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DYNAMICS OF SEDIMENTATION AND GEOMORPHIC HISTORY OF CHACO CANYON NATIONAL MONUMENT, NEW MEXICO*

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INTRODUCTION

Chaco Canyon, located in the middle of the San Juan Basin in northwestern New Mexico, is famous for spectacular multi-storied stone pueblos built about 850 to 1000 years ago. The reasons for the flourishing and subsequent disappearance of these prehistoric people remain obscure. In order to provide answers about the way the people lived in what is presently a semiarid, uncompromising environment, the National Park Service Chaco Center of the University of New Mexico initiated a multidisciplinary investigation of the archaeology, geology and ecology of Chaco Canyon National Monument. As a result, several new reports discuss the geology of the area. Siemers and King (1974) described the bedrock geology and paleontology of the canyon. DeAngelis (1972) summarized the physical geography of the Chaco drainage. Hall (1975) investigated the palynology of the alluvial fill. Nichols (1975) tested the possibility of magnetically dating the sediments of the canyon floor and Ross (in progress) is examining the depth of the canyon fill and the detailed sedimentology of well cores of the alluvium. Investigations by the U.S. Geological Survey concern geomorphic processes and water quality in the canyon (Malde, personal commun.; Lyford, personal commun.).

The purpose of this paper is to summarize the results of my investigation of the dynamics of Quaternary sedimentary deposits in Chaco Canyon. The study included an investigation of the relationships between climate and geomorphic and sedimentologic conditions in the upper Chaco River drainage basin. Consequently, the conditions involved in filling former arroyos are interpreted from arroyo fills exposed in the walls of the present arroyo. The possible conditions in the canyon during the period of extensive occupation by prehistoric peoples, until about 850 years ago, are interpreted from sedimentologic constraints and from tree rings. Besides arroyo cuts-and-fills which predate the pueblos, there is evidence of other geomorphic regimes in the canyon which extends the geomorphic history of Chaco Canyon.

The most famous report on the geology of Chaco Canyon is by Bryan (1954). Besides summarizing the bedrock geology of Chaco Canyon, Bryan interpreted the history of the formation of the canyon and its subsequent alluvial fill. He explored the relationships between climate, vegetative' cover and cycles of arroyo cut-and-fill. Bryan interpreted a buried arroyo containing pottery in the base of the channel as a major factor in the abandonment of the pueblos. His interpretations of the history of Chaco Canyon have been used by archaeologists and geologists for decades, but the results of the present investigation do not substantiate Bryan's conclusions about the relationships between stream behavior and climate, about the initiation of the modern arroyo and about the conditions in the canyon during the occupation of the pueblos.

GEOMORPHOLOGY OF THE CHACO DRAINAGE, CHACO CANYON AND THE MODERN ARROYO

The drainage of the Chaco River covers about 11,500 km^2 in the south central part of the San Juan Basin (fig. 1). The Chaco River is an ephemeral stream except for 20 km above the junction with the San Juan River, where water from Morgan Lake (a man-made cooling pond for the Arizona Public Service Company power plant) provides a permanent source of flow. The Chaco River's headwaters, 40 km east of Chaco Canyon National Monument, consist of small shallow swales, discontinuous washes (relatively wide with low banks) and discontinuous arroyos (relatively narrow with high banks). Chaco Arroyo begins 15 km east of Chaco Canyon, and continues for 37 km through the canyon until Escavada Wash joins the drainage from the northeast. Below the junction of Escavada Wash, the Chaco River is a broad (200-450 m) braided sandy wash that leaves the confines of the canyon, flows west for 70 km, and turns north abruptly. To the north, arroyo walls gradually rise to about 5 m above the channel. After flowing north for 70 km, within 4 km of the San Juan River, the Chaco River is diverted to the west by a gravel terrace of the San Juan River. As a result, the Chaco River cuts

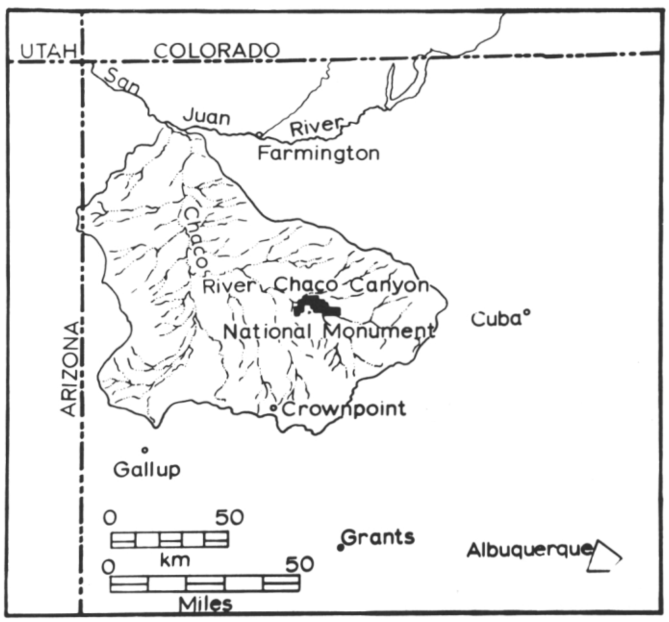


Figure 1. Location of the Chaco River drainage basin and Chaco Canyon National Monument in northwestern New Mexico.

*This paper is inventoried as contribution Number 23 of the Chaco Center, National Park Service and the University of New Mexico, for purposes of bibliographic control of research relating to Chaco Canyon.

through a hogback of Cretaceous Cliff House Sandstone and joins the San Juan River 18 km downstream.

Chaco Canyon is 32 km long, from 500 to 1000 m wide and is entrenched up to 180 m into the northward-dipping Cretaceous Cliff House Sandstone and underlying Menefee Formation. The walls of the canyon are held up by two 30 m cliffs separated by 30 m of slopes and benches. Below the cliffs are pediments and talus cones. Side canyons tend to parallel regional joint patterns trending to the northeast. The side canyons are more numerous and commonly are longer on the south side of the canyon. At the mouths of the side canyons and reentrants to the canyon, alluvial fans spread out onto the main canyon floor. Sand dunes are common on the top of the cliffs and in some of the side canyons.

The alluvial canyon floor is relatively flat with gradients of less than 4 m/km in most places. Silt and clay dunes occur on some parts of the canyon floor. Shallow (less than 1 m deep) yazoo channels commonly parallel the main Chaco Arroyo.

