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CLIMATE AND ACCELERATED EROSION IN THE ARID AND SEMI-ARID SOUTHWEST
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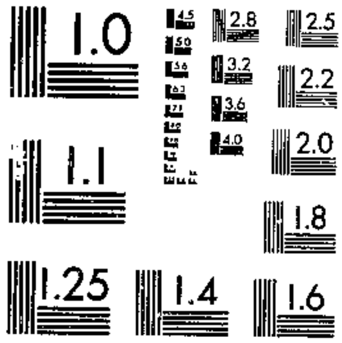

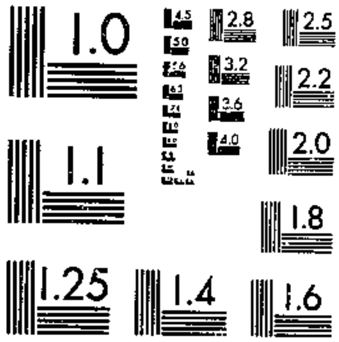

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Climate and Accelerated Erosion in the Arid and Semi-Arid Southwest With Special Reference to the Polacca Wash Drainage Basin, Arizona[1]

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INTRODUCTION

Accelerated stream trenching or arroyo cutting in the Southwest has been noticed for more than 50 years. In that time the gullying of channels in flat-floored valleys with the consequent dissection of bottom land, lowering of the water table, and loss of palatable grasses have become increasingly apparent. Wind action has removed soil from tilled fields and other areas where the vegetal cover has been depleted and has deposited the debris in the form

[1] Submitted for publication June 21, 1941.

of dunes. Ranges that once carried 10,000 head of cattle can now scarcely support one-quarter as many. Valleys that the first white settlers converted into prosperous farms are now deeply cut badlands unsuitable even for grazing.

The cause or causes of the acceleration of erosion in the Southwest is a vital question on which there is still a lack of general agreement. If, as some workers believe, a progressive desiccation of climate has brought about the dissection of the western lands there is little hope that man can stem the quickened erosion. If, as others are convinced, misuse of the land by overgrazing and imprudent methods of agriculture has been the cause there is a good possibility of improving the land by improving the land use.

Understanding of the problem depends primarily on a knowledge of the climate of the Southwest, of the nature and extent of accelerated erosion in that region, and of the correlation of accelerated erosion and land use.

This bulletin contributes an analysis of the climate in the Southwest and of its relation to erosion and overgrazing. It is written in three main sections, any of which may be read separately. The first deals with climate, the second with normal and accelerated erosion in a selected drainage basin, and the third with the history of erosion.

The wide range in precipitation and temperature at a single station, the great variance in seasonal and annual precipitation, and the occurrence of large storms after dry periods or a succession of several abnormally dry years are the most critical features of the climate from the standpoint of erosion and land use.

The field studies of normal and accelerated erosion, reported in the second section, were made in the drainage basin of the Polacca Wash,[2] one of several drainageways by which the run-off from Black Mesa, a broad, youthfully dissected plateau in the Navajo country, flows toward the Little Colorado River (fig. 1). In size, in climate, in vegetation, in soil and bedrock, and in past land use the Polacca Wash is representative of conditions in much of northeastern Arizona. Most of the Navajo country is open range. Only a small percentage of the total area is under cultivation.

In the last section, the records of gully cutting and range depletion for the Southwest in general and for the Polacca Wash in particular are considered. The evidence for and against tectonic disturbances, agriculture, overgrazing, and climatic change as causes of accelerated erosion is weighed.

THE CLIMATES OF THE SOUTHWEST

METEOROLOGICAL ORIGIN OF CLIMATIC FLUCTUATIONS[3]

AIR-MASS TYPES IN THE SOUTHWEST

The climatic pattern on the earth (*106*),[4] as well as the changes in its position from year to year, is explained in terms of at-

[2] The "wash," a characteristic natural land form of the Southwest, is a flat-floored valley generally one to several miles wide, which carries water intermittently and may or may not contain a steep-walled channel.

[3] Assistance in the climatic analysis was given by David I. Blumenstock, of the Climatic and Physiographic Division.

[4] Italic numbers in parentheses refer to Literature Cited, p. 129.

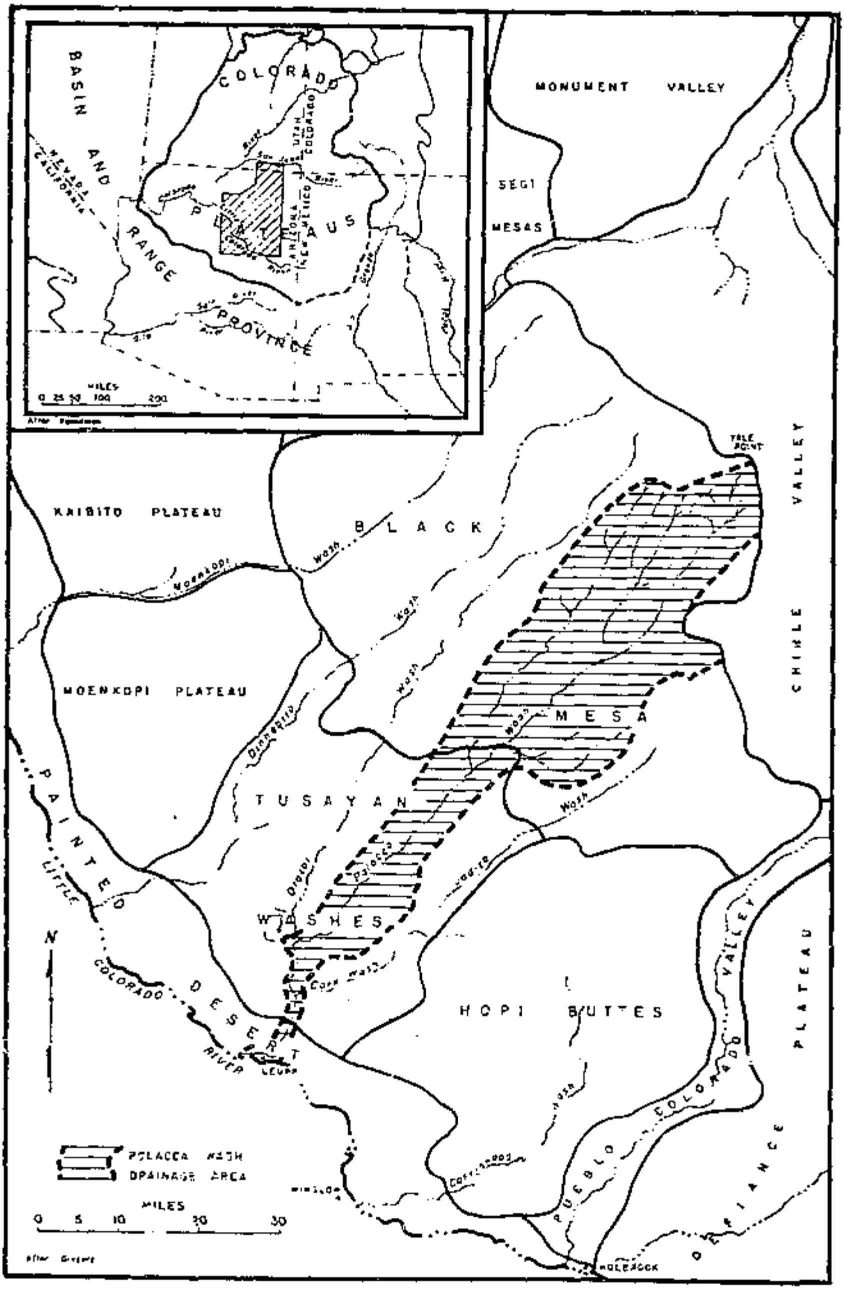

FIGURE 1.—The Southwest and the physiographic setting of the Polacca Wash drainage area, Ariz.

mospheric circulation. Over North America the circulation consists of flows of great bodies of air which have remained in their various source regions long enough to have acquired special individual properties. Outward movement of the air from these centers and interaction of the different types of air masses are chiefly responsible for the weather of the continent.

These air masses are of several types. Air which flows southward from the vast Arctic tundra of northern Canada is cold, dry, and heavy. The North Pacific Ocean is the source region for cool to cold, moist, and moderately heavy air. Air over the north Atlantic Ocean also develops similar properties. Over the Gulf of Mexico and the Caribbean region, and also over the tropical waters of the Pacific, air bodies become warm to hot, very moist, and light. The southwestern part of the United States, together with the Mexican plateau, is itself a source region, where air from upper levels sinks to the surface and becomes hot, light, and very dry (*45, 112*). The source regions for these various air masses are shown in their approximate positions in figure 2. The entire system of air masses is displaced poleward in summer and equatorward in winter.

Air flows outward from all these source regions. All three polar air masses generally move in a southeasterly direction. The tropical air masses generally move in a northeasterly direction. The trajectory of the tropical air from the Atlantic characteristically curves across the Gulf of Mexico, up the Mississippi Valley, and thence eastward back to the Atlantic. However, despite the fact that these air bodies have preferred routes, all except those which originate in the north Atlantic sometimes enter the Southwest. It is the invasion and interaction of air masses that accounts for the day-to-day variations in the weather of that region.

Cool, moist Polar Pacific air may move down the coast and swing in over the mountains to invade the Southwest aloft. Such invasions are especially well marked during the winter, when the Aleutian low-pressure area is well-developed and is at its southernmost position. Cold, dry Polar Continental air may push equatorward from the Canadian tundra and enter the area. This is also predominantly a winter phenomenon. Also during the winter, warm and somewhat moist air may move in at high levels from its place of origin over the tropical waters of the Pacific. Particularly during late spring, summer, and early fall, invasions of warm, moist Tropical Gulf air from the southeast may occur. At any time of year, hot dry Tropical Continental air may descend to the surface from aloft.

Air masses do not follow one another in any definite sequence, nor are any two invasions of one air-mass type exactly the same. Air masses remain over a source region for different lengths of time and follow different trajectories. Each invasion, therefore, has a history different from that of any preceding or subsequent one so that when an air mass arrives in the Southwest its properties are never exactly the same as those of any other invading air mass. Polar Pacific air entering the Southwest is occasionally colder than Polar Continental air or more moist than Tropical Gulf air. Because of such variations in their properties, air masses can be characterized only in a relative sense.

AIR MASSES AND VARIATIONS IN TEMPERATURE

In the interaction of air masses of different density the heavier air will move along the land surface and will displace the lighter air upward. Since there is generally a direct relation between density of air and temperature the replacement of one air-mass type by another in the Southwest results in large variations in the

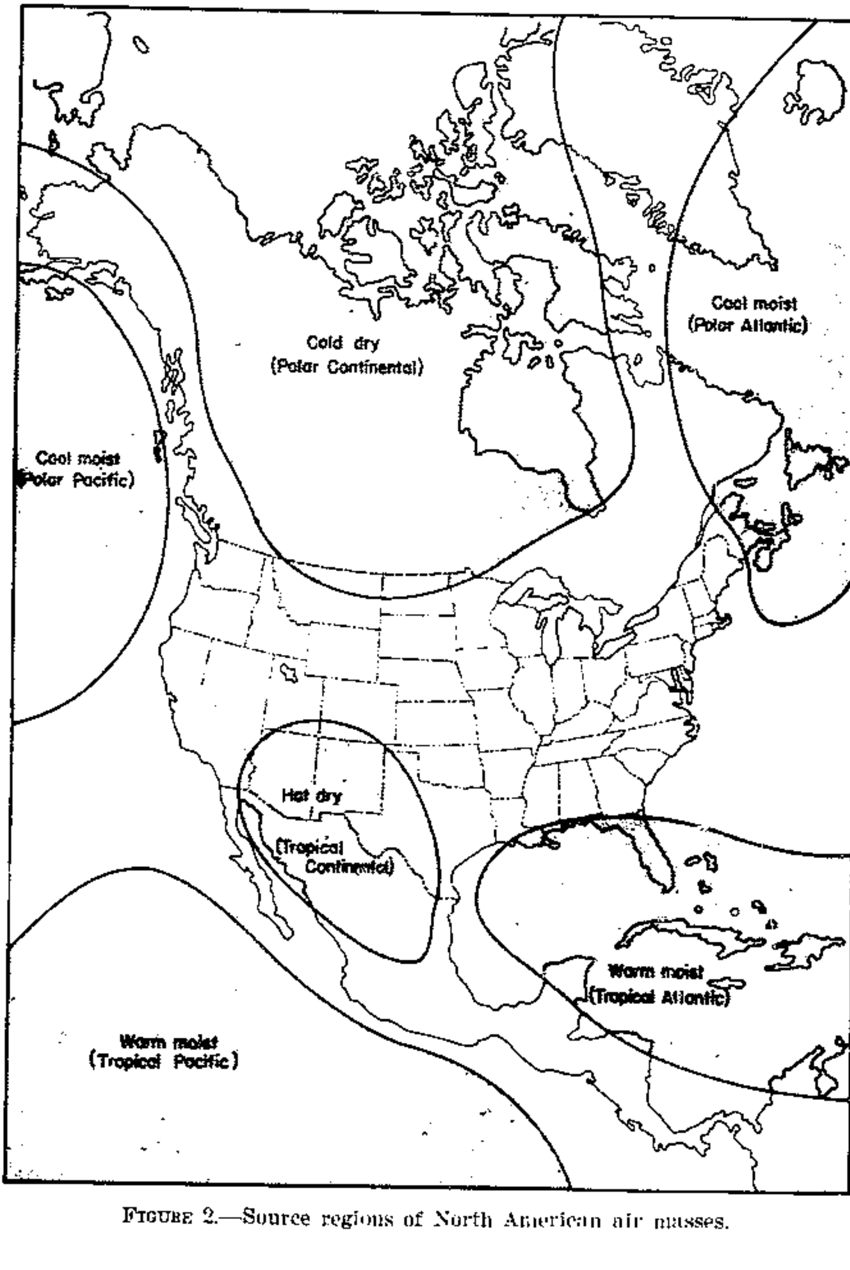

Figure 2.—Source regions of North American air masses.

