channel over considerable distances. Sections of the old channel have been discovered largely through search for lenses of gravel containing late-Bonito potsherds, and in many localities the side contacts of the old channel are poorly exposed. The best evidence found that however round-bottomed the channel may have been, its walls were generally vertical, is its known length and presumed extension both ways.

Supporting evidence that the post-Bonito channel is part of a continuous arroyo is given by the existence of lateral channels representing its important tributaries. A mile downstream from Pueblo Bonito there is an indentation of the north canyon wall which we called "the Rincon del Camino." The present road to Farmington and Aztec goes this way. Drainage from a considerable area falls over the cliffs at the head of this rincon and reaches the main arroyo through a half-mile-long tributary (pl. 8, upper). The material exposed in this tributary consists of irregularly bedded yellow sand, numerous lenses of dirty gravel, and a few lenses, 2 to 6 inches thick, of laminated dark clay. All this material, except the clay, is similar to that now carried by the tributary stream and was undoubtedly derived exclusively from the drainage of Rincon del Camino. Similar sand and gravel are exposed in the north wall of the main arroyo for about 300 yards east of the tributary.

There is thus a triangle of material derived from the alluvial fan of the side stream extending from the main arroyo to the head of the rincon, as outlined in figure 1. This triangular mass contains no material from upstream except the clay beds, and evidently the area could not have been occupied by the main stream of the canyon during deposition of the fan. All other evidence, however, leads to the conclusion that during the period of alluviation the main stream wandered at will over the canyon floor. If, however, an arroyo similar to the present one had been formed, contemporary drainage from Rincon del Camino might easily have excavated a tributary large enough to carry away and destroy the main valley fill over the entire triangular area shown on the map. If conditions of alluviation were restored thereafter and the main arroyo began to fill up, the excavated area would also be filled. The waters of the main arroyo could, however, enter the area only as a gentle overflow or backwater from which clay similar to that of the clay lenses would have been deposited. Most of the filling would consist of sand and gravel brought in by the tributary stream. It seems obvious, therefore, that the fan of Rincon del Camino is later than the main valley fill and was deposited after a period of erosion.

That the area was occupied by human beings during this episode is evident from discovery, at the place marked section 9 on figure 1, of several hearths from 10 feet to 12 feet 8 inches below the surface (pl. 9, lower). A short distance away two potsherds were found in gravel lenses, but they are undecorated ware of indeterminate age. A small sherd collection, gathered among lumps fallen from the bank of the main arroyo but derived from the fan of Rincon del Camino, consists also of fragments indeterminate as to age.

The human remains before us, therefore, do not afford reliable evidence of the synchronous erosion and refilling of the post-Bonito channel and the triangular area at Rincon del Camino. However, it seems impossible to account for the type of sand and gravel found here except on the theory that it was deposited in an area excavated during an earlier period of erosion. The alluvial fan of Rincon del Camino presents general evidence, if not conclusive proof, of a period of erosion and sedimentation contemporaneous with the cycle postulated from a consideration of the post-Bonito channel.

The sequence of geologic events in Chaco Canyon, if the post-Bonito episodes of erosion and sedimentation be accepted, may be summarized as follows:

Recent geologic events in Chaco Canyon

Process	Event	Date
Erosion	Formation of existing arroyo system	1860 to present
Sedimentation	Filling of channels	After completion and perhaps after abandonment of Pueblo Bonito
Erosion	Formation of a main arroyo for full length of canyon and formation of tributary arroyos	Probably post-Bonito
Sedimentation	1. Deposition of upper 4-ft. zone transitional with lower zone	Pueblo III period
	2. Deposition of zone from 21 to 4 ft. below surface	Pre-pueblo (Pit House and earlier?) period
	3. Deposition of unknown amount	Unknown, probably post-Pleistocene
Possible alternations of erosion and sedimentation not as yet differentiated.		
Erosion	Formation of canyon	Unknown, probably Pleistocene

The twofold character of the valley fill is thus well established. The buried channel has been traced from near Una Vida to a point about 1½ miles below Pueblo Bonito where it becomes so large that remnants of the main valley fill cannot be identified.

BURIED CHANNELS SIMILAR TO THE POST-BONITO CHANNEL ON OTHER STREAMS

Discovery of the post-Bonito channel led to a search for a similar division of the flood plains of other streams in northwestern New Mexico. The data obtained are here summarized although it is recognized that the importance of the subject requires additional field study and more complete description.

In 1925 buried channels were detected in the walls of Arroyo en Medio and Arroyo Cedro, both tributaries of the Rio Puerco by way of Arroyo Chico. In 1927 a well-defined buried channel was found and mapped for half a mile in the arroyo of Rio Puerco, between the towns of Cuba and La Ventana. In neither of these localities were potsherds or other human relics found in the deposits of the channel. On Rio Puerco I picked up two sherds of black-on-white pottery that clearly had fallen with a portion of the arroyo bank, but the exact position in which they were deposited is not known. They merely indicate that part of the valley fill was laid down during a time when prehistoric Puebloan peoples inhabited the valley.

In 1929 buried channels were also discovered in the floors of Tijeras and Coyote Canyons on the west slope of Sandia Mountains. In Coyote Canyon many evidences of human occupancy during deposition of the valley fill were found. Hearths, bones, charcoal, and potsherds occur but the localities are so disposed that none provided the critical data that would date the channel.

In 1928 a buried channel was discovered on Galisteo Creek at the town of Galisteo, in Santa Fe County. A similar one occurs west of the road crossing and rock falls on San Cristobal Creek, just below the pueblo of San Cristobal. The channel on Galisteo Creek was carefully traced and mapped. It obviously underlies and therefore must be older than Pueblo Galisteo (Bryan, 1941, p. 231). This particular ruin (Nelson, 1914) contains potsherds which are all of glazed types and no part of it appears to be older than the Pueblo IV period, comparable to Pecos Glaze II (personal communication from A. V. Kidder).

GEOLOGIC EVIDENCE ON THE MEANS OF LIVELIHOOD OF CHACO CANYON PEOPLES

All peoples known to have occupied Chaco Canyon in prehistoric times were dependent for sustenance largely upon agriculture. The Navaho now living there are principally stock raisers, but nearly all of them plant fields of a sort. Two small patches of corn were to be seen near Pueblo Bonito in 1924; farther upstream, beyond Pueblo Pintado, fields were larger and more numerous. The Bonitians, however, lacked domestic animals and although the hunting in their day may have been better than it is now the major part of their food supply doubtless came from cultivated plots.

As pointed out heretofore, the present climate of the Chaco area is unfavorable to agriculture by reason of the unreliability of rainfall, particularly in June and July, and because of the comparatively short growing season. Elsewhere irrigation makes possible the growth of most crops common to the temperate region; corn, beans, and squash, still staples of Indian tribes throughout the Southwest, are known from frequent finds in excavations to have been the main crops in prehistoric times. During the course of this investigation we were constantly on watch for evidence of local irrigation with living water—and found none.

The floor of Chaco Canyon has no irregularities that are not entirely natural in origin except wagon roads, mounds covering ruins, and an ill-advised ditch built some years ago by a white man. The banks of the modern arroyo were carefully inspected for traces of ancient irrigation ditches but none was found in the main valley fill. Such negative evidence would be of little value were it not a fact that in every country in which living water is used for irrigation the ditch banks are routes of travel and are thereby compacted. It is inconceivable that, if ditches had been used by the ancient inhabitants of Chaco Canyon, all their compact ditch banks would have been destroyed, especially when the processes of alluviation were so gentle that charcoal in hearths was buried with little disturbance. Under such conditions the hard-packed surfaces of ditch banks should also have been preserved.

Materials of the valley fill, as already described, do not indicate that there ever was a stream of living or perennial water in Chaco Canyon during the two periods of alluviation determined by these investigations. Such materials all appear to have been laid down during muddy floods similar to those now characteristic of Chaco River. Irrigation by means of a system of ditches continuously maintained is hardly practical on such a stream. Thus geologic interpretation confirms the negative evidence of the ditches and indicates that the prehistoric peoples of Chaco Canyon did not practice irrigation as we commonly understand it. However, in selected places they could have farmed successfully by irrigating with flood water or, as it is usually called, "floodwater farming." For this method the floor of Chaco Canyon, save for the presence of its modern arroyo, is entirely suitable.

FLOODWATER FARMING

The ordinary rainfall throughout most of the southwestern United States and northern Mexico is insufficient to grow crops. Such lands, however, as are overflowed by the muddy water of ephemeral streams or by rainwash from hillsides will support a hazardous agriculture. Floodwater farming was first adequately described by Gregory (1916, pp. 103-105) and a rather complete account with maps of fields has recently been published by the present writer (Bryan, 1929). The additional data given herewith apply particularly to conditions that once obtained in Chaco Canyon.