Chaco Arroyo has walls 3 to 11 m high and averages about 65 m wide. The arroyo walls exhibit various stages of erosion, from freshly broken vertical walls to eroded, badland-like slopes of less than 30 degrees. Benches of alluvium 1.5 to 3 m below the canyon floor are present along the arroyo walls. Within the arroyo is an active inner channel from 3 to 10 m wide between banks 1 to 3 m high. The channel meanders from wall to wall within the arroyo. The different forms of point bars, chutes, natural levees, oxbows and other features of the arroyo are shown in Figure 2.

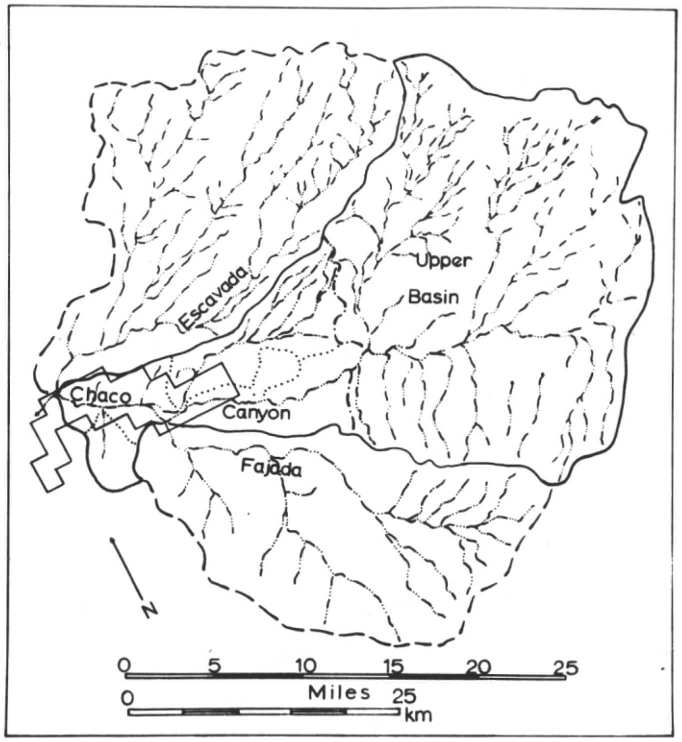


Figure 3. Headwater drainage basins of the Chaco River. Upper Chaco drainage basin enclosed by solid line, with boundary of canyon and upper basin marked by dot-dash line. Subsidiary drainages in canyon bounded by dotted lines. Adjacent drainages bounded by dashed lines. Note funnel shape of Chaco drainage.

DYNAMICS OF SEDIMENTATION IN CHACO CANYON

Sediment Sources and Alluvial Facies

To understand the dynamics of the modern sedimentary environments in Chaco Canyon, the drainage basin of the Chaco River upstream from Chaco Canyon National Monument along with the local conditions must be considered. From the headwaters of the Chaco River to the beginning of Chaco Canyon (fig. 3), the tributary drainages join together to form a large (855 km^2) catchment basin which funnels runoff into Chaco Canyon. Within the Canyon, there is comparatively little increase in drainage area downstream until Fajada Arroyc enters from the southeast. Commonly Chaco Arroyo anc Fajada Arroyo do not flow at the same time, and local runoff which reaches the main arroyo from the canyon sides tends tc precede the floods from the headwaters. As a result, there is commonly no increase in discharge through the canyon, and brought into the canyon from the headwaters or from the local canyon sides are not immediately transported out of the canyon, downstream to the San Juan River.

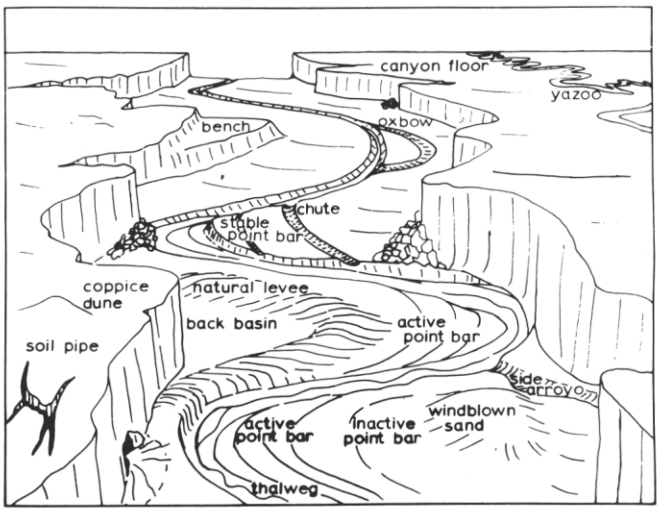


Figure 2. Geomorphic features of Chaco Arroyo in Chaco Canyon National Monument, New Mexico.

The drainages in the headwater catchment area tend to cross strike of the underlying bedrock (fig. 4) whereas the Chacc Arroyo in the canyon parallels the strike of the Cliff House sandstone. Commonly the sediments that are transported tc the lower part of the canyon from the headwaters can be distinguished from locally-derived sediments by sedimentary structures, grain size, color and clay mineralogy.

The headwater-derived and locally derived sediments can be organized into several types of modern facies which have geo. morphological expression. The modern arroyo channel and banks have typical alluvial sedimentary structures, including several types of crossbedded channel sand, fine-grained sand silt and clay overbank deposits, laminated clay oxbow deposits and a channel base composed of moist, sticky gravelly sand and clay. The side-arroyo deposits, talus cones, and colluvium have fewer sedimentary structures and are more poorly sorted than the deposits in the main arroyo. Windblown sand has distinctive sedimentary structures and grain size.

The color of the deposits is related to the mineralogy of the sedimentary grains and to coatings on the grains. The locally