surface temperature of the region. Superimposed on the diurnal and seasonal temperature rhythms, arising from the rotation of the earth on its axis and its revolution about the sun, are day-to-day variations caused by nonperiodic inundations of air bodies in unpredictable sequence. These three types of temperature variation are well illustrated by the daily temperature data for Santa Fe for 1879 and 1880, the warmest and coldest years, respectively, in the period 1850–1939 (fig. 3).

The temperature charts for these years illustrate the components of the temperature regime and show what lies behind temperature variations from year to year. The length of the bars indicates the span between maximum and minimum daily temperatures. The curve fitted to the mean daily temperatures for a 46-year period is shown on the chart for both 1879 and 1880. The march of the daily means in both these years follows the trend of this curve, but the deviations of the daily means from the normal is often large, a few being more than half the range of the curve. These deviations reflect the variability introduced by the invasion of air masses.

The variation in the range of diurnal temperature from season to season is shown by the differences in the lengths of the bars. During early summer the range is greatest, insolation being at a maximum and cloudiness low. The mean June range for the 46-year period is 25.8° F., the December range, 20.3°. Changes in temperature from day to day can readily be seen by comparing the position of adjacent bars on the temperature scale.

The mean annual temperature of 52.5° F. in 1879 is unusually high, principally because it includes unseasonably high winter temperatures for that year. The summer temperatures also are slightly above average. In 1880, when the average annual temperature was only 45.1°, winter and autumn temperatures were far below normal and summer temperatures were slightly so. The high incidence of warm temperatures during the winter of 1879 was associated with frequent invasions of warm air; whereas, in the winter of 1880, cold air masses from the north occupied the area much of the time.

Variation in the mean annual temperature from year to year for the period 1874–1939 is shown in figure 4. Each of the mean values should be thought of as representing a sequence of weather conditions such as that illustrated in figure 3 for the years 1879 and 1880. Occasionally warm years follow warm, and cold years may follow cold; frequently, as in 1879 and 1880, extreme shifts are displayed from one year to the next. Since air-mass invasions impart great irregularity to the daily temperature values it is not surprising that the annual figures made up of these highly variable components should themselves vary considerably from year to year.

The diurnal, seasonal, and annual variations displayed by the temperature of Santa Fe are representative of temperature variations elsewhere in the Southwest. There is, for instance, at Flagstaff, Ariz. (table 1), as at Santa Fe, a much greater range in the mean monthly temperatures in winter than in summer (*97*). Furthermore, the wide range in temperature at Santa Fe (fig. 3) is characteristic of the range at other stations (fig. 13). In Arizona, where the absolute range is greater than in many other parts of the country, the greatest difference between the maximum and minimum at any

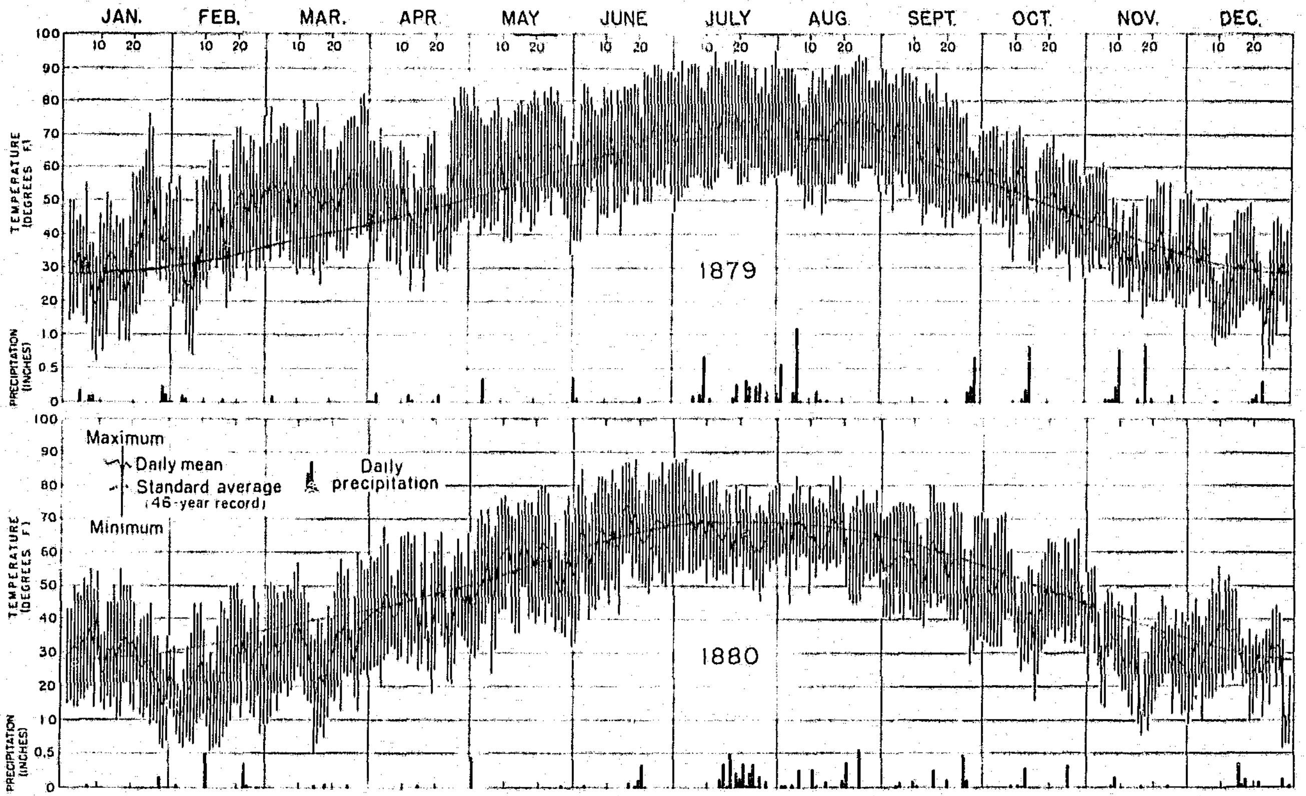

Figure 3.—Daily maximum and minimum temperatures and daily precipitation at Santa Fe, N. Mex., 1879 and 1880.

station is 134°. This is the record for Keams Canyon, where the maximum was 104° and the minimum −30°.

Though the pattern of change is similar at stations throughout the Southwest, there is considerable difference in the range of temperature at different stations and in the frequency of occurrence of various temperatures. The areal contrasts are brought about mainly by variations in elevation, cloudiness, and the incidence of different air masses; perhaps to a small extent they reflect differences in insolation caused by variation in altitude. The highest temperatures are experienced at Yuma, which is at the lowest elevation above sea level, and which also has the least cloudiness. Lowest temperatures occur at stations in the northern part of the region, which are at the highest elevations.

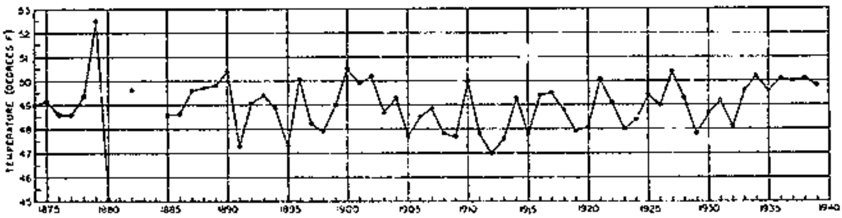

FIGURE 4.—Mean annual temperature at Santa Fe, N. Mex., 1874–1939.

TABLE 1.—*Highest and lowest average monthly and annual temperature and range, Flagstaff, Ariz., 1891–1939*

Month	Temperature				
	Highest average	Year	Lowest average	Year	Range
	°F.		°F.		°F.
January	34.4	1909	12.6	1937	21.8
February	38.0	1904	19.5	1939	18.5
March	41.5	1892	29.0	1917	12.5
April	52.0	1898	37.7	1900	14.3
May	61.0	1897	44.5	1917	16.5
June	64.7	1918	54.2	1907	10.5
July	72.0	1897	61.2	1912	10.8
August	71.4	1897	60.7	1906	10.7
September	63.1	1897	52.3	1912	10.8
October	55.8	1891	41.2	1908	14.6
November	44.4	1897	31.3	1918	13.1
December	38.0	1897	18.8	1905	19.2
Annual	48.8	1934	42.9	1915	5.9

AIR MASSES AND VARIATIONS IN PRECIPITATION

Precipitation cannot take place unless the air is cooled sufficiently to release the atmospheric moisture. The necessary cooling is accomplished by adiabatic expansion wherever air flows up a land slope. Air is similarly cooled when it encounters a heavier air mass and is forced up the air-mass slope. Air ascends and is cooled by convection when an air column is made unstable through heating at the ground or through cooling aloft by radiation from the tops of clouds.

The principal cause of precipitation in the Southwest, as elsewhere in the United States, is the lifting of air along zones of discontinuity, or fronts between adjacent air masses of different properties. Two general types of fronts are recognized. In one, the colder air pushes actively into the area occupied by the warmer air, forcing the warmer air aloft. In the other, the warm air mass is the active one, moving at a more or less uniform rate up the slope of a relatively stationary or slowly moving cold air mass. Whichever air mass may be the active one, precipitation will usually occur if the ascending air is moist. When the cold air is advancing rapidly its front is relatively steep. The warm air therefore ascends rapidly over a relatively narrow belt, and thunderstorms usually result. They cover relatively small areas, are extremely spotty, display high intensities, but continue for only a short time at any one place. When the pressure gradients are such that warm air actively pushes over cold air, the flow is usually steady and uniform over wide areas. If rains result, they are widespread, tend to be homogeneous, are of low to moderate intensity, and may sometimes continue for several days. During summer, heating of the ground causes thermal convection, which ordinarily does not produce much rainfall. However, when air masses characterized by such atmospheric instability flow over denser air bodies or up a slope of the land, considerable precipitation may result.

Winter precipitation in the Southwest is due almost entirely to movement of relatively warm air over temporarily stationary or slowly moving cold air masses. Most commonly, fresh, moist air from the north Pacific region overrides air from the same source which is already in the Southwest and which has been cooled by radiation, or it may move up over colder and denser air from Canada, which has moved in directly or has swung in from the east and south. Moist air from tropical Pacific waters may yield precipitation in the Southwest by overriding cold air from either the north Pacific or Canada.

Also moisture is precipitated from fresh Polar Pacific air masses directly in the form of light, scattered showers or snow flurries. The fresh polar air is cold and becomes topheavy after the lower layers are heated during the day. The resulting convective currents manifest themselves through the development of cumulus clouds, which by late afternoon or evening may release small amounts of precipitation. These small storms occur only in the wake of the passage of a cold front of Polar Pacific air and contribute little to the total winter precipitation.

Although the moisture content of the air masses in winter is relatively low because of lower air temperatures, winter is generally a rainy season because of the vigor of air-mass interactions.