Gregory (1916, pp. 104-105) outlines, as follows, the methods and results of floodwater farming in the Navaho Country, an area that includes Chaco Canyon:

From experience and tradition the Indians have learned to know the areas liable to be flooded during occasional showers as well as those annually inundated by the successive rains of July and August. Along the flood plains of the larger washes the practice is to plant corn at intermediate levels in widely spaced holes 12 to 16 inches deep. The grain germinates in the sand and rises a foot or more above the surface before the July rains begin. With the coming of the flood the field is wholly or partially submerged. After the water has receded parts of the field are found to have been stripped bare of vegetation and other parts to have been deeply buried by silt; the portion of seeded ground remaining constitutes the irrigated field from which a crop is harvested. The Hopis, and to a less extent the Navajos, sometimes endeavor to direct the floods and to prevent excessive erosion within the fields by constructing earthen diversion dams a few inches to a foot or more in height—dams which require renewal each season. . . . Much work is done by the Indians while the flood is in progress, and an everyday sight during showers is the irrigator at work with hoe or stick, or even with his hands, constructing ridges of earth or laying down sagebrush in such a manner as to insure a thorough soaking of his planted field. By these methods of flood irrigation the Navajo and Hopi together cultivate about 20,000 acres of land widely distributed over the reservation in fields about 3 acres in average size, rarely exceeding 200 acres.

Similar methods of cultivation are in wide use throughout the plateau of Mexico and in New Mexico and Arizona (Hoover, 1930, pp. 437-438; Hack, 1942, p. 26). The Mexican calls such a field *sombrado* (planting) or *temporal* (temporary field). The Nahuatl word *milpa* is also used. In favored localities and usually at high elevations these terms are applied to fields dependent on rainfall alone but generally flood irrigation from the rainwash of higher slopes or from ephemeral streams is essential to a crop.

Since they were first visited by whites in 1698 and doubtless long before, the Papago Indians of southern Arizona have supported themselves largely by floodwater farming pursued on the broad plains of their undissected desert valleys. Corn, squash, and *tepari* beans are their main crops (Lumholtz, 1912; Bryan, 1925b; Hoover, 1929).

Floodwater farming for the production of stock feed is widely practiced in northern Nevada. Quinn River valley (Bryan, 1923b) may be taken as typical. The valley—

is bordered on the east by the Santa Rosa and Buckskin mountains and on the west by the Quinn River Mountains. It heads in Oregon about 10 miles north of the Nevada line and extends southward about 45 miles to the Slumbering Hills, which separate it from the broad valley of Humboldt River. The valley is 10 to 12 miles wide and is drained by Quinn River, which runs southward through it for about 40 miles, turns west, and, passing south of the Quinn River

Mountains, is lost in the Black Rock Desert. The river is formed about 4 miles south of the Oregon line by the union of East Fork of Quinn River and McDermitt, Washburn, and other creeks. Its drainage basin includes about 1,164 square miles.

The valley floor consists of plains formed of beds of sand, gravel, and clay deposited by the existing streams. A small part of the valley bounded by a line of bluffs that extends from the Oregon line east of McDermitt southeastward to the National mine differs from the larger part in that the streams flow in flat-bottomed valleys that lie 50 to 100 feet below the level of sloping plains formed by the same streams at an earlier time, when they flowed at a higher level. In general, however, each stream, on leaving the mountains, wanders through circuitous and branching channels over the alluvial slopes to the axial flat, where it joins in grassy meadows the small meandering channel of Quinn River.

The region is arid, none of the streams containing water throughout the year. The principal streams carry considerable water or are in flood in the spring, when the snow on the mountains is melting. The spring floods are not violent, and the water, which may be almost clear, is easily diverted into semi-permanent ditches to irrigate the cultivated fields. In the axial flat there are large fields that are irrigated from Quinn River or from its tributaries. Near the mouths of the canyons of the principal mountain streams there are smaller fields, many of which are irrigated by the water of streams that seldom reach the lower, larger fields. About 14,000 acres is irrigated. Native grasses, which are used both for pasture and for hay, form the principal irrigated crops, but there are also fields of alfalfa and small grain.

Paradise Valley lies east of the Santa Rosa Mountains and is enclosed on the north and northeast by unnamed volcanic plateaus and mountains and on the east by the mountain range that culminates in Hot Springs Peak. It is drained by Little Humboldt River, which is formed by the union of Indian, Martin, and other creeks with the east fork of Little Humboldt River. The topography of this valley is like that of Quinn River Valley, though the central flats are wider and the area irrigated is larger.

In both valleys communication with centers of population elsewhere is difficult. The distance from some of the ranches to Winnemucca, the nearest railroad station, is more than 60 miles. Only cattle on the hoof can be readily marketed, and the irrigated land is devoted to the raising of stock-feed. In April and May the cattle are turned loose in the plains and lower foothills, where they browse on the sage, weeds and grass, and as the snow melts they gradually climb higher into the hills, reaching the summits in midsummer. As the cattle leave the valleys the ranchers begin to irrigate their land, starting with the first floods and continuing to use the water as long as it lasts. In August great quantities of hay are made from the native grass and from alfalfa.

The cattle begin to come down from the hills late in August and early in September—according to the local saying, "as soon as they hear the mowing machines." Late in September and during October the ranchers bring the last of the cattle out of the hills to the owners' fields, where they are pastured on the still green native grass and on greasewood until it is necessary to feed them hay. In ordinary years the cattle are brought through the winter in excellent condition.

About 13 miles east of Pueblo Bonito and beyond Pueblo Pintado, small Navaho fields are cultivated in the floors of valleys more or less obstructed by sand dunes. The effect of sand dunes in spreading the floods of ephemeral streams and in providing localities suitable for floodwater farming is also of large importance in the Hopi country (Hack, 1942). In canyons tributary to Arroyo Salado, in the Rio Grande drainage and some 70 miles east of Pueblo Bonito, there is limited floodwater farming. The Cañada (de) las Milpas doubtless had, before the existing deep arroyo was formed, enough fields to justify its name. Here, as late as 1922 on hill slopes at Juan Chaves's ranch, there were two small fields irrigated by the runoff from high bluffs. In 1921 the writer saw in Rincon de Lopez 40 to 50 acres of corn and beans that had been irrigated by floodwater.

About 10 miles from Cañada las Milpas is Bernalillito, a locality so called because people from Bernalillo on the Rio Grande 35 miles distant formerly moved there each summer to plant and tend their fields. Bernalillito Wash heads on the eastern escarpment of the Mesa Prieta and flows in a broad flat valley eroded in shales and sandstones about 10 miles east to a narrow gap in a massive sandstone cliff. Below this cliff there is a canyon in places broad and in others narrow. About half a mile below the cliff is the single ranch house of Bernalillito. Nearby is one field of 15 acres suitable for planting corn and beans and to one side a smaller area where hay may be cut. The sandy alluvial fan of a tributary gulch causes the main flood to spread and the gentle overflow makes possible the cultivation of the field and the growth of grass on the meadow. The flood is also caused to spread more widely by a low dam of brush and stone (*atarque*) at the lower end of the field. Just below field and meadow is the headwater falls of an arroyo which has already dissected similar flats in the canyon below and now threatens to destroy the remaining fields. In 1920 this ranch came under the control of H. M. Bryan, who has planted with the results shown in the table on the following page.