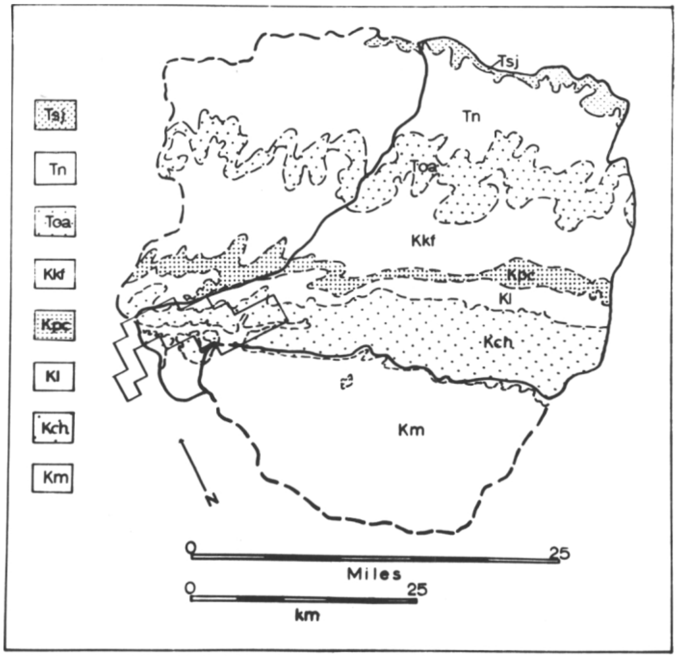


Figure 4. Bedrock geology of the upper Chaco drainage basin. The formations are, in ascending order: Cretaceous Menefee Formation (Km), Cliff House Sandstone (Kch), Lewis Shale (Kl), Pictured Cliffs Sandstone (Kpc), Kirtland and Fruitland Formations (Kkf), Tertiary Ojo Alamo Sandstone (Toa), and San Jose Formation (Tsj). Formations which are predominantly sandstone are stippled. Minor faults in the area are not shown. (Modified from Siemers and King, 1974; Dane and Bachman, 1957; Baltz, 1967; and McIntosh, 1975).

derived fine sand tends to be orange buff in color (10 YR 6/4) but has similar grain mineralogy to sand derived from the headwaters which is light brownish gray (10 YR 7/2). The difference in color is due to the coating of iron oxide and kaolinite clay on locally derived grains. This coating is not worn away during transport over short distances.

Siemers and King (1974) noted that the clay mineralogy of the Menefee Formation is predominantly calcium montmorillonite, that of the Cliff House Sandstone is predominantly kaolinite, and that of the Lewis Shale and Pictured Cliffs Sandstone is predominantly sodium montmorillonite and mixed-layer clays. The clay mineralogy of the uppermost Cretaceous and lower Tertiary units exposed in the headwaters has not been investigated, but clay from the modern sediments in Chaco Wash in the headwater areas is predominantly montmorillonite and mixed-layer illite-montmorillonite. Although some of the sediments of the alluvial fill of Chaco Canyon are mixed, the sediments derived from these different clay sources can commonly be distinguished as locally derived kaolinite-rich sediments and headwater-derived montmorillonite and mixed-layer clay sediments.

Changes Through Time

Comparison of dated photographs of Chaco Canyon show that the facies in the modern arroyo developed after 1934. Tuan (1966) and De Angelis (1972) proposed that the arroyo was filled in and recut an inner channel in the past 30 years, but my investigation of the facies in the arroyo shows that the modern channel has built banks while maintaining its own level. Several reasons may account for the bank build-up during this period of time. The National Park Service, Soil Conservation Service, and Civilian Conservation Corps initiated an erosion control program in the Monument area from 1934 to 1952. The Monument was fenced to eliminate overgrazing; more than 700,000 trees and bushes were planted (most of them in the bottom of the arroyo); numerous wood, rock and wire revetments were built in the bottom of the arroyo to protect the arroyo walls and aid sedimentation; and side arroyos were protected with stone and cement channelways to prevent further erosion. On the canyon floor away from the arroyo, levees were built to impede runoff and to slow the expansion of soil pipes. Native grasses were planted on parts of the floor of the canyon and on the tops of the mesas.

At about the same time, there was a change in the weather pattern over the area, which is reflected in both the regional average precipitation (fig. 5) and in tree-ring indices of the area (fig. 6). Throughout the Southwest, there was a period from the mid-1930's to the mid-1950's which had less than normal rainfall (Thomas, 1963). Fairly complete weather records at Chaco Canyon National Monument begin in 1933. These show extreme variability in pattern over the years (fig. 7). The major exception to less than normal precipitation occurred from July 1940 to December 1941, a period in which more than 29.5 in. (750 mm) of precipitation fell. According to National Park Service documents, Chaco Arroyo flowed during most of the winter and spring of 1941, and Threatening Rock collapsed onto Pueblo Bonito (Schumm and Chorley, 1964).

The period of decreased rainfall was the period of time when the banks built up and stabilized. The bank build-up was not due to the conservation measures in the Monument alone because the banks are built up in areas within the Monument and upstream where no conservation measures were applied. Other drainages in the San Juan Basin experienced the same type of bank build-up. The explanation for the build-up in Chaco Canyon is that with decreased stream power during periods of less runoff, excess sediment transported into the canyon is stored in backwater areas, point bars and banks. These banks may later be reeroded depending on future discharge conditions.

Future developments of the coal resources in the headwater area of Chaco Arroyo should try to maintain the balance between discharge and sediment load reaching Chaco Canyon to minimize changes in the amount of erosion and deposition within Chaco Canyon.

The same kind of bank build-up occurred previously in the modern arroyo. There is a bench along the arroyo walls about 1.5 m below the surface of the canyon floor. The facies exhibited in this bench are identical to the modern arroyo fades. The deposits may date between 1876, when W. H. Jackson described the arroyo, and 1896, when the first pictures of the arroyo show a very fresh-looking bench along the sides of a newly reentrenched arroyo channel. This partial fill may be associated with a "dry" period which shows up in the tree-ring indices of the period (fig. 6).

This partial cycle of cut-and-fill may account for Dodge's (*in* Pepper, 1920) interpretation that a buried arroyo channel found by Jackson (1878) was a modern deposit. By the time Bryan (1925) studied the walls of the arroyo, most of this modern fill had been reeroded and Jackson's buried channel was exposed again. The indented deposits may also explain

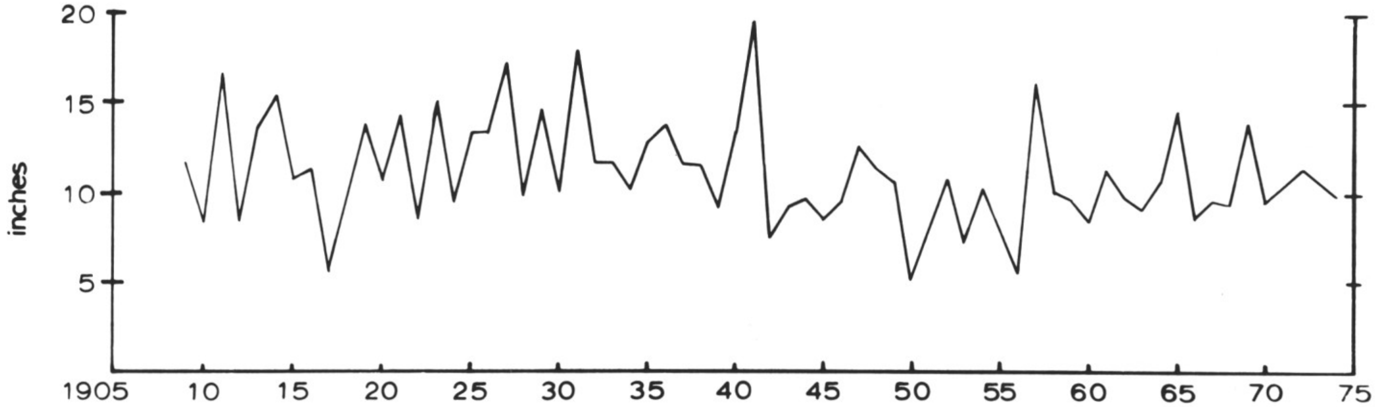


Figure 5. Average annual precipitation of the northwestern plateaus section of New Mexico from 1909 to 1974.