In summer, there is much less contrast in the properties of the various air masses and the fronts between successive advances of air from the Pacific are less pronounced. Furthermore, inroads of cold, dry air from Canada become less and less frequent so that they are of slight importance in releasing moisture as precipitation. However, the moisture content of air masses from the ocean is higher in the summer than at any other time, and the air may be convectively unstable so that moisture is more easily released. During the summer, insolation is at a maximum and instability of the air is induced

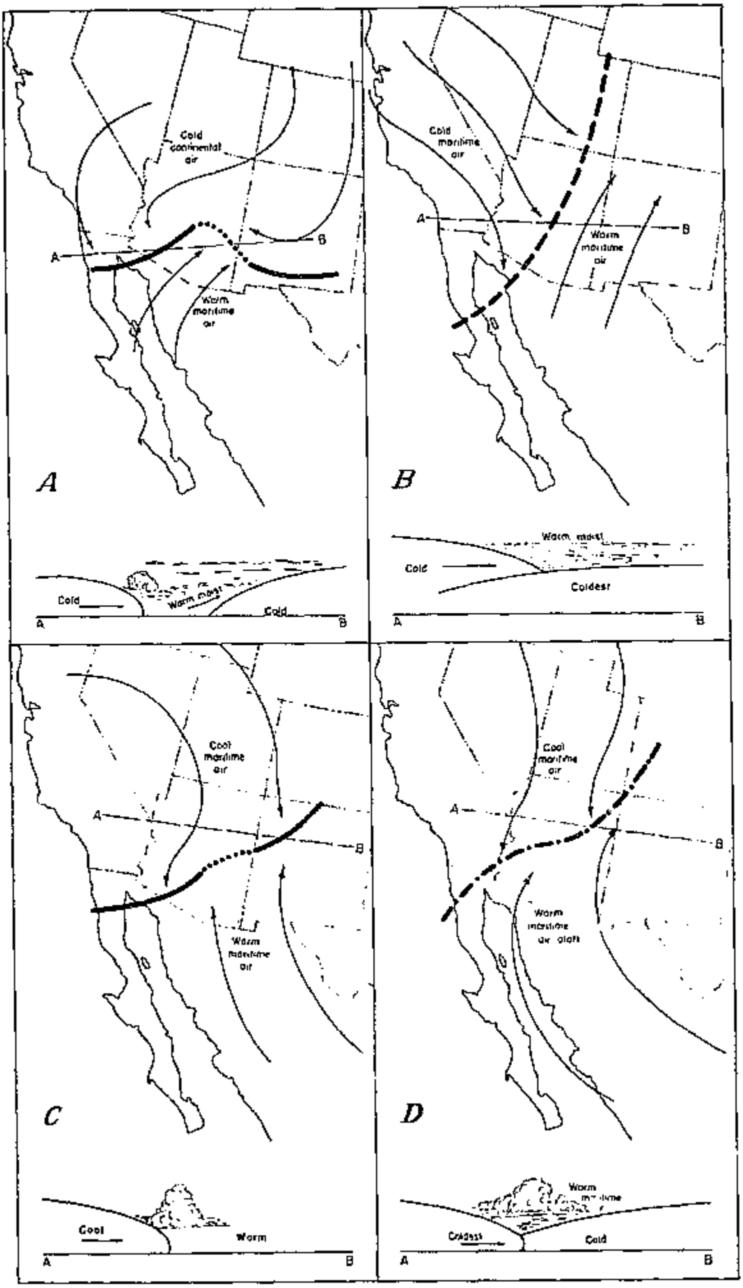

FIGURE 5.—Diagrammatic representation of four meteorological situations which produce precipitation in the Southwest. Arrows indicate direction of air-mass flow; solid black line, cold front; dotted line, warm front; dashed line, upper front; dash-dot line, occluded front. *A* and *B* are typical of winter, *C* and *D* of summer.

by heating of the ground during the day and radiational cooling of moist layers aloft at night. As a result, brief, intense, local thunderstorms take place. Usually they occur along cold fronts, which exist between successively invading masses of cool, moist air from the Pacific or where warm, moist air from the Gulf of Mexico is forced up by cool air entering the region from the north Pacific. Although these fronts are often ill-defined, they frequently provide the means of obtaining precipitation from air already made unstable by insolation and radiational cooling. For these reasons summer is also a rainy season. Four meteorological situations which result in precipitation in the Southwest are represented diagrammatically in much simplified form in figure 5.

Spring and autumn are periods of transition in which neither convective storms nor extensive warm-front storms are well-developed. Both are therefore seasons of low rainfall.

In late summer and early autumn occasional tropical cyclones over the Pacific off the coast of lower California may induce an inflow of moist Tropical Pacific air, which is forced up over Polar Pacific air already occupying the Southwest. Widespread, heavy rainfall generally results. September rainfall may, therefore, occasionally equal or surpass in amount and intensity that recorded during the period of summer thunderstorms. Usually, however, September is characterized by rains of less intensity and smaller total amounts than are July and August.

METEOROLOGICAL ANALYSES OF SELECTED STORMS [5]

To illustrate the effects of certain meteorological conditions, four rainstorms in which large amounts of precipitation fell in Arizona were selected for study and are presented in figure 6. The storm of December 15–16, 1908, is a typical general winter storm in which the moisture was precipitated from warm, moist air forced upward by an invasion of cold Polar Pacific air. On the morning of the 15th, the front of a mass of Polar Pacific air extended across Arizona in a southwest-northeast direction. The cold front had become quasi stationary, and one of the minor waves on the front began to intensify and develop into a well-defined extra-tropical cyclone. This caused widespread rain by forcing warm, moist air from the south to ascend over the colder and denser air to the north. The cyclone moved little during the next 24 hours, and by the morning of the 16th it began to occlude. By evening, colder air had pushed into Arizona, and the rain ended.

The storm of July 21–24, 1915, brought considerable amounts of rainfall to northern Arizona. The meteorology of this storm is more characteristic of winter conditions, but since this particular combination of air masses occurred in summer and involved air which was convectively unstable, the resulting pattern illustrates both the features of warm front widespread rain and convective spotty rain. At the beginning of the storm period a widespread mass of Polar Canadian air covered most of the United States and extended across the Southwest into northern Mexico, the front being roughly

[5] Meteorological analyses of these storms were made by Benjamin Holzman, of the Climatic and Physiographic Division.

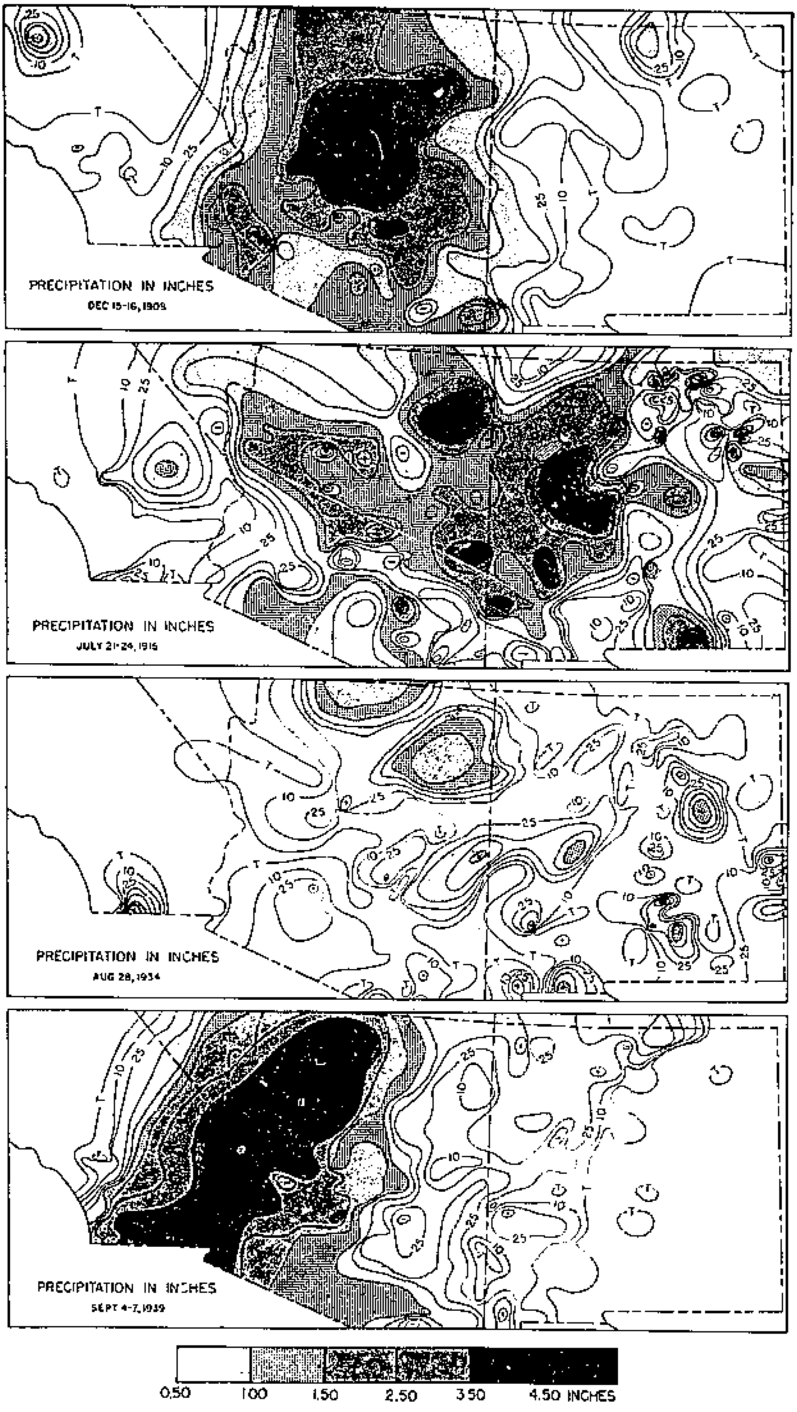

FIGURE 6.—Selected rainstorms in the Southwest.

parallel to the international boundary. Above the Polar Canadian air in the Southwest was moist Tropical Maritime air. During the evening of the 21st, an extensive mass of Polar Pacific air slowly pushed eastward across Washington, Oregon, Nevada, and the Southwest. This air, being less dense than the surface Polar Canadian air and more dense than the Tropical Maritime, tended to wedge them apart. The advance of the Polar Pacific front above the Polar Canadian mass from the west caused an accelerated movement of Tropical Maritime air aloft from the south and resulted in widespread rain. These conditions persisted through the 22d, and on the 23d the front of the Polar Pacific air mass had moved only slightly eastward. Not until the 24th did the storm end. This storm illustrates the generalized conditions illustrated in figure 5, *B*.

The storm of August 28, 1934, is typical of summer and illustrates the spottiness of rainfall when a cold front forces aloft air already convectively unstable. It was associated with an invasion of a simple cold front. On the morning of the 27th, a mass of Polar Pacific air entered the west coast States. This caused an acceleration in the flow of warm, moist air, probably Tropical Atlantic, from the south. By evening the surface winds at Flagstaff and Phoenix had shifted from east to northwest, indicating that the front of the Polar Pacific air had passed these stations. During the morning of the 28th, the front became quasi stationary in eastern Arizona. Later, it continued eastward and by evening had passed out of the region. Many scattered thunderstorms were occasioned by the passage of this front.

The storm of September 4–7, 1939, owed its very large amount of rainfall to a tropical cyclone which moved up the California coast from the tropical waters off the west coast of Mexico. The average September precipitation for northern Arizona, based on a 45-year record, is 1.34 inches. The rainfall of September 1939 surpassed all existing records, with 4.87 inches. For the State as a whole, 38 stations received the greatest total September precipitation on record, and new records, exceeding amounts for any previous month of the year, were established at 17 stations. A large proportion of this precipitation occurred in the storm of September 4–7.

On September 3d, there had been an upper-air invasion of Polar Pacific air overriding the modified Polar Pacific air already occupying the region. On the 4th, the upper-air mass migrated across Arizona in the early morning. General rains accompanied by considerable thunderstorm activity occurred throughout the central and northern sections of the State. Rainfall amounts generally averaged over 0.50 inch. Six stations in northern Arizona received over 1 inch; the largest amount, 3.32 inches, was reported at Truxton.

General rains continued on the 5th, when moisture was being precipitated from a Tropical Pacific air mass that had invaded California and Arizona from the south. The vigor of this invasion was due to a tropical cyclone off the Pacific coast, which originated to the southward of Acapulco on the 5th and was dissipated over the upper part of Lower California on the 12th. In northern Arizona, 14 stations received more than 1 inch of rain; 7 stations, more than 2 inches; and 2 stations, more than 3 inches.