The years 1920 to 1923 were generally unfavorable in this part of New Mexico and similar planting in years of greater rainfall might have produced better results. However, the flood of September 1921, which broke down and washed out part of the corn, is an incident that might happen any year. When this flood arrived, a bean crop estimated at 1,000 pounds was ready for harvesting but only 200 pounds —the equivalent of the seed planted—were saved. Similarly, the loss from intruding cattle that broke through the outside fence to obtain water in 1920 and 1922 might have been avoided. Such hazards are, however, a part of this type of farming although the prehistoric flood-

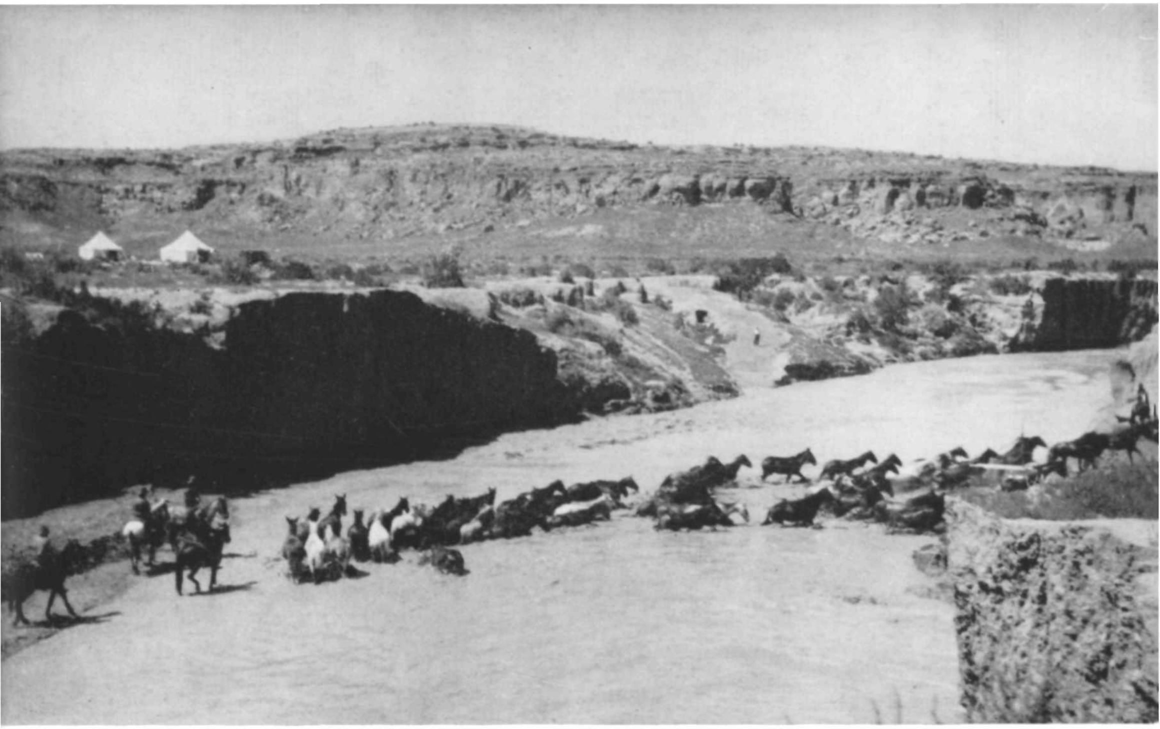


PLATE 10

Upper: The Chaco in flood. Tents of a General Land Office surveying party at left; men on opposite bank and rider at right stand on approaches to the wagon crossing. Pump on Wetherill's well, destroyed a few weeks later, is seen above the fourth horse from the right. (Photograph by Neil M. Judd, 1921.)

Lower: Middle south wall of Pueblo del Arroyo with a partially refilled section of Jackson's "old arroyo" in the foreground. (Photograph by Neil M. Judd, 1920.)

PLATE 11

Left: A pit house with floor 13 feet 6 inches below the present surface, 9 miles east of Pueblo Bonito, had been long forgotten before the Pubelo III village was constructed on an upper level a few feet distant. (Photograph by Neil M. Judd, 1926.)

Right: An Early Pueblo cooking pot covered with a sandstone slab lay 6 feet below the surface of a sand dune in Wirito's Rincon, about 1½ miles southeast of Pueblo Bonito. (Photograph by Neil M. Judd, 1927.)

Crops at Bernalillito, N. Mex., 1919 to 1925

(Data furnished by H. M. Bryan)

Year	Corn	Cropped forage	Beans	Natural hay	Remarks
1919	Not planted	Not planted	Not planted	10 tons	Good year; no planting
1920	None	None	None	None	Good year; no planting
1921	Fair	5 tons corn fodder	200 pounds	Fair, pastured	Flood in September destroyed 800 pounds of beans and destroyed corn fodder
1922	Few good ears	None	None	None	June flood gave corn good start but it was eaten by cattle. $100 crop damage collected
1923	50 bushels gathered	Corn fodder	None	2 tons	Corn not properly cultivated, but favorable year
1924	Small crop	2 tons barley hay	About half of expected crop	8 tons hay and Russian thistle	Three floods in August and September made harvesting difficult
1925	Not planted	Not planted	Not planted	Pastured	Floods, Aug. 8, 15, and 16, Oct. 9 and 12

Note.—In 1925 no planting was done and the land was encouraged to revert to grass. In the fall of that year a stand of grass about 30 percent of full stand had been attained.

water farmers were saved at least the risk due to domestic animals. It is true also that this piece of ground was poorly farmed during these years. The owner at the time was a sheep man whose herds during the summer season were in the mountains more than 60 miles away. Consequently the farming was done during intervals of other, more important work, and by hired labor. Cockleburs and Russian thistle grow so rapidly that strict attention to cultivation is necessary. Because this attention could not be given, the owner converted the plowed land into meadow with the intention of cutting hay for winter use.

The record of these six years indicates that, with an adequate reserve for lean years, this field would support a family requiring no more than was necessary for prehistoric Pueblo peoples. But this family would need to give the crop the constant attention which modern Hopi lavish on their own fields.

It is obvious that the condition of aggradation that once prevailed in the valleys and canyons of the Southwest was favorable to floodwater farming. At that time the floods spread widely and were confined to channels at only a few places. Small localized showers that fell on the walls of canyons, if sufficient to produce runoff, flooded the adjacent flat floor, whereas now the runoff flows into an arroyo below the general level of the plain.

Water that soaked into the ground could not so easily drain away and consequently underlay the valley floors at moderate depths. It was thus available to supply the roots of trees and bushes which doubtless once flourished in valleys where they are now absent. At favorable places, lakes and swamps existed in which grew the rushes (tule) frequently found in prehistoric ruins. Because of this higher water table a thinner layer of earth was dried out between floods; smaller floods were sufficient to wet the dry ground. These smaller floods also covered larger areas since less of their flow was absorbed by the dry ground. The result of such a regimen was a denser vegetation on the canyon floors.

Of this denser vegetation an important part was perennial grasses. Even today where floods spread widely over the floors of undissected tributaries to Chaco Canyon there is a fairly dense cover of perennial grass, usually alkali sacaton. Meadows of this type were so numerous in the Rio Puerco region, 80 miles to the southeast, that a principal occupation of the Mexican inhabitants in the late 1890's was the cutting of hay to be hauled 30 miles or more to market in Albuquerque.

The presence of these meadows was advantageous to white men, and their destruction by the formation of arroyos has been a distinct loss. The forage they were capable of producing naturally was of no value to prehistoric farmers without domestic animals to feed, and their agricultural potentialities remained untested because those same prehistoric farmers lacked tools adequate to the task of uprooting sod. At the present time grass is apt to grow thickest on the more clayey soils and, to the extent that they are effectual in spreading floodwaters, grassy areas tend to postpone arroyo cutting. The inhabitants of Pueblo Bonito undoubtedly planted on the sandier soil bordering such grassed areas, on alluvial fans below the cliffs, and along the vague and meandering course of the main stream. Such soils were more or less disturbed by successive floods but, despite annual loss of part of the planted crop, they were doubtless recognized as the best agricultural land because of their superior tilth and relative freedom from deep-rooted perennial grasses.

In 1921 Mr. Judd dug a trench 20 feet in depth to study the stratigraphy of the west refuse mound at Pueblo Bonito. Four years later when he extended it out into the flat fronting the mound, the trench cut across several obviously artificial canals or ditches. They ran parallel to the front of the refuse mound and, therefore, essentially east and west. They were from 4 to 10 feet wide and were enclosed on the downhill (south) bank by walls of slushed mud (adobe) laid with care and in places supported by the dumping of house refuse. Filled with both fine and coarse materials, including Late Bonito potsherds, these ditches presumably had carried floodwaters from upcanyon, perhaps from the rincon of Chettro Kettle, to fields west of Pueblo Bonito. As each filled up or was washed out, a new one was constructed along the same route. Such more or less temporary ditches for the spreading of water are fairly common features of floodwater fields in New Mexico. If these before Pueblo Bonito were more elaborately constructed than is usual, it is doubtless because they lay close to the village where labor was readily available. The data Mr. Judd has gathered relative to comparable structures for control of floodwaters in Chaco Canyon will be presented by him in connection with the subsistence problem of the Bonitians.

ARROYO FORMATION AND FLOODWATER FARMING

From the foregoing it should be evident that in Chaco Canyon conditions were favorable for floodwater farming from the beginning of alluviation. The area available also gradually increased as the plain widened with the filling of the canyon. The canyon, therefore, afforded a locality for the initiation and development of a civilization based on agriculture. That this agriculture was precarious and that crops might fail owing either to lack of rain and consequently of floods, or to the occurrence of unusually cold seasons, does not constitute a factor that would prevent the development of a local community of relatively high culture. These hazards merely limit the number of people and fix their standards of living. In pre-Spanish times the Hopis are said to have insured themselves against crop failure from these causes by the storage of a year's supply, or more. A like necessity may have been one of the compelling causes which led to development of more houses and a house cluster more elaborate than the simple pit dwelling.