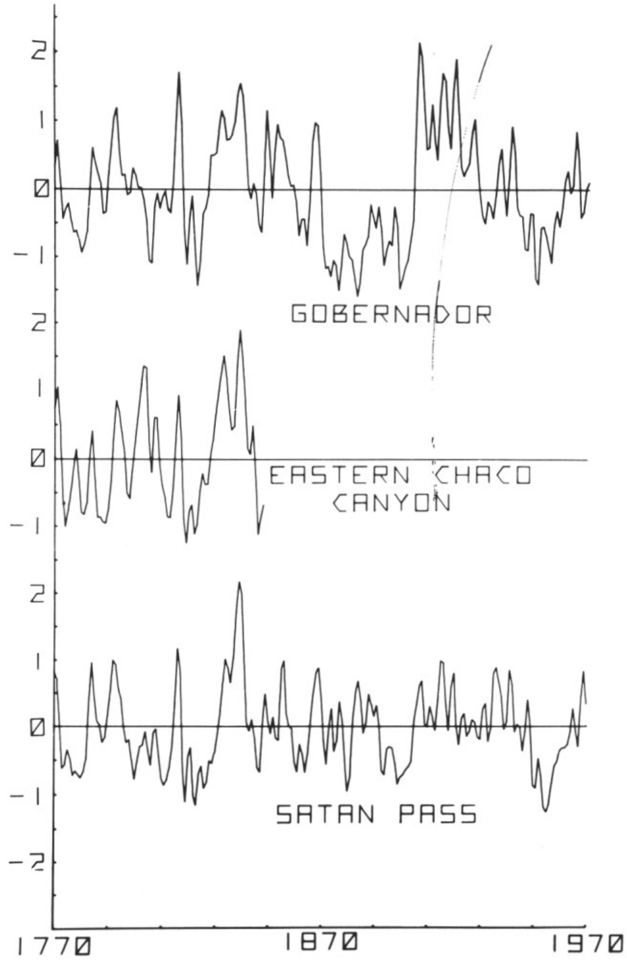


Figure 6. Three-year weighted average, standardized tree-ring indices for Gobernador (80 km north of Chaco Canyon), eastern Chaco Canyon, and Satan Pass (56 km south of Chaco Canyon) for the period from 1770 to 1970. Positive values indicate more than average moisture and negative values indicate less than average moisture. The "drought" of the 1940's and 1950's was a period of bank build-up and stabilization after a period of arroyo widening from 1905 to 1934. An earlier period of infilling is inferred for the period from ca. 1870 to 1885. Arroyo initiation in Chaco Canyon may have occurred with the moist period around 1840. (Data from the Tree-ring Laboratory of the University of Arizona).

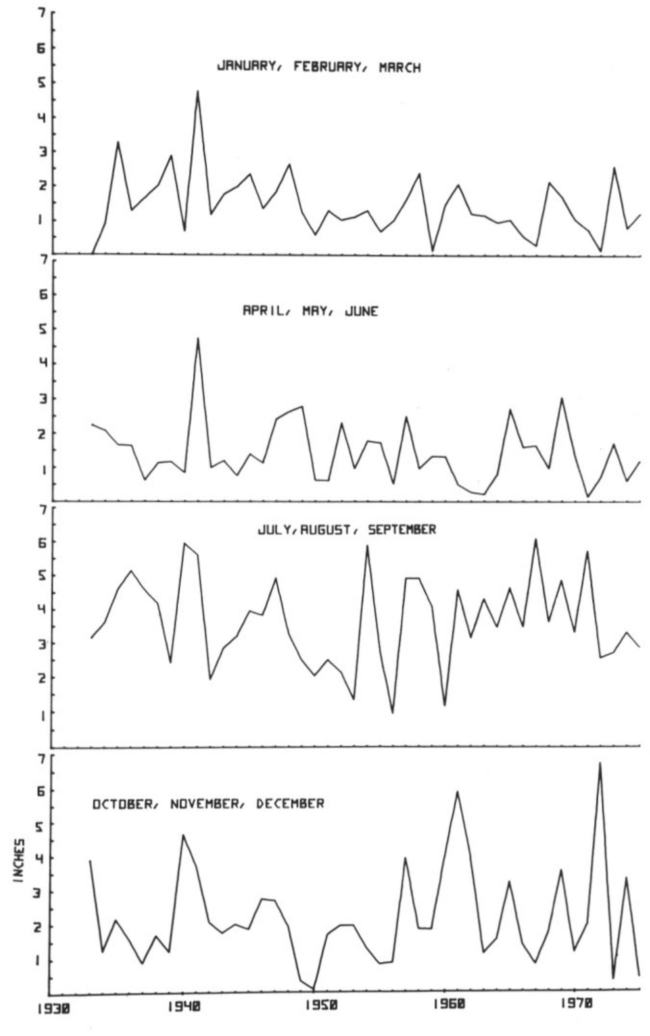


Figure 7. Variation in seasonal precipitation for Chaco Canyon National Monument, New Mexico, from 1933 to 1975. The three-month segments correspond to natural breaks in the annual cycle (e.g. July, August and September are the months of summer thunderstorms). Note the periodicity from the late 1950's to the early 1970's in each season. During this period of time, the growing season decreased from about 140 days to 110 days between 0° C. temperatures.

why the Navajos who were raised in Chaco Canyon remembered a shallow channel.

Formation of Arroyos

Arroyos may be caused by several factors that bring about increased stream power and increased soil erodability. Arguments about the roles of climate, vegetation and overgrazing have been summarized by numerous authors (e.g. Leopold, 1951; Bryan, 1954; Antevs, 1955; Tuan, 1966; Cooke and Reeves, 1976). Drainage basins may respond in different ways to changes in these factors, and timing of their response may also be different. Size, shape, underlying geology and ground water of a drainage basin all play roles in its response as well.

It is unlikely that vegetation in many parts of the Chaco drainage was abundant enough to be effective in retarding runoff. Overgrazing probably did not affect the canyon until after the arroyo was formed.