On the 6th, the moist tropical air continued to flow over the Southwest and general rains combined with thunderstorms persisted. In northern Arizona, 20 stations reported over 1 inch of rain and 6, over 2 inches. On this day a new mass of Polar Pacific air moved into the Pacific Northwest and by the 7th had reached the Southwest. The moist tropical air flowed up the slope of this dense air mass. Rain continued for several days but never in such large amounts as had been recorded in the 3-day period from the 4th through the 6th.

The tropical cyclone of September 5–12 was only one of three which moved up the coast of Lower California during the month. The second was particularly violent over and in the vicinity of the mouth of the Gulf of California, and the third did much damage in southern California. It was the most severe tropical storm that has ever been observed in that region (*68, p. 358*).

The severity of the storm along the coast is indicated by a loss of 45 lives at sea, and a property damage approximating $2,000,000, mostly to shipping, shore structures, power, and communication lines, and to crops. Unprecedented September rains accompanied the storm along the southern California coast.

VARIATION IN MONTHLY AND ANNUAL PRECIPITATION

Rainfall totals for a month or a year are aggregates of individual rains. Hence the amount of variation from one year to another in monthly and annual rainfall is due entirely to variations in the number of occurrences and the size and position of individual storms. Similarly, variations in rainfall from one region to another are to be accounted for in terms of rainstorm size, position, and frequency.

Fort Defiance, in 1853, furnished a complete year's record of precipitation in northern Arizona. Records have been continuous since 1890 at Natural Bridge, since 1897 at Flagstaff, and, with an interruption of only 4 months, since 1876 at Prescott. Within the period for which rainfall observations have been made at these stations, the range in annual precipitation amounts has been large (fig. 7).

The largest amount of precipitation recorded in a year at any Weather Bureau station in northern Arizona was 50.17 inches in 1905 at Natural Bridge. This station has been in operation for 50 years, and during that time the annual precipitation in over half of the years was less than 20 inches. The minimum, 12.28 inches, fell in 1900.

At the other extreme is Leupp, whose greatest precipitation, 9.09 inches in 1915, is less than the maximum recorded at any other station in northern Arizona. At Leupp, the least rainfall received in any year for which there is a record was 2.52 inches in 1938. The average for the 13 years of record is 6.27 inches.

The maximum and minimum annual rainfall for stations in northern Arizona having a record of at least 10 years is shown in figure 8.

Throughout Arizona and in western New Mexico there are "rainy" seasons in winter and summer and "dry" seasons in late spring and autumn. This double peak in the distribution of rainfall disappears both to the west and to the east. In California, the only rainy season is in winter, summer being drier than either spring or autumn. In eastern New Mexico there is no winter rainy period, the precipitation being at a minimum in January and at maximum in July. The transition from California to New Mexico is shown in figure 9.

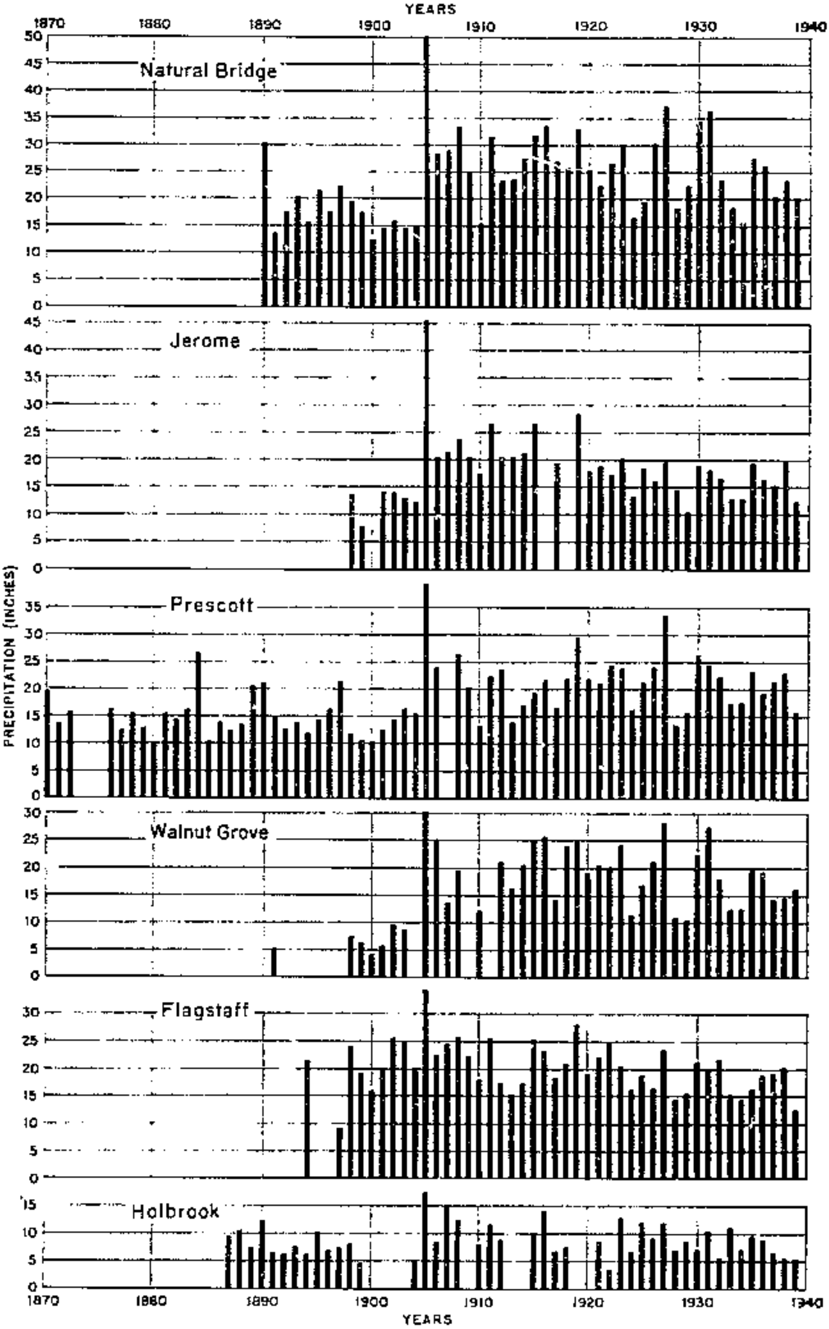

FIGURE 7.—Annual precipitation at selected stations in northern Arizona, 1870–1920.

Despite large variations in annual precipitation, there is a striking similarity in the pattern of monthly distribution within each of these three rainfall regions.

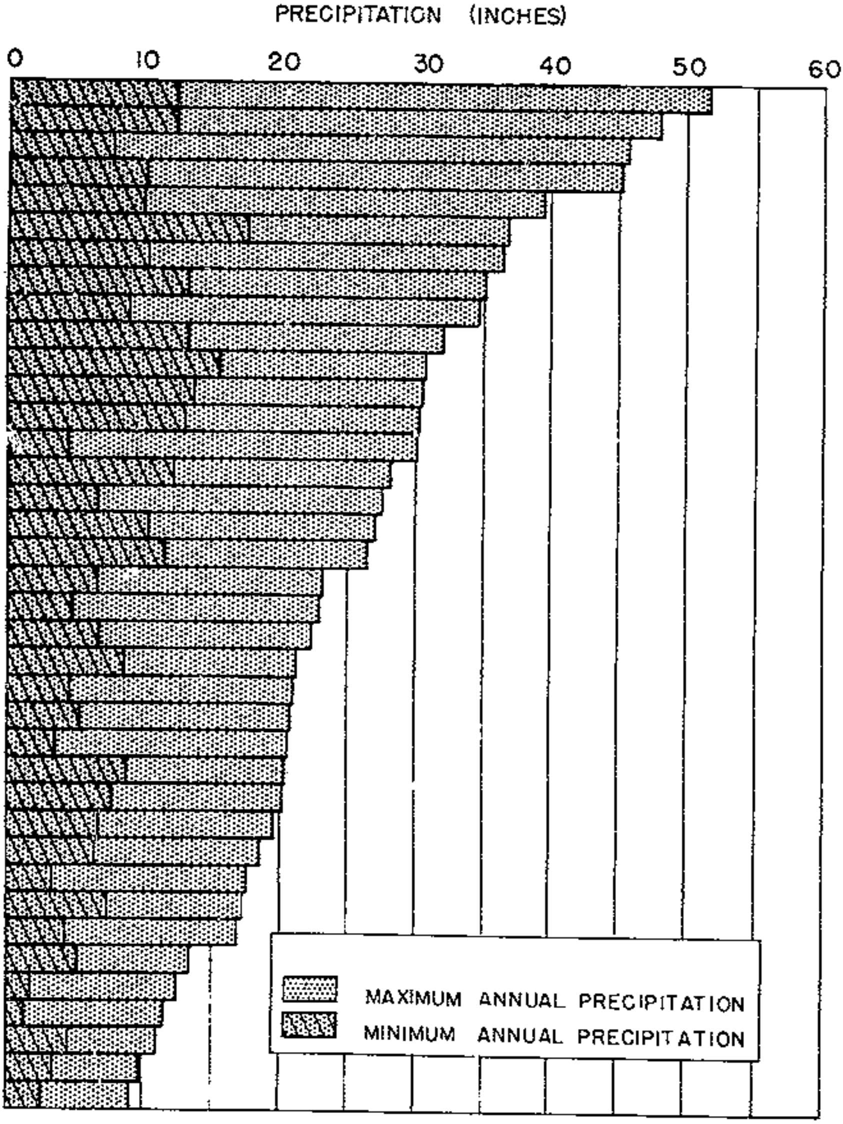

FIGURE 8.—Maximum and minimum annual precipitation for stations in northern Arizona having at least 10 years of record through 1939.

Precipitation varies widely from month to month, and even at the rainiest of stations as many as 10 of the 12 months have in one year or another experienced a complete absence of rain. For Natural Bridge, the only station in northern Arizona with a continuous record for 50 years, figure 10 shows the frequency of occurrence of various monthly precipitation amounts. At this station, the likelihood of complete absence of rain is greatest in May and June and least in July and August. The latter two are the only months which have not been rainless during the 50-year period. On the other hand, frequencies of largest monthly amounts are greatest in December, January, and February. Monthly totals above 3 inches were never experienced during May and June.

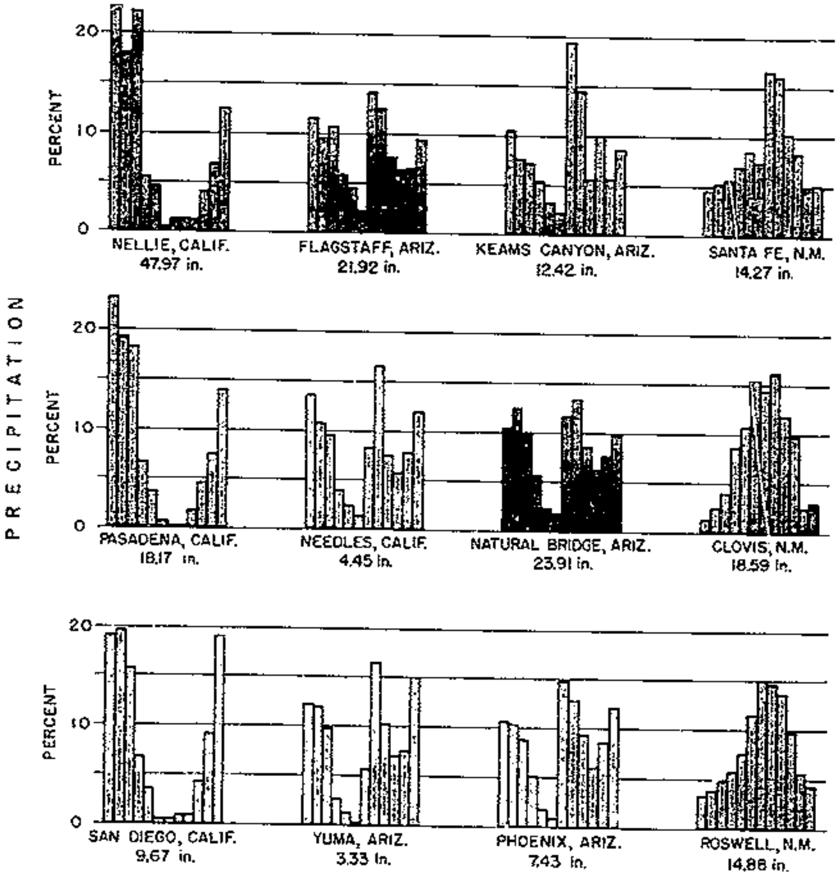

FIGURE 9.—Percentage of the average annual precipitation (shown in inches) received in each month at selected stations in California, Arizona, and New Mexico.