The same comments may be applied to the problem of water. Lack of a local water supply does not prevent the use of suitable floodwater fields, for at the present time the Hopi farmer may cultivate tracts 10 or even 20 miles from his home. Moenkopi, 40 miles northwest of Oraibi, was a farming community when seen by Oñate in 1604 and remained so until the Navaho forced its temporary abandonment about a century ago. An alluvial plain in the process of sedimentation always has local depressions which fill with water after rains or floods. These pools or *charcos* (Bryan, 1920) afford a limited water supply during the growing season. The Papagos of southern Arizona were entirely dependent on charcos during the planting and harvesting of their crops until, within the past few years, the United States Indian Service drilled wells at the fields. Before coming of the Spanish, these Indians not only cultivated the same fields while dependent on charco water but carried the crop on their backs to winter residences located at permanent, or at least longer lasting, water many miles distant. Thus lack of permanent water is not necessarily a hindrance to floodwater farming, although it may be an obstacle to permanent residence.

In Rincon del Camino one of the Navaho workmen employed by the Pueblo Bonito Expedition developed a small spring in a rock shelter or niche under a cliff. At other similar localities on the north side of Chaco Canyon the rock is damp and covered by an efflorescence of salts. Here it might be possible to develop water by systematic digging, and springs of this type may have been the principal source of domestic water to the ancient people. It is certain that a very slight increase in rainfall over the present annual average would produce springs in such localities.

Conditions of alluviation lead also to a relatively high water table. At present, water may be obtained by digging about 10 feet below the bed of the arroyo, or some 40 feet below the plain. Before the modern arroyo was cut the stream ran in a shallow channel and ground water must have saturated the valley fill to within 10 feet of the surface, a distance comparable to the present depth of water below the bed of the arroyo. As the dry season advanced, the prehistoric peoples may have scraped holes in low places and thus formed a primitive type of well.

No evidence of such wells has been found but the digging of them would have been entirely feasible for the inhabitants of Pueblo Bonito even though they lacked metal tools.

The formation of an arroyo similar to the present one, or the one we have called the post-Bonito channel, confines floodwaters to a narrow belt below the level of the plain. The ground-water level is also lowered and floods from tributaries are less effective in wetting the ground. Farming by means of floodwater is consequently impossible over the whole plain and is limited to insignificant areas.

If, therefore, the geologic chronology tentatively outlined on page 37 be accepted, Chaco Canyon enjoyed a relatively long period of alluviation with conditions favorable to floodwater farming. As indicated by finds of potsherds and other relics, people of Early Pueblo culture occupied the valley at least during the time required to build the fill from a level 21 feet below the present surface to 4 feet below. The favorable conditions then existent led to development of the relatively complex civilization of the Great Pueblo period, a culture that flourished during deposition of the upper 4 feet of valley fill.

Formation of the arroyo system represented by the post-Bonito channel may be given as the approximate cause for abandonment of the valley by these Pueblo III people, although other factors such as war, invasion, disease, or gradual decrease in means of subsistence may also have had their effect. However great the changes these other factors might have produced, it seems unlikely that any one or two of them would have kept out of use for long a place so eminently suitable for floodwater farming as Chaco Canyon.

CAUSE OF ALTERNATE EROSION AND SEDIMENTATION

If, as outlined in the preceding pages, the alternate erosion and sedimentation in Chaco Canyon resulting in the production of a plain of alluviation suitable for farming at successive times and the dissection and partial destruction of this plain in the intervening intervals is an adequate cause for the rise and destruction of human cultures, the ultimate reason for changes in the habit of streams becomes of large importance. A river or stream deposits sediment when it has a load greater than it can carry on a given grade. It erodes when it can carry more material than is furnished to it. The quantity of water, variations in this quantity, grade, supply of sediment, size of grain of the sediment, and shape of the channel are factors which determine the habits of a stream. The complex interrelationships of these factors are difficult to determine quantitatively, and are summed up in the word "regimen." The regimen of streams in the Chaco Canyon region is such that they now erode whereas formerly they deposited material on the canyon floors.

As this change in regimen is general, general causes must be sought. A number of writers [5] attribute the present epicycle of erosion to introduction of livestock. Formation of trails and destruction of vegetation by overgrazing are supposed to have concentrated floodwaters and to have allowed these floods to erode the present channels. The argument of these writers is best expressed by Duce (1918, p. 452): "We may, therefore, summarize the effect of cattle by saying that they increase the rapidity of the run-off and the rate of erosion by destroying vegetation, by compacting the soil, and by forming channels for the passage of water."

The apparent coincidence in time of the initiation of overgrazing and the beginning of dissection is significant and more data on this phase of the problem are needed. Coincidence of settlement and the deepening of the channel of Rio Puerco seems well established (Bryan, 1928a). The theory that erosion is caused by a slight uplift and increase in the gradient of streams has been generally rejected because erosion of about equal magnitude affects streams of different drainage systems that flow in all possible directions. Uplift so nicely adjusted to the drainage pattern is inconceivable.

Huntington (1914, pp. 33-34) was doubtless the first to advocate a climatic change as the cause of erosion, and Bryan (1923a, pp. 77-80) has brought together available evidence that a slightly wetter climate was characteristic of southern Arizona at the time of the first Spanish explorations.

Gregory (1917, pp. 131-132) advocates climatic change and rejects the argument for overgrazing in the following words:

> It is important to note in this connection that the balance between aggradation [alluviation] and degradation [erosion] is nicely adjusted in an arid region where the stream gradients are steep, and that accordingly small changes in the amount of rain, its distribution, or the character of storms and changes in the amount and nature of the flora result in insignificant modification of stream habit. Even the effect of sheep grazing is recorded in the run-off, and this influence combined with deforestation has been considered by many investigators as the sole cause of recent terracing in the Plateau province. For the Navajo Country these human factors exert a strong influence but are not entirely responsible for the disastrous erosion of recent years. The region has not been deforested; the present cover of vegetation affects the run-off but slightly, and parts of the region not utilized for grazing present the same detailed topographic features as the areas annually overrun by Indian herds.

[5] Dodge, 1910; Thornber, 1910; Smith, 1910; Rich, 1911; Duce, 1918; Olmsted, 1919.

Reagan (1922, 1924a, 1924b) presents the interesting hypothesis that prehistoric peoples, by means of small reservoirs, check dams, and embankments designed to spread floods, used or distributed most of the water so that floods of the main arroyos were decreased in volume and violence. Hence, sediment was deposited and the arroyos filled up. When these ancients disappeared and their structures fell into decay, erosion was resumed. Reagan also supposes that the prehistoric peoples killed off the game, and thereafter the vegetative cover increased until it gave a maximum of protection to the soil. This cover was destroyed with introduction of domestic animals after the Spanish conquest. Thus Reagan assumes that the structures built by prehistoric men were sufficient to reduce floods without complete consideration of the difficulties involved. He ignores the fact that alternation between erosion and alluviation began before entrance of the Puebloan peoples into the area. The earlier epicycles could not have been influenced by such causes as Reagan advances.

Olmsted (1919, p. 88) estimated the cost of check dams and bank structures for control of Gila River above the San Carlos dam site at a total of $6,401,029. Elaborate as these plans seem, engineers by no means agree that they are adequate to control floods on Gila River, much less to restore channel conditions to those obtaining before 1880. In recent years the Soil Conservation Service has built structures for control of erosion which exceed in magnitude anything possible to the ancients. Success has been rare and modest. That primitive man could erect barriers sufficient in number and size to accomplish this result seems improbable. If such attempts had been made, remnants should remain to be easily identified.

All the investigators mentioned above considered that they were dealing with only one period of sedimentation and one period of erosion, although Huntington thought these minor changes of the geological Recent were the latter part of a series of such changes running back into Pleistocene time. If the post-Bonito channel represents a valid cycle of erosion and sedimentation then three complete local cycles of erosion and sedimentation and part of a fourth must be explained. These events may be put in tabular form, as follows:

Cycles of erosion and sedimentation in Chaco Canyon

1st cycle	Erosion of canyon or later part of this erosion	Sedimentation and formation of terrace
2d cycle	Erosion of terrace	Sedimentation and formation of main valley fill
3d cycle	Erosion of post-Bonito channel	Sedimentation and fill of post-Bonito channel
4th cycle	Erosion of present arroyo	Future?