Bryan (1954) placed the beginning of the modern arroyo about 1860 because Simpson (1852) did not mention seeing an arroyo in 1849. However, as Judd (1954) points out, Simpson's guide named one of the major ruins in the canyon "Pueblo del Arroyo" which would not have made sense if no channel had existed.

If stream power is decreased during a period of decreased moisture, and this decrease is correlated with filling of the arroyo, then the converse may indicate when the modern arroyo was initiated. A peak in precipitation is shown by the tree-ring indices at about 1840. For other parts of New Mexico, Leopold (1951) demonstrated that years which have above average precipitation have more numerous precipitation events and larger individual rainfalls than years with less than average precipitation. Leopold correlated rainfall intensity with arroyo formation. If the moist period around 1840 indicated by tree-rings had more precipitation with larger precipitation events, the modern arroyo could have formed from increased runoff funneled into the canyon from the headwaters. The date of 1840 is consistent with remembrances of old Navajos recorded by Pepper (1920) and Judd (1954, 1959, 1964).

Bryan (1954) ascribed the formation of the arroyo to progressive upstream migration of a headwall. This type of entrenchment has been described by numerous authors (Leopold and Miller, 1956; Schumm and Hadley, 1957; Heede, 1967) and appears to be common in drainage basins that have integrated drainage areas of less than 75 km^2. Some side drainages in Chaco Canyon probably formed arroyos in this way, but the pattern of Chaco Arroyo in Chaco Canyon does not support such a mechanism. The arroyo meanders back and forth across the canyon floor and, at one place, a meander loop points up-canyon. Such a pattern cannot be formed by headward erosion of a flat canyon floor. Instead, there must have been a channel established along the canyon floor which became entrenched after it was established. Entrenchment may have taken place by progressive erosion of the base of the pools and riffles along the established menaders. This process was described by Leighly (1936) for another arroyo in western New Mexico.

Another form of channel entrenchment exists in Chaco Canyon in some of the tributary arroyos that have developed on alluvial fill. These channels have no headwall, but are progressively entrenched as their dendritic headwaters become integrated with the already established arroyo system.

Ways of Filling Arroyos

The modern bank build-up suggests a way of refilling arroyo channels by building banks and aggrading the active channel at progressively higher levels in an arroyo until the overbank floods overtop the arroyo wall and inundate the canyon floor. With the change in flood geometry, the channel may become less active and fill in completely to form a flat canyon floor. This type of arroyo fill is found in buried arroyos exposed in the alluvial walls of the modern arroyo.

Other types of arroyo channel fill exposed in Chaco Canyon show that an arroyo may fill under different geometric and sedimentologic constraints. In general, arroyo fills reflect a decrease in the ability of the stream to transport sediment out of the canyon to maintain a given channel level. These other types of fill are shown in Figure 8. Another type of arroyo fill seen in other drainages, but lacking in Chaco Canyon because of sparse soil development, is channel fill by soil build-up.

Once the canyon floor is flooded, any low area, including yazoo channels and swales, is inundated as a backwater area, and is filled with laminated silt and clay. Previously, these laminated fills have been mistaken for buried arroyo channels.

Conditions on the Canyon Floor When There Is No Channel

What are conditions like after an arroyo has been filled totally or before an arroyo is initiated? If there were no channel, the present peak discharge of about 125 m^3/sec would flood the entire flat canyon floor in some sections of the canyon. Under such conditions, sediments from the headwaters should spread out across the canyon floor and interfinger with locally-derived deposits along the canyon margins. This type of relationship is found in many places and at numerous levels in the alluvial fill, showing that the canyon floor has been alternately flooded with headwater-derived sediments and local sediments. When the local sediments dominate, either the headwater sediments are not reaching that area of the canyon, or they are confined in an arroyo. The two situations are shown in Figures 9 and 10.

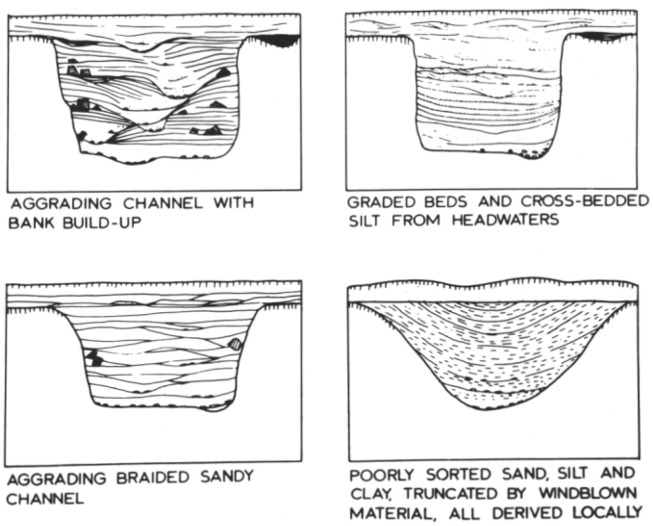


Figure 8. Ways of filling former channels generalized from exposures in the arroyo walls of Chaco Arroyo, Chaco Canyon National Monument, New Mexico. All channels may not be the same size.

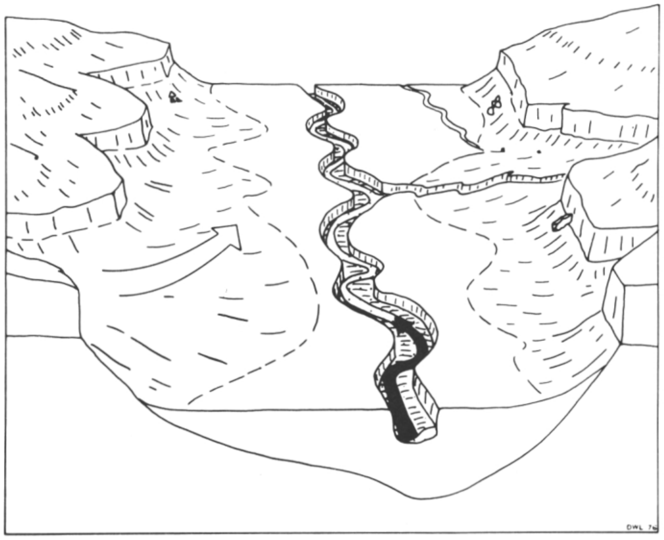


Figure 9. When sediments from the headwaters are confined to a channel (black arrow, light stipple), sediments from the canyon margins (white arrow) and reworked sediments on the canyon floor dominate deposition away from the central channel. Local side drainages may also be confined. Sediments from these two areas may be distinguished by sedimentary structures, grain size, color and clay mineralogy.