The monthly distribution of rainfall at Natural Bridge is representative of that of most of the Southwest, although the climate at Natural Bridge is moist subhumid, whereas in most of the Southwest it is semiarid or arid. At most stations rain may be totally absent in July or August as well as in the other months of the year. The likelihood of rain during May and June is generally less in other parts of Arizona than at Natural Bridge. Large monthly amounts may be experienced even in the arid areas.

Figure 10.—Frequency of monthly precipitation of specified amounts at Natural Bridge, Ariz., 1880–1939.

Within much of the Southwest, 1905 was the rainiest year experienced since observations have been made on any considerable scale. At only 4 of the 14 stations in operation in northern Arizona that year has the rainfall of 1905 been exceeded. In fact, the rainfall at most of these stations in 1905 was several inches higher than that of the next rainiest year and at one station it was seven times the rainfall of the driest year (table 2).

Table 2.—*The precipitation of 1905 and other precipitation values at selected stations in northern Arizona*

Station	Length of record	Annual precipitation: 1905	Next highest	Minimum	Average
	Years	*Inches*	*Inches*	*Inches*	*Inches*
Congress	21	31.29	23.77	5.72	13.55
Flagstaff	14	31.73	28.28	9.12	20.56
Greer	8	30.19	21.47	15.15	22.12
Holbrook	14	17.63	15.16	3.40	8.84
Jerome	39	45.93	28.57	7.86	18.17
Natural Bridge	50	50.47	37.62	12.28	24.10
Prescott	66	39.17	33.97	10.62	18.71
Walnut Grove	40	30.28	28.44	4.33	17.05
Yarnell	14	45.57	28.62	10.63	19.76
Young	21	48.19	32.37	15.28	22.55

For several years prior to 1905, the rainfall throughout Arizona was far below the normal, and for most of the stations for which records exist the minimum rainfall occurred or was closely approximated in one of the years between 1896 and 1904. Extreme variability from year to year is well illustrated by the maps showing annual precipitation for 1904 and 1905 (fig. 11). Whereas in 1904 not more than 3 percent of the area of the State received as much as 20 inches, in 1905 fully 70 percent received 20 inches or more. During these years, there were relatively few stations, but in 1905 two of them recorded more than 50 inches of rainfall. At no other time has as much as 50 inches of precipitation been recorded anywhere in Arizona.

The extreme variations in the rainfall of Arizona for 1903, 1904, and 1905 are presented graphically in figure 12. In figure 12, *A* the days with rain are shown for all Weather Bureau stations in operation in those years. Each dot indicates a report of rain of at least 0.01 inch on a certain day at a particular station. The number of stations increased considerably during the period: 23, in 1903: 33, in 1904; and 41, in 1905. The stations are arranged alphabetically, just as they appear in the published reports of the Division of Climate and Crop Weather of the Weather Bureau. Station names have been omitted because the purpose of the chart is merely to permit an over-all comparison of the rainfall patterns in the different years.

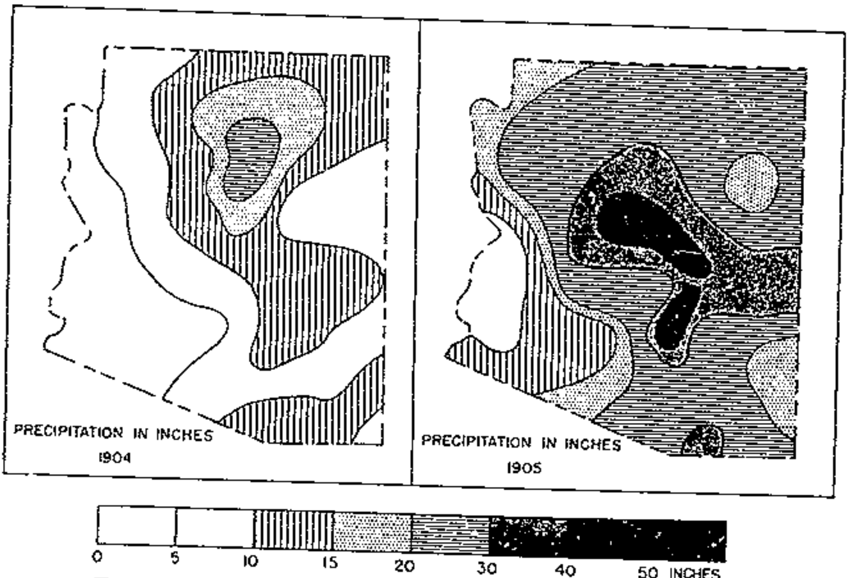

FIGURE 11.—Annual precipitation in Arizona, 1904 and 1905.

Dots in vertical alignment indicate the occurrence of precipitation on the same day at various stations. Dots in horizontal alignment show successive days of rain at the same station. Total rainfall at each station is shown by the solid horizontal bars at the right.

The great contrast between the total rainfall in 1905 and in the two earlier years can be seen clearly. Whereas in both 1903 and 1904 only 1 station received more than 20 inches of precipitation, in 1905 only 9 of the 41 stations received less than that amount. The characteristic rainy seasons in winter and summer separated by dry periods in spring and autumn are apparent only in 1905. In the other years there was great deficiency of winter rain. From October 4 to December 5, 1903, no rain was recorded anywhere in Arizona. At Natural Bridge, only 4.35 inches of rain fell between October 1, 1903, and July 1, 1904, whereas the average rainfall for this period is 15.90 inches. In Parker, only 0.04 inch fell between October 1, 1903, and May 1, 1904. During July and August 1904, rainfall was above normal throughout Arizona despite the fact that the summer rainy season was late, not commencing until July 19. The autumn months of 1904 were considerably below normal in most of the State; in northern and western Arizona, rain was recorded at only 1 station between October 9 and December 2.

Although 1905 was the wettest year on record, 5 months of the year—May, June, July, August, and October—were below normal in precipitation at most stations. July and August were not lacking in storm periods, but storm amounts of rainfall were low. The rainfall surplus for the year is accounted for by the unusually great number of large storms in January, February, March, and November.

Between 1905 and the two earlier years there is a much greater contrast in total rainfall and in the number of rainy days than in the number of distinct storm periods. There were 45 storm periods in 1905, 31 in 1903, and 36 in 1904. However, the amount of rain falling in individual storms was much greater in 1905 than in either of the other years. This is brought out in table 3, where the number of occurrences of 1 inch or more of precipitation in 24 hours is given for the three years. Because the number of stations reporting was different in each of these years the data have been adjusted to a common base of 100 stations to facilitate comparison.

TABLE 3.—*Number of occurrences of 1 inch or more of precipitation in 24 hours in Arizona during the years 1903, 1904, and 1905, by months, adjusted to 100 stations*

Year	January	February	March	April	May	June	July	August	September	October	November	December	Total
1903	0	26	70	4	4	14	44	74	78	0	0	0	314
1904	0	4	6	0	16	0	104	124	6	18	0	6	284
1905	142	152	156	74	0	14	14	30	56	2	256	6	902

Despite the tremendous difference in the amount of precipitation in 1905 and in the two preceding years, the march of temperature through the three years was near normal (fig. 12, *B*). The mean monthly temperatures at Phoenix for 1903, 1904, and 1905 and the average monthly temperatures for the period 1876–1930 are presented in table 4. The mean annual temperature of 1905 is exactly the same as the normal for the whole period. The mean annual temperatures of 1903 and 1904 are respectively only 0.2° and 0.8° F. above the normal. The monthly mean temperatures of the three years are all close to the normals.

TABLE 4.—*Mean monthly temperatures at Phoenix, Ariz., for the years 1903, 1904, and 1905, and average monthly temperatures for the period 1876–1930*

Period	January	February	March	April	May	June	July	August	September	October	November	December	Year
	° F.	° F.	° F.	° F.	° F.	° F.	° F.	° F.	° F.	° F.	° F.	° F.	° F.
1876–1930	50.9	55.1	60.5	67.1	74.7	84.4	89.7	88.4	82.0	70.3	59.2	51.9	69.5
1903	51.8	48.8	59.8	66.3	74.6	85.4	90.0	90.8	81.7	71.0	62.4	53.4	69.7
1904	48.4	58.9	62.9	68.0	77.0	86.3	88.4	88.0	80.5	70.8	62.2	52.7	70.3
1905	55.2	56.4	60.0	64.4	70.5	83.6	89.6	90.0	84.2	71.6	58.5	50.0	69.5

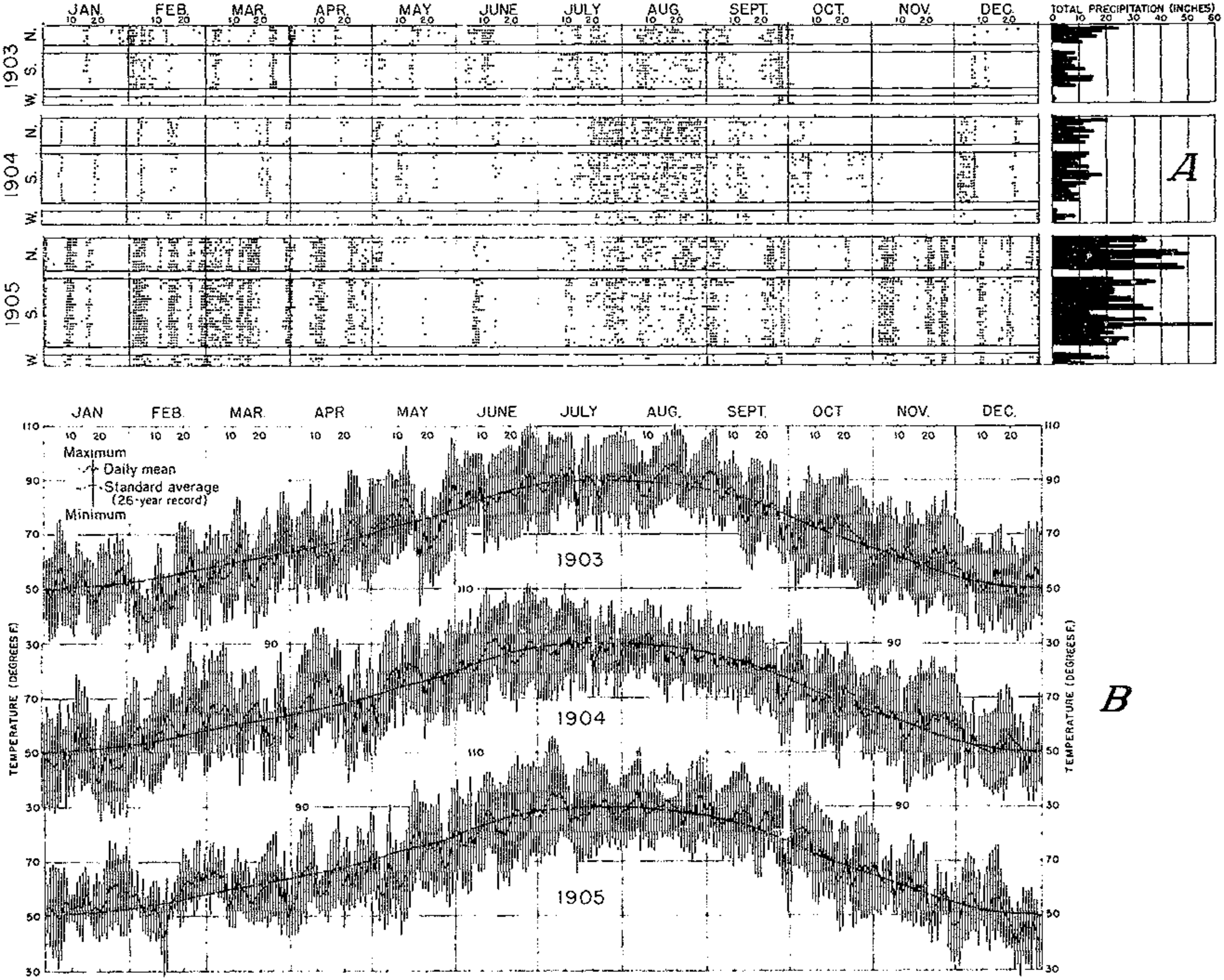

FIGURE 12.—*A*, Daily precipitation in Arizona, 1903, 1904, and 1905; *B*, daily maximum, minimum, and mean temperatures at Phoenix, Ariz., 1903, 1904, and 1905. In *A* the stations are arranged alphabetically by divisions of the State—northern, southern, and western—as they appear in the Climatological Summaries of the Weather Bureau.