Presented in this form it seems evident that a postulate of climatic change has greater inherent possibilities as a true explanation of the facts. Domestic animals certainly cannot be charged with inception of the post-Bonito erosion. However great the influence of overgrazing, therefore, it must be regarded as a mere trigger pull which initiated an epicycle of erosion that was brought about by other causes.

Reagan (1924a, p. 285) has carried the factor of overgrazing into prehistoric times and suggests that incoming and increasing hordes of herbivorous animals may have overgrazed the country and thus caused formation of arroyos. Thereafter, the animals having starved to death or left the region, vegetation would again spring up and sufficiently protect the land surface so that streams would again begin to aggrade. Thus he postulates recurrent overgrazing with consequent cycles of erosion and aggradation. That animals in a state of nature would overgraze an area is an assumption without proof. It seems best to pass this interesting postulate since there exists ample evidence that at least one period of sedimentation in the not-distant past was wetter than the present.

Douglass [6] has described briefly the valley deposits of the Rio de Flag, a small creek near Flagstaff, Ariz. Here an arroyo dating from 1890 to 1892 has dissected a valley fill; standing stumps of pine trees are found from 4 to 16 feet below the surface and prostrate logs in the upper 4 feet. Both stumps and logs belong to the living species, *Pinus ponderosa*, now growing on the adjacent hillside. The stumps, however, have wide growth rings similar to those found in trees of humid lands. The prostrate logs have narrow rings like living trees of the region. It seems evident, therefore, that the zone from 4 to 16 feet below the surface was deposited under a climate much wetter than now. In addition, human relics have been found in the fill at depths from 4 to 9 feet but their relation to the stumps is uncertain. Evidence in the valley fill of the presence of man seems to indicate that the humid period demonstrated by the stumps is not very ancient. It may represent one of the cycles of sedimentation disclosed in Chaco Canyon or an older cycle not yet identified there.

Study of the Chaco Canyon deposits has not produced incontestable evidence that wetter climates prevailed there in the past. From the main valley fill—2d cycle of the table, page 49—we collected a few fresh-water shells but similar shells were also found in the post-Bonito channel. In some of the sandy and silty beds of the main valley fill impressions that resemble rushes were noted. The adobes are dark

[6] 1924, pp. 238-239. This reference supplemented by an oral communication, and by inspection of the locality by me in September 1921.

brown from included organic matter, but this might have derived from a heavy growth of grass or other vegetation.

There is, however, nothing in the character of these sediments that precludes their deposition under a slightly wetter climate. It is possible there may have been a sufficiently greater rainfall so that pine trees grew in favored places on the hills, cottonwood and willows may have bordered the river, the valley floor may have had large areas of perennial grass and in a few places there may even have been marshy ground with cattails. Currently existing damp places under the north cliffs may have been small springs in times past. Such an environment seems compatible with the type of alluvium deposited and yet sufficiently favorable to have provided an adequate food supply for the peoples of the thirteen villages of Chaco Canyon. Such a climate cannot be inferred from the nature of the sediments themselves but, on the other hand, those sediments present no evidence that a relatively slight modification of climate did not exist when they were being deposited.

[NOTE.—Bryan's speculations in the foregoing paragraphs have been substantiated in large measure by data from our excavations and from further exploration. Our old Navaho neighbors reported pine stumps at various places about the valley; dead and prostrate pines were photographed on the south cliff and a couple of dozen trees and stumps were seen at the head of the canyon, 16 miles to the east (Douglass, 1935, p. 46). These last few remnants of former forests suggest that the annual rainfall in their time was considerably greater than our postulated 10-inch average for the present. Even more suggestive is the fact that thousands of logs, large and small, went into construction of Pueblo Bonito and its neighboring villages between A.D. 900 and 1100. The forests that furnished those logs must have been close at hand since none of the timbers we uncovered was scarred in transportation and such forests, at 6,500 feet, could have flourished as they did only in a climate somewhat wetter than that of today. Indeed, many of the old ceiling timbers from Pueblo Bonito exhibited growth rings so uniform in width they obviously had grown where moisture was fairly constant year after year. In addition, we know that rushes were then abundant and readily accessible, for quantities were utilized in the building of Pueblo Bonito.—N. M. J.]

DETAILED SECTIONS IN THE RECENT ALLUVIUM

SECTIONS IN THE MAIN VALLEY FILL

The following sections, measured at various places along the main arroyo, record the character and thickness of the several strata from the top of the bank to its base, and give a record of human relics found therein. Each station is indicated on the accompanying map, figure 1, by its corresponding number.

Section 1

South bank of main arroyo, 200 yards east of expedition camp. No potsherds were recovered in this section but opposite, in the north bank, plain ware of coarse texture was found at a depth of about 12 feet.

	Thickness		Depth	
	Feet	Inches	Feet	Inches
Laminated dark clay and sand, more clayey above	4	0	4	0
Silt with streaks of clay	3	0	7	0
Sand	2	0	9	0
Laminated dark silt	0	6	9	6
Silt and sand with thin streak of clay 18 in. above base	3	4	12	10
Dark clay, with shells	0	8	13	6
Sand	3	0	16	6
Covered below.				

PIT HOUSE

At the place on the map marked "Pit House" there was discovered in 1922 a structure partly destroyed by erosion of the arroyo bank. What remained was excavated and studied by Neil M. Judd, who has described it at length (Judd, 1924). It consisted of a single circular room with the middle of its slightly concave floor 12 feet 2 inches below the present surface. The original excavation was 6 feet deep (pl. 6, lower). The builders of this subterranean house lived when the flood plain was 6 feet lower than it now is, and doubtless they or their contemporaries are responsible for the human relics at deeper levels shown in the sections to follow.

Section 2

In a small tributary entering the main arroyo from northwest of Pit House.

	Thickness		Depth	
	Feet	Inches	Feet	Inches
Soil and clay, more sandy above	1	10	1	10
Sand	0	2	2	0
Clay	0	2	2	2
Sand	0	7	2	9
Clay	1	7	4	4
Hard compact sandy clay with fragments of charcoal and 2 potsherds	1	4	5	8

	Thickness		Depth	
	Feet	Inches	Feet	Inches
Clay with scattered bits of charcoal and with fireplace at base marked by crescentic streak of charcoal and burned ground below	0	5	6	1
Sandy adobe	3	0	9	1

Near section 2 and in the same small arroyo, there is a ruined house now almost destroyed by erosion. Its foundations reach to a depth of 8 feet below the surface, yet the walls appear to be quite similar to masonry of the neighboring great pueblos and the potsherds are of both early and late types.

Two alternatives must be considered, either the pit house and this small pueblolike dwelling are contemporaneous, which is unlikely, or, granting that the pit house is older, the pueblo-type dwelling and section 2 are located in a later deposit.

Section 3

Section 3, on the south bank about 300 yards east of the pit house, represents a normal succession of beds. A potsherd at 4 feet below the surface is of undetermined type. Sherds found between depths of 17 feet and 20 feet 6 inches, are of Pit House or older age. This is the greatest depth at which potsherds were found.

	Thickness		Depth	
	Feet	Inches	Feet	Inches
Soil and clay, upper 8 in. the most clayey	2	6	2	6
Silt	1	0	3	6
Alternate layers of clay and silt; potsherds 6 in. from top of this layer and 4 ft. from surface	1	6	5	0
Clay	1	0	6	0
Sand	2	6	8	6
Alternate layers of clay and silt	1	6	10	0
Silt and sand laminated and crossbedded and grading into lower layer	7	0	17	0
Clayey sand; much scattered charcoal, sandstone fragments, some of which are reddened by fire, potsherds and worked cores of quartzite and agate	2	0	19	0
Sand, with a few sandstone fragments and potsherds at bottom. Marks base of culture layer.	1	6	20	6
Sandy adobe darker than that above with plant impressions	3	5	23	11
Covered to bed of arroyo	7	1	31	0

Section 4

In the north bank of the main arroyo and near the "store" at southeast corner of Pueblo del Arroyo (pl. 7, lower). The section was measured in the middle of a channel deposit which lies beneath a horizontal clay layer. The deposit itself is 13 feet 5 inches thick at the deepest point exposed, and its base is 15 feet below the level of the adjacent plain. Nearby, in 1877, Jackson found potsherds, bones, and a human skull at a depth of 14 feet, as discussed on page 32.