The facies exhibited in the alluvial fill in Chaco Canyon can be explained by alternating these two types of situations. The total number of cut-and-fill cycles in the exposed 11 m of fill remains to be determined, but at least seven arroyo channels existed in the last 10,000 years (fig. 11). The arroyo channels containing archaeological materials are of particular interest.

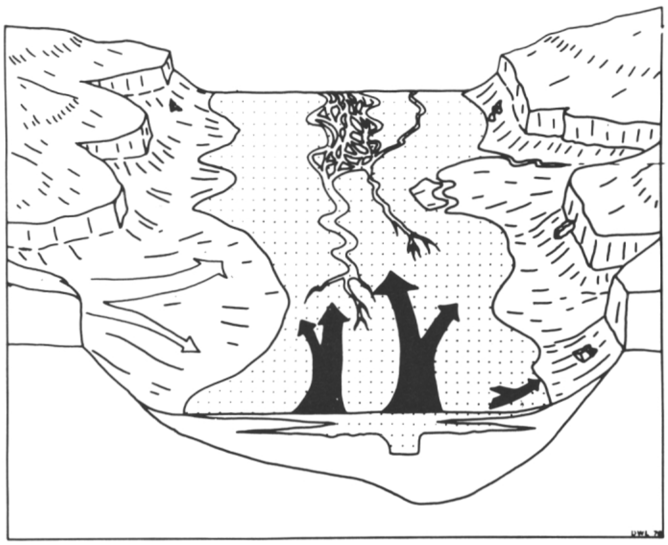


Figure 10. When there is no entrenched channel, sediments from the headwaters flood the canyon floor (black arrows, light stipple). Headwater sediments may be transported in sheet flood, in a single shallow channel, or in numerous shallow braided channels. Former side channels may be flooded. Some sediment from the headwaters may be windblown onto the canyon margins (black arrow on right). Canyon margin deposition may keep pace with deposition from headwaters in some areas so that there are no alternations between the two kinds of deposits.

Previous Conditions in Chaco Canyon

The exposed 11 m of alluvial fill in Chaco Canyon show that alluvial conditions similar to the present regime have resulted in the progressive filling of the canyon during the past several thousand years (fig. 11). To determine the depth of alluvial fill and to determine the nature of the alluvium beneath the present exposures, several holes were drilled through the alluvium to the bedrock floor of the canyon (Ross, in progress). Unfortunately, the water table was reached at a depth of 12 m, and the sediments were so soupy beneath the water table that no detailed cores were recovered.

However, deposits reflecting former alluvial conditions are found in the canyon. Two types of flow regimes are represented. One is similar to the present semiarid regime and the other indicates conditions of runoff at least an order of magnitude larger than the present conditions.

The deposits exhibiting characteristics of greater stream power are found at several levels in the canyon. The deposits are dominantly crossbedded gravel, containing clasts as much as 20 cm long derived from the headwaters, mixed with larger and more numerous locally-derived cobbles of sandstone. Figure 12 illustrates an exposure of cross-bedded gravel which also includes large blocks of fine-grained alluvium similar to the present alluvial fill, and lenses of sand. The deposit is capped with colluvial and windblown deposits and more than one red paleosol.

Deposits formed under conditions similar to the present are perched along the south margin of the canyon above the present alluvial fill (fig. 13). The deposits include talus blocks which are separated from the modern cliffs by more than 50 m. Farther out into the canyon, colluvial deposits, soil and arroyo-like crossbedded channel sand overlie outliers of Cretaceous Menefee Formation.

Many of these deposits are preserved because they are well cemented with calcium carbonate. Commonly the sedimentation is aligned toward the center of the canyon in finger-like protrusions. The cementation is not the result of caliche formation. Instead, the cement probably was deposited by shallow ground water. Because the Cretaceous deposits dip toward the canyon on the south side, carbonate leached from the Cliff House Sandstone by percolating rain water could have emerged from the base of the cliffs into the talus and colluvial deposits, ultimately cementing and preserving these deposits. On the north side of the canyon, the bedrock dips away from the canyon; as a result, ground water could not cement the deposits and they were eroded during later cycles of greater discharge.

The alternation of two kinds of flow regimes in the canyon is similar to the alternation between entrenched channels and flat valley floor, but on a larger scale. Periods of increased flow could have flushed most of the fine-grained alluvium from the canyon, eroded the canyon to a deeper level, and provided gravel for the coarse-grained deposits. Between periods of increased stream flow, the canyon partially filled with alluvium. The number and ages of such alternations remain to be determined.

Loose gravel is scattered on the mesa tops surrounding the canyon and evidence exists for more than one high-level erosion surface. Apparently a meandering stream, flowing along the strike of the Cliff House Sandstone, intermittently incised its course below an erosion surface to form Chaco Canyon. Parallel side drainages were beheaded or captured by the

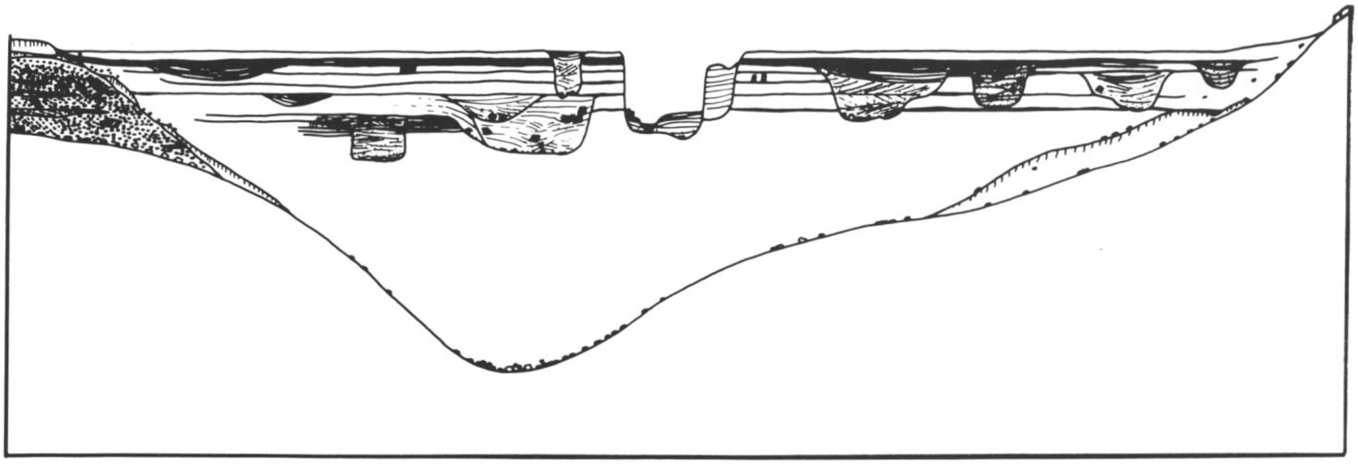


Figure 11. Generalized cross section of the alluvial fill of Chaco Canyon to a depth of 12 m. Maximum depth of fill may be 38 m (Ross, in progress). Remnants of earlier fill are perched on margins of canyon, but partially buried by modern alluvium. Horizontal lines indicate wide-spread inundation of the canyon floor by sediments from the headwaters, and are connected with filled-in entrenched channels and laminated fills of swales and yazoo channels.