(Faces p. 20)

In figure 12, *B*, the daily temperatures for 1903, 1904, and 1905 at Phoenix are plotted for comparison with the daily precipitation in Arizona for these years. It is seen that the sequence of air masses as revealed by the daily march of temperature is in no year particularly unusual. However, on analyzing the daily weather maps for the three years it was found that there was a greater tendency for the cold fronts to stall over Arizona in 1905 than in either of the earlier years. Polar Canadian air-mass invasions were also more frequent in 1905.

In 1903, there were approximately 60 invasions of Polar Pacific air masses, of which 6 became quasi stationary over Arizona, and 4 invasions of Polar Canadian air, 1 of which became quasi stationary. In 1904, approximately 79 Polar Pacific air masses moved over, with 2 stalling for a time. Of 4 Polar Canadian air masses crossing Arizona, only 1 stalled. In 1905, approximately 83 invasions of Polar Pacific air masses occurred, with 23 quasi stationary, and there were 14 invasions of Polar Canadian air, with 4 quasi stationary. Conditions favoring warm-front storms were more numerous in 1905 than in either of the earlier years. Otherwise there was little difference. Certainly, no one studying only the meteorological conditions of the three years could have determined that one of these years was the wettest on record and the others practically the driest.[6]

The influence of individual large storms on monthly and annual rainfall totals was well illustrated in 1939. Despite several large storms in September, one of which was discussed on pp. 13–14, most of Arizona was deficient in precipitation for the year. In figure 13, *A*, the days with rain are shown for all stations in operation in Arizona in 1939. As in figure 12, each dot indicates a report of rain of at least 0.01 inch on a certain day at a particular station. Widespread rainfall is most marked in the winter, early spring and late fall months.

In figure 13, *B*, are shown the daily maximum, minimum, and mean temperatures at Flagstaff and Natural Bridge, Ariz., in 1939 and the normal of the means. The fluctuations of the line representing the daily mean result from the temperature changes brought about by the influx of cool and warm air masses. The relation of large changes of temperature to incidence of precipitation is clearly shown, which demonstrates the control exercised by air-mass interactions on precipitation.

Daily precipitation amounts at Flagstaff and at Natural Bridge are shown in figure 13, *C*. Precipitation was lower than usual during the early months of the year.

Flagstaff experienced below-normal rainfall in every month except September, and despite large amounts in that month, the deficiency for the year was 9.89 inches. In the 8 months prior to September, only 6.66 inches had fallen, whereas the normal for the period was 15.47 inches. At Natural Bridge, where the normal is 13.19 inches, prior to August 1 there had been only 5.76 inches of precipitation.

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[6] Meteorological analyses by Benjamin Holzman, of the Climatic and Physiographic Division.

EXCESSIVE PRECIPITATION IN THE SOUTHWEST

Both general and local storms have characteristic patterns of structure and migration, both have definite limits of areal distribution, and both have centers of maximum intensity. If stations are evenly spaced throughout a storm area, it is obvious that low intensities and small amounts of precipitation will be recorded more frequently than high intensities and large amounts since the periphery of a storm is larger than its center.

Similarly, a single station having a reasonably long record of rainfall will report many occurrences of precipitation of small amount and low intensity, and few of large amount and high intensity. Records of very intense falls and large amounts will be few. The location of individual rainstorms in a region is more or less random. Thus, since a storm center is comparatively small it is more probable that the station will be in some part of the periphery of the storm rather than in its center. Storms vary in size, also, and this variation helps to explain the frequency distribution of recorded amounts of precipitation at an individual station (*107, pp. 480–481*).

Santa Fe is the only station in the Southwest having a continuous rainfall record extending back to 1850. The frequency of various 24-hour amounts of precipitation at this station for the 90-year period 1850–1939 is given in table 5. The overwhelming preponderance of precipitation amounts under 0.20 inch does not mean that rainstorms are usually limited to those amounts in the Southwest, but rather that the more or less random distribution of storms results in the station at Santa Fe being much more often marginal than central with respect to the storm area.

TABLE 5.—*Number of occurrences of specified 24-hour amounts of precipitation at Santa Fe, N. Mex., 1850–1894, 1895–1939, and 1850–1939*

Precipitation (inches)	1850–1894		1895–1939		1850–1939	
	Number of occurrences	Accumulated total	Number of occurrences	Accumulated total	Number of occurrences	Accumulated total
4.00–4.99	1	1	0	0	1	1
3.00–3.99	1	2	0	0	1	2
2.00–2.99	1	3	3	3	4	6
1.50–1.99	8	11	8	11	16	22
1.40–1.49	2	13	6	17	8	30
1.30–1.39	10	23	5	22	15	45
1.20–1.29	13	36	4	26	17	62
1.10–1.19	15	51	6	32	21	83
1.00–1.09	17	68	18	50	35	118
0.90–0.99	18	86	21	71	39	157
0.80–0.89	28	114	28	99	56	213
0.70–0.79	23	137	40	139	63	276
0.60–0.69	61	198	60	199	121	397
0.50–0.59	80	278	90	289	170	567
0.40–0.49	138	416	136	425	274	841
0.30–0.39	208	624	225	650	433	1,274
0.20–0.29	287	911	370	1,020	657	1,931
0.10–0.19	600	1,511	739	1,759	1,339	3,270
0.01–0.09	1,380	2,891	2,230	3,989	3,610	6,880

The 90 largest 24-hour amounts of precipitation which have been recorded in Santa Fe during the 90 years from 1849 to 1938 are plotted in figure 14. The distribution of these storms in time is ex-

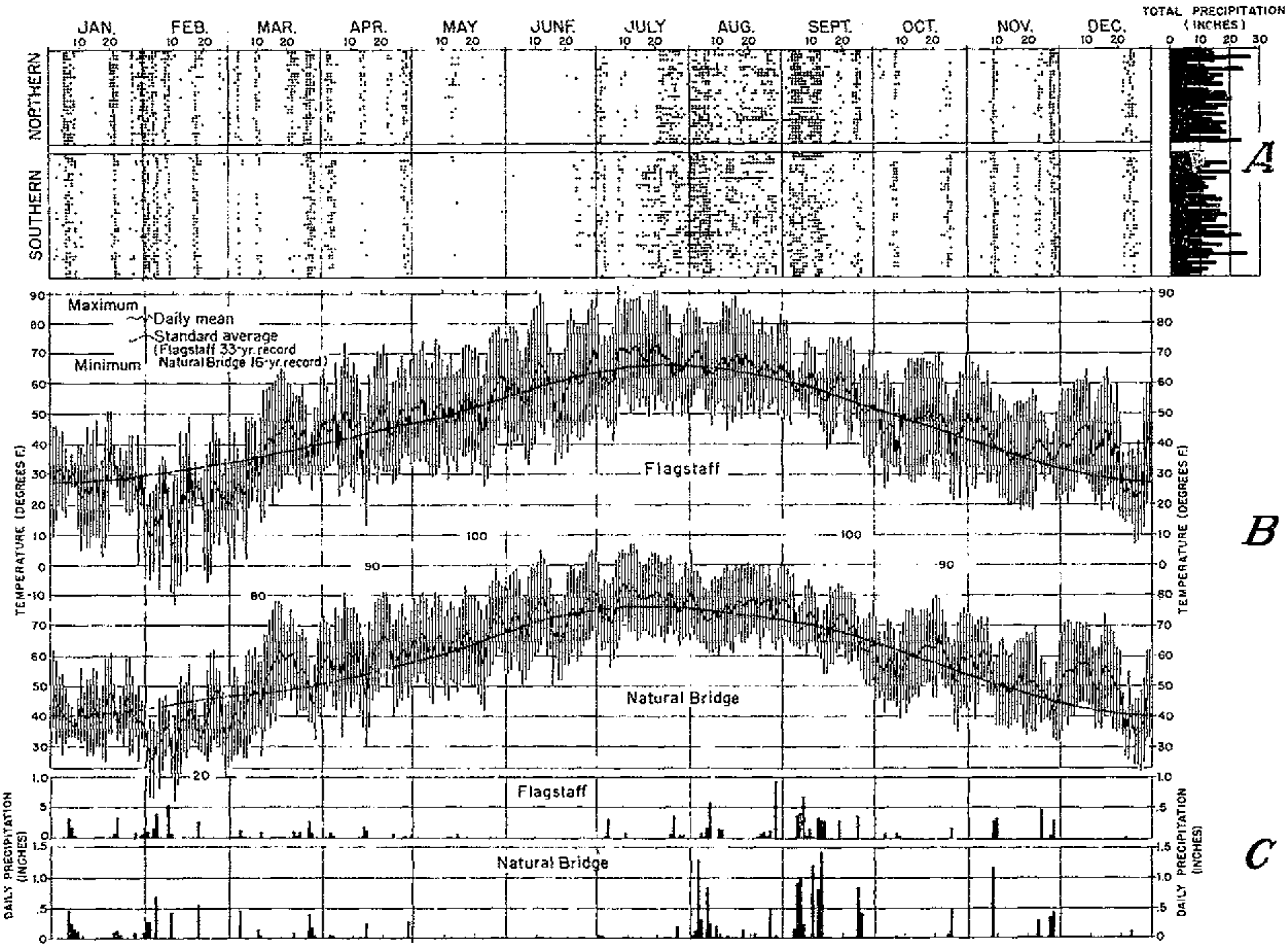

FIGURE 13.—*A*, Daily precipitation in Arizona in 1939; *B*, daily maximum, minimum, and mean temperatures at Flagstaff and Natural Bridge; *C*, daily precipitation at Flagstaff and Natural Bridge. In *A* the stations are arranged alphabetically by divisions of the State as they appear in Climatological Data, from which the station names can be obtained. Each dot in *A* indicates a report of at least 0.01 inch of rain.

(Faces p. 22)

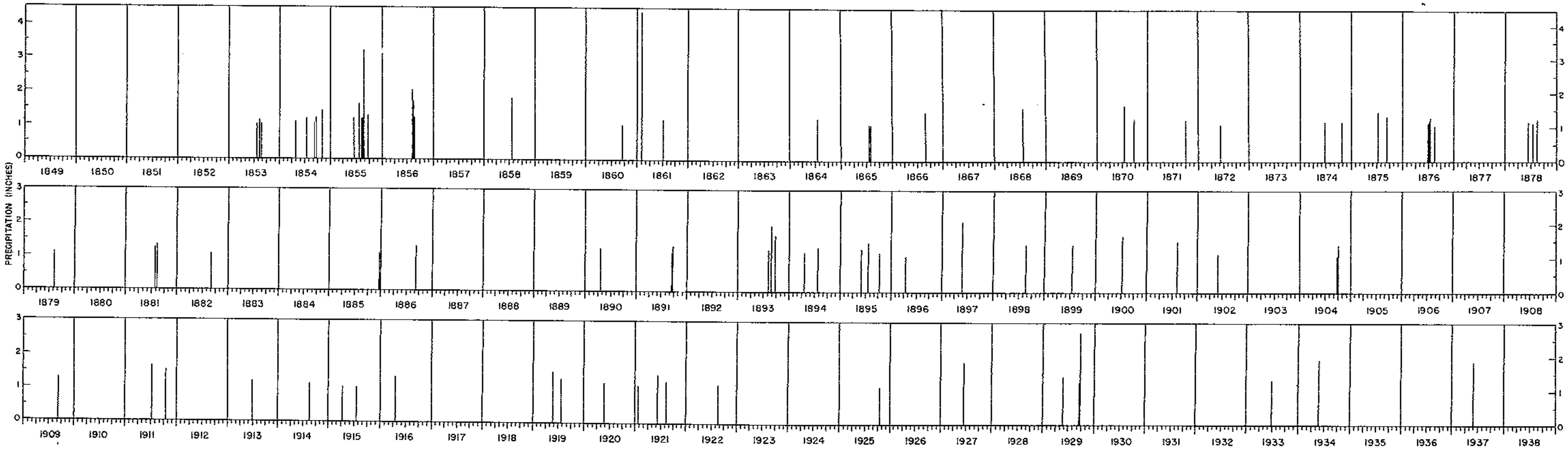

FIGURE 14.—Distribution of the 90 maximum 24-hour storms at Santa Fe, N. Mex., 1849–1938.