	Thickness		Depth	
	Feet	Inches	Feet	Inches
Clay	1	8	1	8
Sand, with lenses of fine gravel and clay which dip toward center of old channel. Crescentic lense of laminated clay; depth of lowest part 12 ft., thickness 6 in. Sandstone blocks imbedded in this clay like steppingstones. Gravel layer at base. Many fragments of bones, broken rocks, a few shells and many potsherds especially near base	13	5	15	1
Clay and laminated silt, scattered charcoal to depth of 21 ft. 6 in.	7	0	22	1

Section 5

South bank of main arroyo opposite Ruin No. 8 and a short distance east of section 16 (see pp. 29-30). Of special note is a Pueblo III fireplace (pl. 3, right) built when the surface was 5 feet lower than it is now, a second hearth at 12 feet 8 inches, and charcoal at 16 feet 3 inches.

	Thickness		Depth	
	Feet	Inches	Feet	Inches
Dark clay, a fairly continuous layer that thickens and thins	0	8	0	8
Fine-grained sand, finely laminated and cross-bedded, with impressions of roots	0	8	1	4
Clay	0	2	1	6
Sand, laminated and containing streaks of charcoal and chunks of clay	1	6	3	0
Dark clay and laminated sand. Clay is in irregular thin layers which slope from south to north and fade out in irregular broken chunks of clay imbedded in sand. A firebox formed of nearly vertical sandstone slabs at depth of 5 ft. is of P. III type	2	9	5	9

	Thickness		Depth	
	Feet	Inches	Feet	Inches
Compact rusty sandy clay with fragments of stone, potsherds, and charcoal. Potsherds are 6 ft. 3 in. from surface and of indeterminate type	0	6	6	3
Crossbedded sand to crescentic hearth 12 ft. 8 in. below top of section; scattered charcoal at 14 ft. 8 in. and, 50 ft. south of section, at 16 ft. 3 in.	13	0	19	3
Covered below.				

Sections 6 and 7

Sections 6 and 7 are near each other and in the north branch of the main arroyo opposite Una Vida (fig. 1). The bedding is very irregular in this vicinity, and none of the layers listed is persistent. Section 6 has potsherds considered to be of Pueblo III type between 4 feet 6 inches, and 5 feet below the surface. Section 7 shows a very large hearth 8 feet from the surface.

Section 6

In north bank of north channel, near Una Vida.

	Thickness		Depth	
	Feet	Inches	Feet	Inches
Dark clay. Potsherds at 4 ft. 6 in. and 5 ft.	5	0	5	0
Crossbedded sand, with lenses of clay a few feet off the line of the section	3	6	8	6
Clay	1	6	10	0
Crossbedded sand and silt	2	6	12	6
Clay	2	0	14	6
Clayey silt to bottom of arroyo	4	0	18	6

Section 7

In south bank of north channel, 100 yards upstream from section 6.

	Thickness		Depth	
	Feet	Inches	Feet	Inches
Clay	3	0	3	0
Sand	3	0	6	0
Clay, with open hearth at base. Hearth is 8 ft. long and burnt (red) ground is nearly 1 ft. thick with much charcoal above	2	0	8	0
Sand and silt	1	2	9	2
Adobe	1	5	10	7
Sand and silt to bottom of arroyo	3	7	14	2

Section 8

South bank of main arroyo 2 miles east of Wejegi and outside the area of our map.

	Thickness		Depth	
	Feet	Inches	Feet	Inches
Dark clay	2	0	2	0
Laminated and crossbedded sand with a few lenses of gravel. At depth of 10 ft. 4 in. there is a streak of charcoal resting on burnt (red) earth; at 13 ft. 2 in., a second streak of charcoal, directly below the first but no red earth; scattered charcoal occurs to depth of 21 ft.	25	4	27	4
Covered below.				

Section 9

In arroyo of Rincon del Camino, about 300 feet south of the road and in the fan of the rincon.

	Thickness		Depth	
	Feet	Inches	Feet	Inches
Compact rusty sandy clay with fragments of stone and charcoal; potsherds at 6 ft. 3 in.	6	3	6	3
Crossbedded sand with impressions of plant stems and scattered charcoal to depth of 14 ft. 8 in. At depth of 12 ft. 8 in. there is a hearth crescentic in section and consisting of baked and reddened floor 2 ft. 1 in. across and rising 3 in. at the ends with layer of charcoal from ½ to 1½ in. thick. South 50 ft. from this section, scattered charcoal occurs to a depth of 16 ft. 3 in. from top of bank	13	0	19	3

Section not numbered

North bank of main arroyo west of 1924 dump. [South of the Wetherill corrals and 100 yards, more or less, west of the expedition camp.—N. M. J.]

	Thickness		Depth	
	Feet	Inches	Feet	Inches
Apparently uniform indurated sand mixed with adobe and a little silt	6	0	6	0
Laminated clay interbedded with slightly indurated sand. Fine interbeddings well defined and nearly parallel. Lower 0.7 ft. has broader laminae	2	7	8	7
Indurated sand laminated without adobe	1	6	10	1
Fine white sand slightly indurated and finely laminated	1	0	11	1

	Thickness		Depth	
	Feet	Inches	Feet	Inches
Nonlaminated clayey sand, indurated	0	5	11	6
White sand slightly and inconspicuously laminated	0	9	12	3
Well-indurated inconspicuously laminated sand with large content of fine silt or clay	2	8	14	11
Gray sand slightly laminated and indurated	2	8	17	7
Clay containing sand and showing tendency to granulate and fissure on shrinkage (adobe)	2	8	20	3
Fine nonlaminated sand slightly indurated	1	2	21	5
Clay containing some sand and showing tendency to granulate and fissure on shrinkage	2	7	24	0
Pulverant loamy sand containing minute black fragments (moist)	3	0	27	0

Section 15

In middle of buried channel, on south bank of main arroyo and 200 yards upstream from mouth of Rincon del Camino.

	Thickness		Depth	
	Feet	Inches	Feet	Inches
Alternate bands of sandy clay with internal cracks and compact sand	4	0	4	0
Compact sand	1	7	5	7
Sandy clay with internal cracks and streaks of compact sand	1	2	6	9
Minutely crossbedded compact sand with a few lenses of clay 3 to 4 ft. long near base	3	4	10	1
Crossbedded compact sand with lense of gravel 1 ft. thick and 4 ft. long at base, containing burnt sandstone blocks up to 6 in. across, clay pellets, blocks of clay, and potsherds of late type, base of buried channel	3	0	13	1
Crossbedded sand, crossbedding on larger scale, streaks of pieces of black shale and coal	2	3	15	4
Compact crossbedded sand	2	7	17	11
Covered	5	0	22	11

Section 17

At the mouth of Rincon del Camino a narrow point projects into the main arroyo from the north. On the east face of this point a well-defined buried channel is exposed. Section 17 was measured in the middle of this exposure.

	Thickness		Depth	
	Feet	Inches	Feet	Inches
Yellow pulverant sand derived from Rincon del Camino	0	6	0	6

	Thickness		Depth	
	Feet	Inches	Feet	Inches
Sandy clay with internal cracks	1	0	1	6
Yellow pulverant sand derived from Rincon del Camino	1	4	2	10
Sandy clay with internal cracks contains sand lense to south of section	2	8	5	6
Gray, minutely laminated sand; laminae slope to south, are interbedded there with clay layers	4	10	10	4
Yellow crossbedded compact sand with gravel lenses. To the south a clay lense. Upper gravel at 13 ft. 7 in., lower at base, contains clay balls, pellets, and potsherds of late type in both lenses	5	8	16	0
Sandy clay, upper part has internal cracks; base of buried channel	2	4	18	4
Compact laminated sand with lenses of clay having internal cracks to bed of arroyo	6	2	24	6

SECTIONS IN THE BURIED, OR POST-BONITO, CHANNEL

In 1922 Mr. Judd had dug a number of pits in the vicinity of Pueblo Bonito in order to obtain soil samples for analysis. None of these pits exceeded 10 feet in depth because that appeared to be well below the level of fields once cultivated by the villagers and subsequently overlain by post-Bonito alluvial deposits. Pit number 3, located in the plain between the expedition camp and the ruin, had been fenced and left open for possible further tests. When this pit was deepened at my suggestion in 1925 we were all surprised to find late Bonito potsherds at depths of 10 to 18 feet. This meant we were right in the middle of the buried channel. Some fragments showed the influence of contact with the Mesa Verde culture, thus further identifying the channel fill as contemporaneous with the last years of Pueblo Bonito or even later and, of course, much later in age than the main valley fill.