Chaco River because of its water source along the Continental Divide and the drainage from Chacra Mesa.

The possible framework for considering the geomorphic history of Chaco Canyon is shown in Figure 14. An appreciation of the dynamics of alluviation in Chaco Canyon, especially the repetitive nature of alternating magnitudes and geometrics of alluvial processes, will help answer many questions concerning the living conditions of past inhabitants and questions concerning the history of Chaco Canyon can be investigated in greater detail.

Prehistoric Populations in Chaco Canyon

Prehistoric Indians were in the San Juan Basin by at least 13,000 years ago. The earliest abundant evidence of people in Chaco Canyon dates from the Archaic Period, which ranges from about 7,000 to 1,500 years ago. Beginning about A.D. 500, people designated as Basketmakers raised crops in the canyon and built semi-subterranean structures known as pithouses. Living structures above ground gradually appeared and evolved into pueblos by A.D. 770, while the pithouses acquired ceremonial significance and evolved into kivas. The major building phase in Chaco Canyon which produced the multistoried pueblos and large kivas began about A.D. 1050 and came to an end sometime after A.D. 1127. Although the canyon was not completely abandoned after that time, the population of the canyon was reduced drastically. The canyon was occupied sporadically by shifting Pueblo peoples and later by Navajos until the time of the historic visit by Simpson (Vivian and Mathews, 1964).

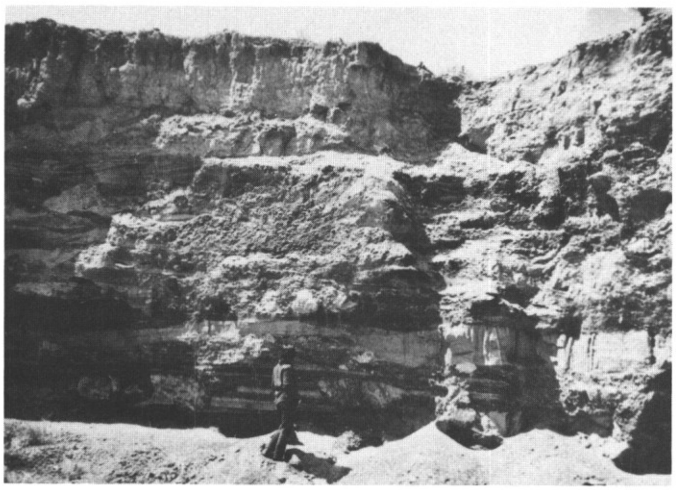


Figure 12. Exposure of cross-bedded gravel with lenses of sand. Note large blocks of alluvium included in the gravel. The top third of the exposure is colluvium and windblown sand with more than one red paleosol and caliche horizon developed in it.

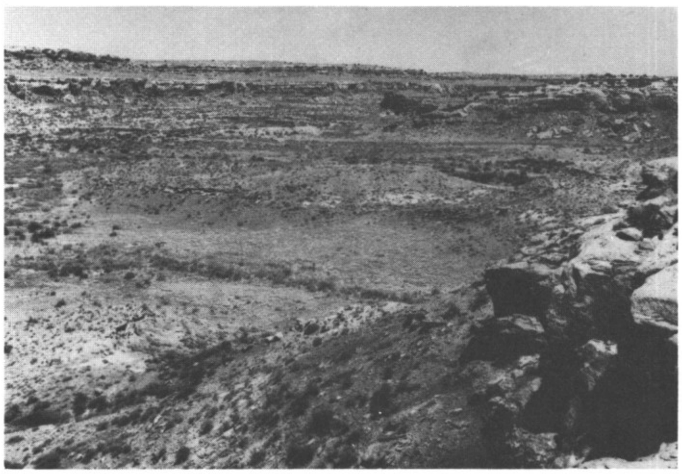


Figure 13. Remnants of former canyon fill perched above Recent alluvium on the south side of Chaco Canyon. The deposits are separated from the cliffs of Cretaceous sandstone by an erosional gap of more than 50 m. The deposits in the middle ground unconformably overlie a sandstone tongue of the Menefee Formation and grade from predominantly talus and colluvium near the margin of the canyon to cross-bedded pebbly sandstone near the center of the canyon. A second remnant of cemented colluvial facies is shown on the lower left (photograph by H. E. Malde, 1974).

0.1 year 1975

Sept. 9, channel sands swept out of channel, deposited on banks, channel base exposed and scoured; chute cutoff erosion continues; undercut arroyo walls collapse into channel

channel sand partly eroded by April

Chaco Arroyo flows intermittently for week in early Spring

1 year 1974

Oct. 17, Chaco Arroyo flows; previously mapped arroyo wall collapses, exposing burn which is dated at 3700 years at 6.1 meter depth

August Chaco Arroyo flows twice

2 years 1973

Sept. 10-11, Arroyo flows, channel built up further

color transparency aerial photographs

wet Spring, Arroyo flows several times, channel built up

1972

Sept. Arroyo flows; Black and White aerial photographs

summer precipitation shows two-year oscillation; frost-free season declines by thirty days