(Faces p. 22)

tremely irregular. Only 3 storms occurred in the 9 years 1930–1938; on the other hand, 17 occurred in the 4 years 1853–1856. During the 7-year period, 1896–1902, 1 storm occurred each year. Of the 90 maximum 24-hour storms, 60 occurred during July, August, and September. Of the 90 maximum 48-hour rainfall amounts, 53 were recorded during these months. The comparative data are shown in table 6. It must be remembered that Santa Fe is in the part of the Southwest which has a winter minimum of precipitation. In western New Mexico and Arizona, where there are 2 rainy seasons, large storms are to be expected in winter as well as in summer.

TABLE 6.—*Frequency of 90 maximum storms at Santa Fe, N. Mex., 1849–1938*

Storm duration (hours)	January	February	March	April	May	June	July	August	September	October	November	December
	Number	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*
24 [1]	1	1	0	6	6	9	21	22	17	5	1	1
48 [2]	0	3	0	5	10	10	25	15	13	3	4	2

[1] Storm restricted to 1 calendar day.
[2] Storm recorded on more than 1 calendar day but not on more than 2.

There is no reason to expect that years of numerous excessive storms will necessarily be followed by other years of heavy rains. The Santa Fe record indicates that large storms may be concentrated in one period, as during 1853–56, and that a single large storm may be isolated, as was the largest storm of record, which took place in February 1861. Indeed, as the storm sequence in figure 14 shows, the spacing of large rainfall amounts has been highly irregular.

The annual rainfall at Santa Fe for the 90-year period 1850–1939 is presented in figure 15 to permit a comparison with the distribution of the 90 greatest storms shown in figure 14.

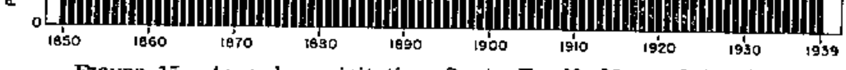

FIGURE 15.—Annual precipitation, Santa Fe, N. Mex., 1850–1939.

The coincidence of the various conditions necessary for the formation of rain does not occur with any regularity. Not only is moisture in the air necessary but there must also be present some mechanism, frontal activity, convection, orographic lifting, or a combination of the three, for releasing the moisture. It is not unusual for heavy thunderstorms to occur in summer at heights of 2,000 to 5,000 feet aloft without wetting the ground. Sometimes the only result of a heavy thunderstorm will be the falling of a few hailstones (*49, p. 111*). Tropical air, unless moist, will yield no precipitation when uplifted by cold fronts passing across the Southwest. On the occasions when all the conditions which make for rains are present, however, excessive amounts are possible even in the arid parts of the region, as the storm of September 4–7, 1939, demonstrates (fig. 6).

Fort Mohave [7] is a desert station on the Colorado River in western Arizona with an average annual rainfall of 5.09 inches. In 1889, the total rainfall of the year was 21.38 inches, 11.17 inches of which came during the month of December. In this month there were 8 days on which rain was recorded; the smallest daily amount being 0.62 inch. On 5 days the precipitation exceeded 1 inch, and rainfall amounts recorded in 4 storm periods were 2.90 inches, 2.70, 2.30, and 1.90 inches. In the 521 scattered months of the record at Fort Mohave, monthly precipitation totals exceeded 1.00 inch only 59 times.

Monthly rainfall amounts exceeding 11.00 inches are extremely few in the Southwest, yet the fact that such an amount was recorded in a desert station indicates that the occurrence of that much rainfall in a month is not impossible anywhere. An unofficial excessive fall of precipitation was reported at Fort Mohave for August 1898 by Henry Schlegel (*92, p. 3*), the cooperative Weather Bureau observer, as follows:

> On the 28th, we had the biggest rain in 10 or 15 years, and to my regret, between the rain and furious wind, my rain guage was upset. To give an idea of the amount of rain that fell, and which lasted only 45 minutes, I had a wash tub set out on the mesa, clear of everything, and the water after the rain, measured 8 inches.

Records of excessive precipitation in the Southwest are extremely few. There are only three Weather Bureau stations with long records from automatic rain gages, and only within the past 6 years have other agencies installed self-recording gages in any number in the region. The records from cooperative Weather Bureau stations do not ordinarily give the time of beginning and ending of storms. Frequently, too, the records of large storms have been lost, either through damage to the gage, as at Fort Mohave on August 28, 1898, or through failure to make an observation over a period of several days.

Maddock and Leopold [8] have tabulated 40 storms of 2 inches or more in Arizona and New Mexico for which the times of beginning and ending have been recorded, and the storm duration can consequently be determined. In figure 16, these 40 storms have been plotted and the envelope curve drawn. Thirty-five of the storms did not exceed 4 hours in duration, and, as would be expected, nearly all of them occurred in July, August, or September. More than two-thirds of the storms were reported from the eastern margin of the Southwest, where summer rainfall is proportionately greater than in the Southwest proper. Consequently, the enveloping curve represents precipitation intensities somewhat larger than those typically experienced in the Southwest.

Figure 17 reproduces the mass diagrams of precipitation of six large storms recorded during the summer months. Except for Las

[7] Prior to December 1898 the station name was Fort Mojave.

[8] MADDOCK, THOMAS, JR., and LEOPOLD, LUNA B. [CHARACTERISTICS OF HIGH RAINFALL IN NEW MEXICO AND ARIZONA.] [Unpublished manuscript.]

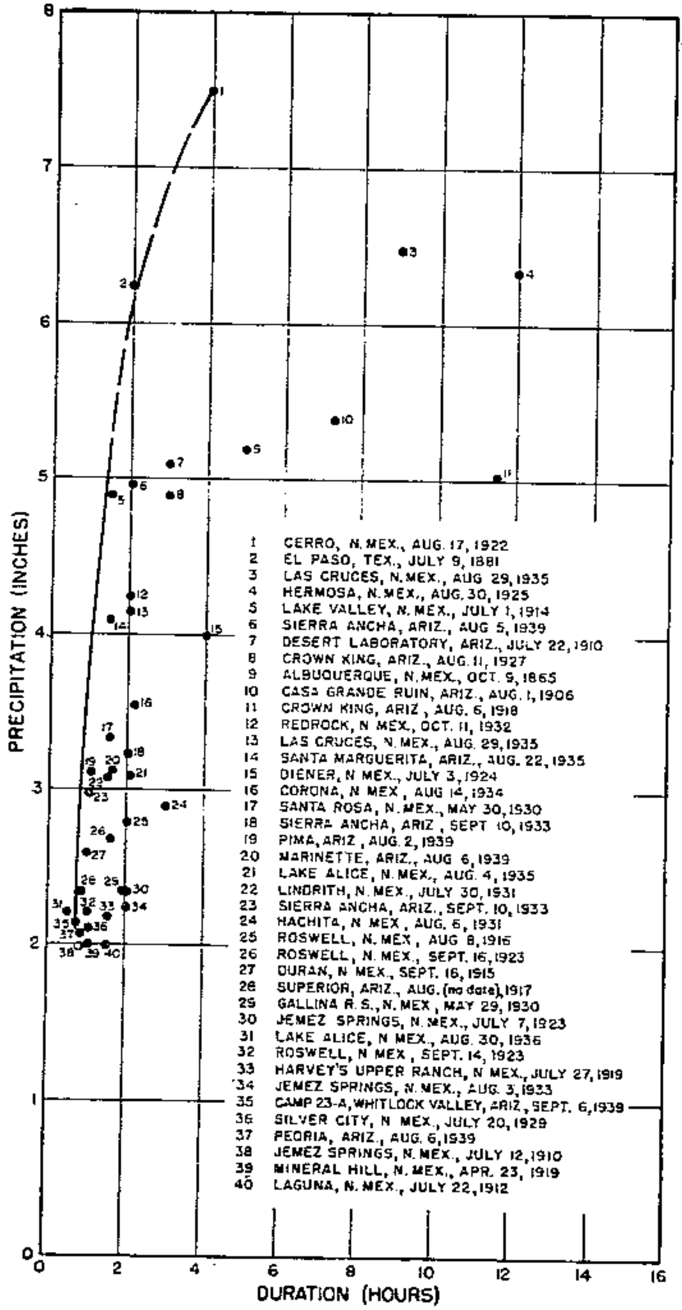

FIGURE 16.—Total precipitation and duration of 40 large storms in Arizona, Texas, and New Mexico.

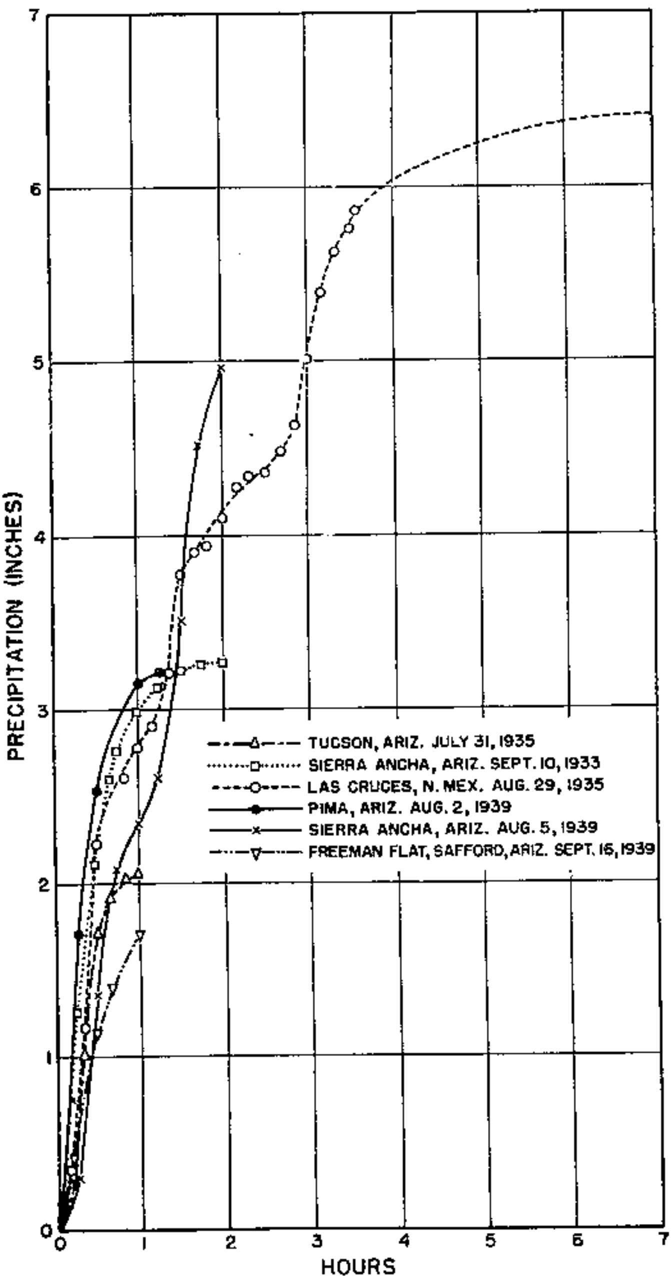

FIGURE 17.—Precipitation in six large storms in Arizona and New Mexico.

Cruces, the stations are all in Arizona, and the curves may be taken as representative of extremes of precipitation intensity for short periods in the Southwest.

RAINSTORM FREQUENCIES IN THE SOUTHWEST[9]

Reliable estimates of the probable frequency of large storms of specified precipitation amounts are difficult to make under the most favorable conditions (*34, 35, 107*), but in the Southwest, where rainfall records are fragmentary and the country is lacking in topographic uniformity, the task is doubly difficult. However, despite diversity of surface features and consequent variation in average rainfall from place to place and despite lack of meteorological homogeneity, considerable useful information on average frequencies of precipitation amounts in the Southwest can be obtained by use of the familiar station-year method of analysis (*77*).

In northern Arizona, there are approximately 75 Weather Bureau stations with precipitation records ranging in length from only a few years to nearly 70 years. In all, 1,269 station-years of record are available for study. In these records there were 1,269 reports of 24-hour rains exceeding 1.42 inches. This amount then represents the precipitation which might be expected at each station once every year. There were 634 reports of 24-hour rains of 1.73 inches or over, which amount could be expected at each station once in 2 years. Other frequencies for northern Arizona are given in the following tabulation:

Maximum 24-hour amounts of precipitation to be expected once in—	*Inches*
1 year	1.42
2 years	1.73
3 years	1.95
5 years	2.15
10 years	2.55
15 years	2.74
20 years	2.91
25 years	3.00
50 years	3.53
100 years	4.10

The largest recorded 24-hour precipitation in northern Arizona in the period studied is 6.46 inches.