Log of test pit number 3

Between Pueblo Bonito and expedition camp

Materials found	Thickness		Depth		Potsherds	Found at	
	Feet	Inches	Feet	Inches		Feet	Inches
Dark sandy clay (adobe)	2	0	2	0			
Laminated fine sand and silt	2	2	4	2			
Dark sandy clay (adobe)	0	9	4	11			
Sand with thin layers of laminated silt and clay	1	11	6	10			
Laminated layers of silt and dark clay	4	1	10	11		10	
Dark sticky clay	0	11	11	10	A few	to	
Laminated fine sand	2	5	14	3		12	2

Materials found	Thickness Feet	Thickness Inches	Depth Feet	Depth Inches	Potsherds	Found at Feet	Found at Inches
Laminated clay	0	7	14	10			
Laminated and minutely crossbedded coarse sand. This bed grades to south into gravelly clay that extends to depth of 16 ft. 10 in.	1	5	16	3	Many	16 1 to 16 8	
Dark clay	0	5	16	8			
Fine sand	0	2	16	10			
Gravelly clay containing large and small stones, grades into sand to south	1	5	18	3	Numerous	17 3 to 18 3	
Fine sand	0	3	18	6			

Log of test pit number 4

Sixty feet east from arroyo bank at section 4

Materials found	Thickness Feet	Thickness Inches	Depth Feet	Depth Inches	Potsherds	Found at Feet	Found at Inches
Gray-brown sandy clay (adobe)	1	10	1	10			
Laminated sandy adobe, a lense	0	2	2	0			
Hard brown sand with pieces of charcoal	2	2	4	2			
Brown sand in part finely laminated with lenticular streaks of dark laminated clay ½ to 1 in. thick and spaced 2 to 10 in. apart	3	3	7	5	One only	7	0
					" "	7	2
Hard brown sand, containing at north end of pit an irregular lense of sandy and gravelly adobe containing charcoal and bones	2	5	9	10	Many	9	6
Dark sandy clay (adobe) with small lense of gravel	4	7	14	5	Many in gravel	10 6 to 10 8	
					Many	11 6 to 11 8	
Sand (a lense) that extends to 15 ft. at north end of pit	0	3	14	8			
Adobe to bottom of pit	0	9	15	5	Many	15	0

SUMMARY

Chaco River, a river only during occasional floods, entrenched itself at some past time, doubtless Pleistocene, in a broad plain that then existed in the San Juan Basin of northwestern New Mexico. In the nearly horizontal sandstones and shales that underlie San Juan Basin, the Chaco River flows, when it flows at all, alternately in broad valleys and narrow canyons. To one of these latter the name Chaco Canyon is applied almost exclusively, and here, in a stretch of about 12 miles, there are numerous ruins of prehistoric villages, the largest of which is Pueblo Bonito.

Chaco Canyon, after its excavation, was partly refilled with sand and silt during a period of alluviation common to most streams of the southwestern United States. On the flat floor of the canyon, resulting from this alluviation, the prehistoric peoples lived and left evidence of their long-time occupation in hearths, scattered charcoal, potsherds, and other relics. These remains extend to a depth of 21 feet below the present surface of the alluvium. An ancient type of dwelling known as a pit house has been found at a depth of 6 feet below the surface, but the typical Pueblo III type of construction has not been surely identified below 4 feet.

Alluviation in Chaco Canyon and generally throughout the Southwest has more recently been interrupted by the formation of an arroyo or steep-sided gully in which the floods of the stream are now wholly confined. The Chaco Canyon arroyo is presently 20 to 30 feet deep and from 150 to 400 feet wide, yet a military expedition of 1849 did not mention the gully, if it then existed. In 1877 an arroyo 16 feet deep and 60 to 100 feet wide was reported. Available evidence indicates that the arroyos of other streams were mostly formed in the decade 1880 to 1890 and that the process is still going on. The beginning of the Chaco arroyo appears to have been somewhat earlier and the date may, with some assurance, be placed in the decade 1860 to 1870.

A study of the deposits that make up the valley fill indicates that Chaco River never had a permanent low-water flow. No signs of irrigation ditches or other diversions of flowing water have been found in the alluvial deposits. It seems probable, therefore, that the prehistoric inhabitants of the canyon practiced floodwater farming, a form of agriculture still in use in the region. For this type of farming wide-spreading floods are a prerequisite, and the beginning of erosion, with formation of an arroyo that confines the floods and lowers the water table, puts an end to agriculture of this type.

The main body of the valley fill is of unknown depth. Only the upper 30 feet is exposed and of this the uppermost 21 feet contains relics of man. Pottery made by the ancient people varies in texture and design according to locality and age. Differences between the kinds of pottery typical of different stages in human culture are not wholly known, nor has a definite chronology of the stages been determined, but broad distinctions can be made between the older and younger civilizations.

Collections of potsherds can therefore be used as fossils in studying the stratigraphy of the valley alluvium. Generally, only a few potsherds are found at any one place and many of these are indeterminate, hence of no diagnostic value. Somewhat meager collections of sherds from depths of 6 to 21 feet have been examined by the expedition's archeologists who identify them as mostly a coarse ware characteristic of the Pit House culture. On the basis of these fragments, therefore, we may draw the inference that people of the Pit House period were the principal inhabitants of Chaco Canyon during the time required for deposition of those 15 feet of alluvium.

Potsherds collected from the zone of valley fill less than 6 feet below the surface are generally of Pueblo III type. This fact, together with ruins whose foundations are partly buried in alluvium, indicate that Pueblo III people occupied the valley during the period represented by the last 6 feet of alluviation.

In the bank of the arroyo near Pueblo del Arroyo there is exposed a buried channel which extends to a depth of 15 feet below the present surface. At this point the channel is a well-defined ancient arroyo that had been refilled and then buried under an additional 2 feet of sediment in the interval between abandonment of Pueblo Bonito and American Army penetration of Chaco Canyon in 1849. Potsherds removed from the gravel lenses of that buried channel included fragments of the latest Pueblo Bonito types. The channel, therefore, must have been refilled late in the occupancy of Pueblo Bonito or after its abandonment.

By means of test pits in which similar pottery was found, we traced this buried channel for about 1,000 feet across the plain fronting Pueblo Bonito and later discovered remnants of it both up and down the canyon. This buried channel clearly represents a period of dissection and arroyo formation for the full length of the valley and, assuming that the dissection occurred late in the occupancy of Pueblo Bonito, an adequate cause exists for abandonment of the canyon by aboriginal farmers whose floodwater fields were destroyed by confinement of the floods within this channel, and by concurrent events.

Our examination of the main valley fill suggests alternate dissection and alluviation of Chaco Canyon: three periods of dissection and two of alluviation. If this alternation represents a true cycle, we may expect the present arroyo to run its course and then be refilled and perhaps covered over. However plausible it may be to attribute formation of the present arroyo to destruction of the vegetative cover by overgrazing, the previous dissection and subsequent alluviation were in no way affected by domestic animals. It seems probable, therefore, that the ultimate cause of this periodic change in the regime of streams is climatic. A slightly increased rainfall would increase the vegetative cover and thereby both reduce the violence of floods and protect the soil from erosion. Any decrease in rainfall would produce a reversed effect. Although the deposits of Chaco Canyon contain no definite evidence of a more humid climate during the two periods of their deposition, it seems likely that an increased humidity did exist and was a factor in development of the distinctive Chaco culture. The subsequent change to more arid conditions was doubtless of less effect until it culminated in formation of the twelfth-century arroyo that unexpectedly became a dominant feature of this study.

BIBLIOGRAPHY

Bauer, Clyde Max.

1917. Stratigraphy of a part of the Chaco River Valley. U. S. Geol. Surv. Prof. Pap. 98, pp. 271-278.

Bauer, Clyde Max, and Reeside, John B., Jr.

1921. Coal in the middle and eastern parts of San Juan County, New Mexico. U. S. Geol. Surv. Bull. 716, pp. 155-237.

Brown, Barnum.

1910. The Cretaceous Ojo Alamo beds of New Mexico, with description of the new dinosaur genus *Kritosaurus*. Bull. Amer. Mus. Nat. Hist., vol. 28, pp. 267-274.

Bryan, Kirk.

1920. Origin of rock tanks and charcos. Amer. Journ. Sci., ser. 4, vol. 50, pp. 188-206.

1923a. Erosion and sedimentation in the Papago country, Arizona, with a sketch of the geology. U. S. Geol. Surv. Bull. 730, pp. 19-90.

1923b. Ground water in Quinn River and Paradise Valleys, Nevada. U. S. Geol. Surv. press notice, Jan. 29, 1923.

1925a. Date of channel trenching (arroyo cutting) in the arid Southwest. Science, n.s., vol. 62, No. 1607, pp. 338-344.

1925b. The Papago country, Arizona—a geographic, geologic, and hydrologic reconnaissance, with a guide to desert watering places. U. S. Geol. Surv. Water-Supply Pap. 499.