10 years 1965

U.S. Geological Survey aerial photographs

1963 Tuan notes banks and inner channel

1956 dry year, 3.37 inches precipitation

20 years 1955

Mathews photographs inner banks

1951 dry year, 3.35 inches precipitation

erosion control program, Monument fenced

1941 18.93 inches precipitation

1939 Judson photographs arroyo

1934 SCS aerial photographs, weather data begins

1925

archaeology by Judd, geology by Bryan

arroyo walls retreat in moist period

1900

Holzinger, Pepper photographs, geology by Dodge

1877-1890 Arroyo fills to within 1.5 m of top and recuts

100 years 1875

1877 Jackson describes Chaco Canyon, maps arroyo 16 ft deep, 40-60 ft wide

1849 Simpson visits Chaco Canyon, names pueblos

1840 moist conditions, modern Chaco Arroyo initiated

200 years 1775

American Independence declared

Chaco tree-rings

refugees from revolt in Chaco Canyon

1680 Pueblo revolt against Spanish

archaeomagentic dates on meander fill

1630 Navajos have obtained livestock, sheep

1540 Coronado visits New Mexico

1492 Columbus

Navajos enter area

small arroyo cuts-and-fills in this period

Late Pueblo III archaeomagnetic dates

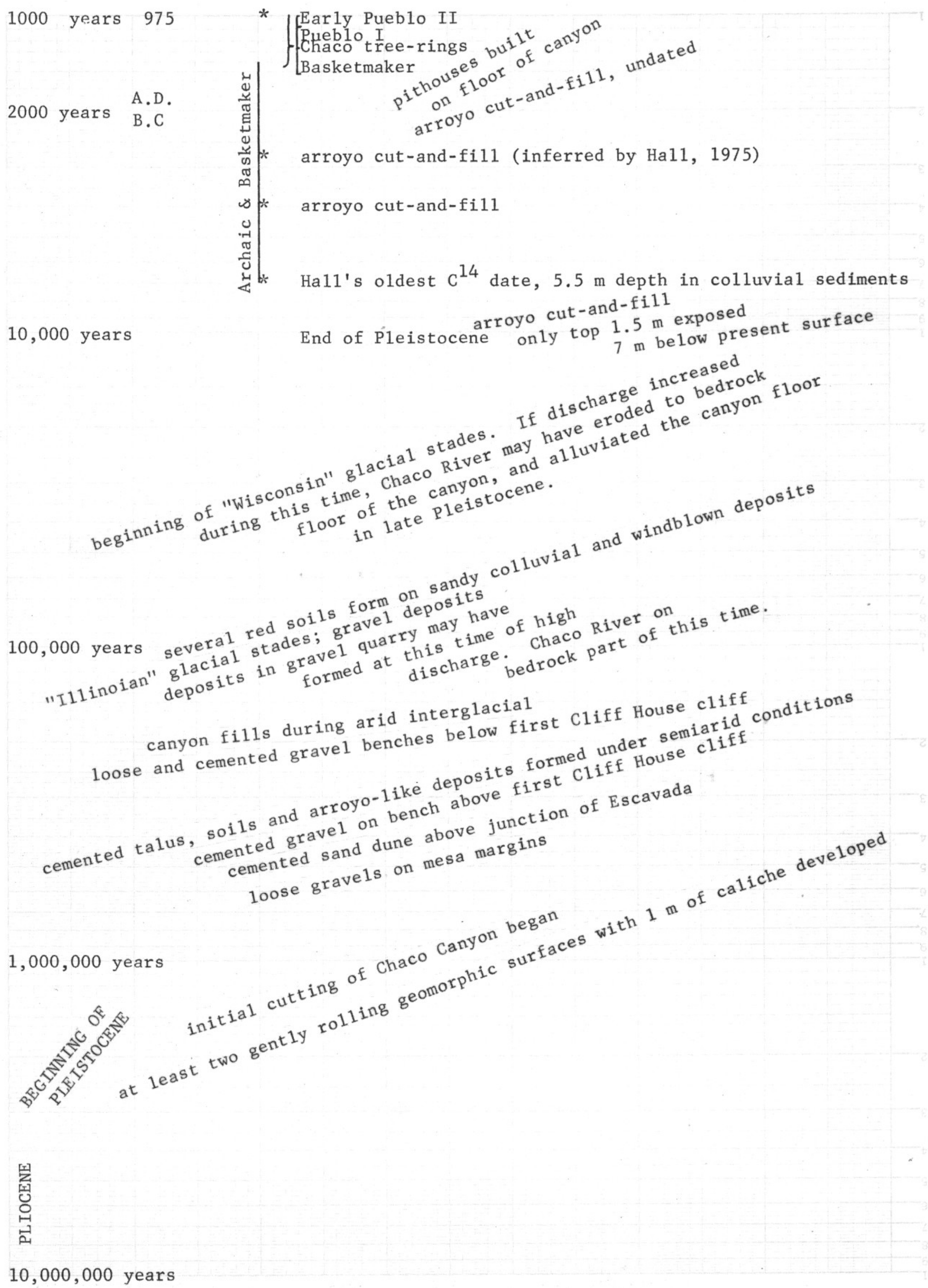
last tree-ring date on occupation

Early Pueblo III

1000 years 975

Late Pueblo II

Figure 14. General outline of geomorphic history of Chaco Canyon. Asterisks indicate radiometr



ates. Undated events are tilted to show possible span of time when they could have taken place.

The reasons for the major decline in population in the canyon during the 12th century are not clear. No cause such as warfare, famine or disease has been demonstrated. Bryan (1925, 1954) argued that a drought caused the formation of an arroyo during the 12th century. He indicated that an arroyo would have been devastating to prehistoric agriculture because downcutting would no longer permit irrigation of the canyon floor and would lower the near-surface water table. He described a buried arroyo channel containing early Pueblo III pottery (from late in the period of occupation) along the bottom, 4 to 5 m below the present canyon floor.

However, as Tuan (1966) pointed out, the timing of the past arroyo was not worked out in detail. The latest pottery found in the channel was made as early as A.D. 975. Cross sections through the alluvium near Pueblo Bonito drawn by Judd (1964) show that several channels contained cultural debris in them and on top of them. The sections show that the occupants were used to having channels as much as 4 m deep while Pueblo Bonito was being built. At Pueblo del Arroyo, structures built around the beginning of the 12th century appear to overlie a large buried channel containing pottery. In the vicinity of the large pueblos, there is no indication that the ground water was close to the surface prior to arroyo formation. Tree-ring indices for this period of time show neither prolonged "drought" nor excessive moisture. The evidence does not support Bryan's interpretation for the timing of arroyo formation or his reasons for the decline in the population of Chaco Canyon.

An alternative explanation could be that the runoff from the headwaters had been contained in some sort of channel until the end of the 11th century, when the channel filled and flooding of the canyon floor became common. This would have brought impermeable sodium-rich montmorillonite clay to cover the low areas along the canyon floor and would have flooded structures such as pithouses or underground storage bins. Periodic inundations of mud across the canyon floor would have made it a less attractive place to live.

Although this alternative explanation is supported by sedimentary deposits in the canyon, dating the deposits remain a problem. Moreover, because the prehistoric Pueblo population continued to shift in the entire region during the 12th and 13th centuries, some other regional phenomena may be a more likely explanation for the population decline in Chaco Canyon. A subtle shift in precipitation pattern, in the length of the growing season, or in regional cultural attitudes may have been some of the causes for the changing populations.

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