1926a. Recent deposits of Chaco Canyon, New Mexico, in relation to the life of the prehistoric peoples of Pueblo Bonito. (Abstr.) Journ. Washington Acad. Sci., vol. 16, No. 3, pp. 75-76.

1926b. Channel erosion of the Rio Salado, Socorro County, New Mexico. U. S. Geol. Surv. Bull. 790A, pp. 17-19.

1928a. Historic evidence on changes in the channel of Rio Puerco, a tributary of the Rio Grande in New Mexico. Journ. Geol., vol. 36, No. 3, pp. 265-282.

1928b. Change in plant associations by change in ground water level. Ecology, vol. 9, No. 4, pp. 474-478.

1928c. Niches and other cavities in sandstone at Chaco Canyon, N. M. Zeitschr. Geomorph., vol. 3, pp. 125-140. Leipzig.

1929. Flood-water farming. Geogr. Rev., vol. 19, pp. 444-456.

1941. Pre-Columbian agriculture in the Southwest as conditioned by periods of alluviation. Ann. Assoc. Amer. Geogr., vol. 31, No. 4, pp. 219-242.

BRYAN, KIRK, and McCANN, FRANKLIN T.

1936. Successive pediments and terraces of the Upper Rio Puerco in New Mexico. Journ. Geol., vol. 44, No. 2, pt. 1, pp. 145-172.

DAVIS, W. M.

1903. An excursion to the Plateau province of Utah and Arizona. Bull. Mus. Comp. Zool., Harvard Coll., vol. 42, pp. 1-50.

DODGE, RICHARD E.

1902a. An interesting landslide in the Chaco Canyon, New Nexico. Science, n.s., vol. 15, p. 746.

1902b. Arroyo formation. Science, n.s., vol. 15, p. 746.

1910. The formation of arroyos in adobe-filled valleys in the southwestern United States. (Abstr.) Rep. British Assoc. Adv. Sci., vol. 79, pp. 531-532.

1920. *See* Pepper, George H.

DOUGLASS, A. E.

1924. Some aspects of the use of the annual rings of trees in climatic study. Ann. Rep. Smithsonian Inst. for 1922, pp. 223-239.

1935. Dating Pueblo Bonito and other ruins of the Southwest. Nat. Geogr. Soc., Contr. Techn. Pap., Pueblo Bonito Ser., No. 1.

DUCE, JAMES TERRY.

1918. The effect of cattle on the erosion of canyon bottoms. Science, n.s., vol. 47, pp. 450-452.

DUTTON, C. E.

1882. Tertiary history of the Grand Canyon district. U. S. Geol. Surv. Monogr., No. 2.

ENDLICH, F. M.

1877. Geological report on the Southeastern district. 9th Ann. Rep. U. S. Geol. and Geogr. Surv. Terr. for the year 1875, pp. 103-235.

GARDNER, J. H.

1909. The coal field between Gallina and Raton Spring, New Mexico, in the San Juan coal region. U. S. Geol. Surv. Bull. 341, pp. 335-351.

GREGORY, H. E.

1915. The oasis of Tuba, Arizona. Ann. Assoc. Amer. Geogr., vol. 5, pp. 107-119.

1916. The Navajo country: A geographic and hydrographic reconnaissance of parts of Arizona, New Mexico, and Utah. U. S. Geol. Surv. Water-Supply Pap. 380.

1917. Geology of the Navajo country: A reconnaissance of parts of Arizona, New Mexico, and Utah. U. S. Geol. Surv. Prof. Pap. 93.

HACK, JOHN T.

1942. The changing physical environment of the Hopi Indians of Arizona. Pap. Peabody Mus. Amer. Archaeol. and Ethnol., Harvard Univ., vol. 35, No. 1.

HOLMES, W. H.
1877. Geological report on the San Juan district. 9th Ann. Rep. U. S. Geol. and Geogr. Surv. Terr. for the year 1875, pp. 237-276.
HOOVER, J. W.
1929. The Indian country of southern Arizona. Geogr. Rev., vol. 19, No. 1, pp. 38-60.
1930. Tusayan: The Hopi country of Arizona. Geogr. Rev., vol. 20, pp. 425-444.
HUNTINGTON, ELLSWORTH.
1914. The climatic factor as illustrated in arid America. Carnegie Inst. Washington Publ. 192.
JACKSON, W. H.
1878. Report on the ancient ruins examined in 1877. 10th Ann. Rep. U. S. Geol. and Geogr. Surv. Terr. for the year 1876, Chaco Canyon, pp. 431-450.
JUDD, NEIL M.
1924. Two Chaco Canyon pit houses. Ann. Rep. Smithsonian Inst. for 1922, pp. 399-413.
LOEW, OSCAR.
1879. Report on the ruins in New Mexico. Report upon U. S. geographical surveys west of the 100th meridian (Wheeler Surveys), vol. 7, pp. 337-345. (Abstr. from Ann. Rep. Chief of Engineers for 1875, App. LL, Sect. J-2, pp. 174-178.)
LUMHOLTZ, KARL SOFUS.
1912. New trails in Mexico. New York.
MATTHEW, W. D.
1897. A revision of the Puerco fauna. Amer. Mus. Nat. Hist. Bull. 9, pp. 259-323.
MORRISON, C. C.
1879. Notice of the Pueblo Pintado and of other ruins in the Chaco Canyon. Report upon U. S. geographical surveys west of the 100th meridian (Wheeler Surveys), vol. 7, pp. 366-369. (Abstr. from Ann. Rep. Chief of Engineers for 1876, App. JJ, Sect. E, pp. 359-360.)
NELSON, N. C.
1914. Pueblo ruins of the Galisteo Basin, New Mexico. Anthrop. Pap. Amer. Mus. Nat. Hist., vol. 15, pt. 1, pp. 1-124.
OLMSTED, FRANK HENRY.
1919. Gila River flood control: Report on flood control of Gila River in Graham County, Arizona. Dep. Interior, 65th Cong., 3d Sess., Senate Doc. 436.
PEPPER, GEORGE H.
1920. Pueblo Bonito. Anthrop. Pap. Amer. Mus. Nat. Hist., vol. 27.
REAGAN, ALBERT B.
1922. Archaeological notes on Pine River valley, Colorado, and the Kayenta-Tuba region, Arizona. Trans. Kansas Acad. Sci., vol. 30, pp. 244-331, 394-429.
1924a. Recent changes in the Plateau region. Science, n.s., vol. 60, pp. 283-285.
1924b. Stream aggradation through irrigation. Pan-Amer. Geol., vol. 42, pp. 335-344.

REESIDE, J. B., JR.
1924. Upper Cretaceous and Tertiary formations of the western part of the San Juan Basin, Colorado and New Mexico. U. S. Geol. Surv. Prof. Pap. 134.

RICH, JOHN LYON.
1911. Recent stream trenching in the semi-arid portion of southwestern New Mexico, a result of removal of vegetative cover. Amer. Journ. Sci., ser. 4, vol. 32, pp. 237-245.

ROBINSON, H. H.
1907. The Tertiary peneplain of the Plateau district and adjacent country in Arizona and New Mexico. Amer. Journ. Sci., ser. 4, vol. 24, pp. 109-129.

SCHRADER, F. C.
1906. The Durango-Gallup coal field of Colorado and New Mexico. U. S. Geol. Surv. Bull. 285, pp. 241-258.

SENTER, DONOVAN.
1937. Floor deposition and erosion in Chaco Canyon. Univ. New Mexico Bull. No. 308, App. I, pp. 134-139.

SHALER, MILLARD K.
1907. A reconnaissance of the western part of the Durango-Gallup coal field of Colorado and New Mexico. U. S. Geol. Surv. Bull. 316, pp. 376-426.

SIMPSON, JAMES H.
1850. Journal of a military reconnaissance from Santa Fe, New Mexico, to the Navajo country . . . in 1849. Rep. Secretary of War, 31st Cong., 1st Sess., Senate Ex. Doc. No. 64, pp. 56-168.

SINCLAIR, W. J., and GRANGER, WALTER.
1914. Paleocene deposits of the San Juan Basin, New Mexico. Bull. Amer. Mus. Nat. Hist., vol. 33, pp. 297-316.

SMITH, G. E. P.
1910. Ground water supply and irrigation in the Rillito Valley. Univ. Arizona Agr. Exp. Stat. Bull. No. 64, pp. 98-99.

THORNBER, J. J.
1910. The grazing ranges of Arizona. Univ. Arizona Agr. Exp. Stat. Bull. No. 65, pp. 335-338.

WILLIAMS, GEORGE O.
1925. Radium-bearing silts of southeastern Utah. Eng. and Min. Journ.-Press, vol. 119, pp. 201-202.