However, the frequency of large storms varies greatly from place to place. In northern Arizona, the stations range from 350 feet to more than 8,500 feet above sea level, and the average annual precipitation ranges from less than 5 inches to more than 30 inches. Large storm amounts of rainfall increase in frequency with increase in average annual rainfall in areas meteorologically similar.

The frequency of large storms also varies with variation in meteorological conditions. Both Tuba City and Parker are arid, their average annual precipitation being 6.78 and 5.32 inches, respectively. Yet of all 24-hour storms of 0.50 inch or over, at Parker,

[9] The term "frequency" here has the special meaning given the word in hydrologic and climatic literature. The frequency of a rainfall of any amount is the mean interval between rains of that amount and greater. A rainfall of 2.00 inches, for example, has a 10-year frequency, or is a 10-year storm, if the mean interval between rains of 2 inches and more is 10 years. This explanation applies to use of the word in tables, illustrations, and text.

33.1 percent were 1 inch or over, and at Tuba City, only 12.4 percent. At Parker, two storms have exceeded 3 inches, but at Tuba City no recorded storm has exceeded 2 inches. Parker is only 350 feet above sea level and, like Fort Mohave, is in the region where convective storms reach their maximum intensity. Tuba City, on the other hand, is on the plateau, 4,500 feet above sea level, and although severe thunderstorms are experienced (*40*) they do not equal those at lower elevations. These two stations are not meteorologically homogeneous.

Since the most intense rains are usually associated with thunderstorm activity a negative correlation between storm intensity and regional elevation is to be expected. The total depth of moisture in the atmosphere over a station at a low elevation is much greater than that over a station at a high elevation. Consequently equally intense convective activity will result in greater storm intensities at the station at low elevation than at the other. No similar control is exercised by elevation over the rainfall intensities and amounts resulting from warm-front storms.

Cedar Glade and St. Michaels have average annual precipitation of 14.10 inches and 13.15 inches, respectively. Both stations are semiarid. Cedar Glade is in a valley in the mountainous central part of the State, 4,610 feet above sea level. St. Michaels is nearly 7,000 feet above sea level in the plateau country in the northeastern part of the State. Of all 24-hour storms of 0.50 inch or over, at Cedar Glade, 33.3 percent were 1 inch or over, and at St. Michaels, only 19.7 percent. Cedar Glade and St. Michaels are not meteorological homogeneous.

Local surface variations tend to cause differences in storm intensity. Even within a small watershed, variations in the proportion of the total rainfall which comes at high rates may be considerable. Extremes of meteorological conditions at the stations in northern Arizona are illustrated by Flagstaff and Fort Mohave. Although the average annual precipitation at Flagstaff is 20.56 inches, only 24.0 percent of the 24-hour rains of 0.50 inch or over exceed 1 inch. On the other hand, at Fort Mohave, with an average annual precipitation of only 5.09 inches, 42.1 percent were in excess of 1 inch. The average annual number of rainy days at Fort Mohave is only 15, in contrast to 84 at Flagstaff, but when precipitation occurs, large amounts are more likely to fall at Fort Mohave than at Flagstaff.

It is probable that most of the stations in northern Arizona lie somewhere between the meteorological extremes of Fort Mohave and Flagstaff, and no doubt the transition in meteorological conditions from place to place is more or less gradual. To illustrate the generalization that rainstorm intensity-frequencies increase as the average annual rainfall increases and also that they vary with surface configuration, two groups of stations have been selected, the average 24-hour storm frequencies for which are given in table 7. The records are not long, even the combined records for similar stations, and the reliability of the frequency determinations is low (*107*). In group A, comprising Crown King—Pinal Ranch, Cedar Glade, Winslow—Holbrook, and Tuba City, the average annual precipitation ranges from 25.59 inches to 6.78 inches. In group B, consisting of Natural Bridge, Jerome, and Keams Canyon—Jeddito,[10] the average annual precipitation ranges from 24.24 inches to 11.87 inches. In each group of stations the variation in storm frequencies is related directly to variation in average annual precipitation. The fact that storm frequencies in one group of stations are not comparable to those of the other indicates variations in meteorological conditions corresponding to variations in situation of the stations, such as was illustrated by Tuba City and Parker and by Cedar Glade and St. Michaels in the preceding paragraphs.

TABLE 7.—*Average frequency of 24-hour precipitation amounts at selected stations in Arizona*

Group and station	Average annual precipitation	24-hour amounts of rainfall occurring once in—				
		1 year	2 years	5 years	10 years	20 years
Group A:	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*
Crown King—Pinal Ranch	25.59	2.07	2.54	3.34	4.15	5.40
Cedar Glade	14.10	1.28	1.59	2.11	2.61	3.22
Winslow—Holbrook	8.52	.88	1.10	1.45	1.79	2.20
Tuba City	6.78	.72	.89	1.18	1.45	1.79
Group B:						
Natural Bridge	24.24	2.05	2.38	2.84	3.40	3.96
Jerome	19.20	1.70	1.97	2.42	2.82	3.30
Keams Canyon—Jeddito	11.87	1.12	1.31	1.60	1.87	2.18

In figure 18 storm frequencies for these two groups of stations are plotted on a logarithmic scale, with the average frequencies in northern Arizona for comparison. In each group of stations, straight lines fit the data and all lines have the same slope. The parallelism of the lines is interpreted to indicate meteorological similitude. That the lines which fit the data of one group of stations are not parallel to those which fit the data of the other group shows a lack of similarity between groups.

Because of the proportionality existing between average annual rainfall and storm frequency in these stations it was possible to prepare simple nomograms giving 24-hour storm amounts in terms of annual precipitation totals. These nomograms are reproduced in figure 19,*A* for meteorological conditions prevailing at the stations headed by Crown King—Pinal Ranch, and in 19,*B* for meteorological conditions at the other group of stations.

Frequencies of the larger storm amounts vary tremendously from place to place with variation in meteorological conditions and with annual precipitation. Under one set of meteorological conditions the 24-hour precipitation to be expected at a station only once in 100 years ranges from 3.85 inches to 9.47 inches as annual precipitation increases from 10 inches to 30 inches. Under another set of meteorological conditions for the same range of annual precipitation the range for the 100-year storm is from 2.70 inches to 6.85 inches.

Meteorological conditions other than those represented in the nomograms in figure 19 are to be found in northern Arizona. Fre-

[10] The spelling "Jadito" is prescribed by the United States Geographic Board for the canyon and spring. The names of the trading post and Weather Bureau station are still spelled "Jeddito."

quencies at Parker and Fort Mohave are higher than would be determined from figure 19, *A*, and frequencies at Williams and Flagstaff are lower than would be indicated in figure 19, *B*. Meteorological conditions and consequently the rainstorm amounts to be

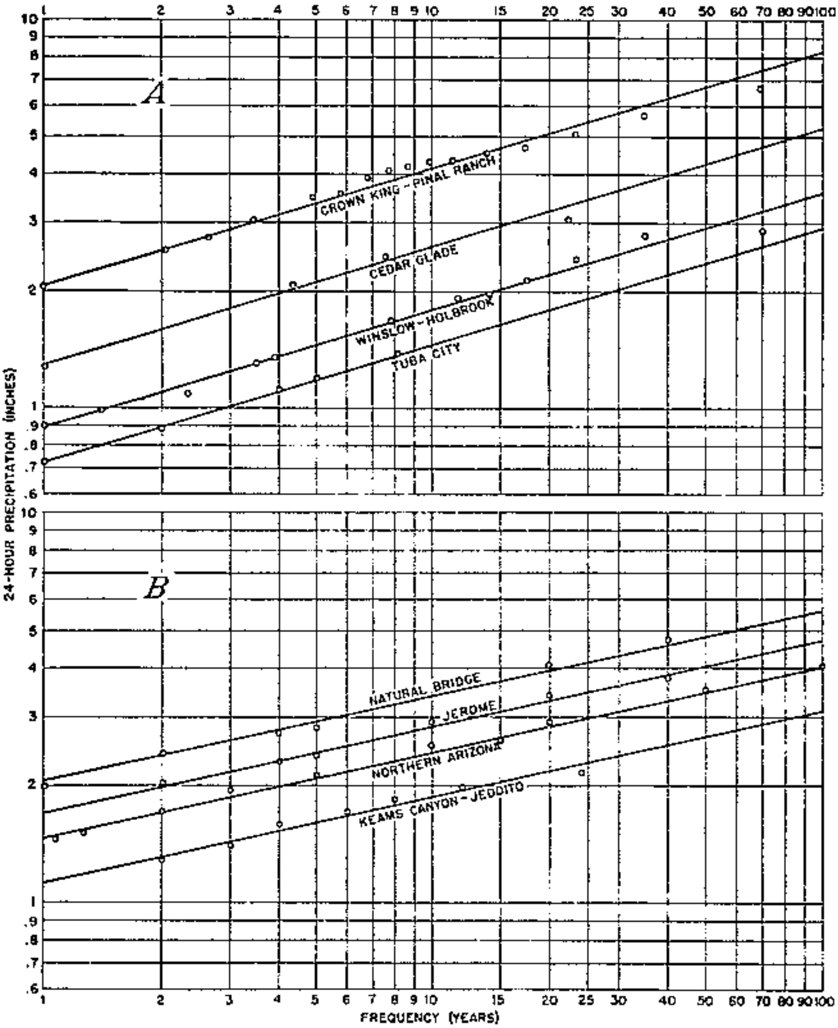

FIGURE 18.—Frequency of 24-hour precipitation amounts at selected stations in Arizona: *A*, group A; *B*, group B.

expected with given frequency will vary from one side of a valley to another and at different levels on a slope.

Thus, it is obvious that the nomograms in figure 19 cannot be used as the basis for design of erosion-control or flood-control structures. Before entirely reliable frequency data can be obtained for a single watershed, a detailed survey of its meteorological conditions must be made. The nomograms indicate that light storms are relatively numerous and heavy storms few, but that occasional storms of very high intensity may be experienced.

The probability of exceptionally large storms in Arizona, as would be expected, is greatest in July or August and least in May. Frequencies of 24-hour precipitation amounts for the 12 months at Keams Canyon (table 8), although based on a short record, appear to be representative of the month-to-month changes in the probability of heavy rainfall in the Southwest.

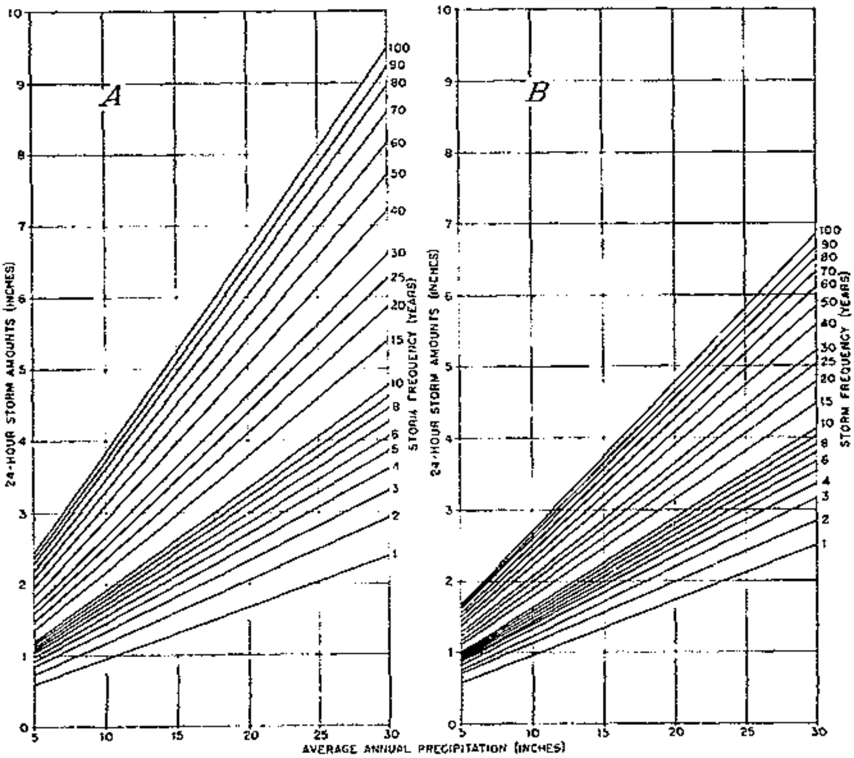

FIGURE 19.—Nomograms expressing the relationship between average annual rainfall and 24-hour rainfall for two meteorological conditions in northern Arizona: *A*, Data from Crown King—Pinal Ranch, Cedar Glade, Winslow—Holbrook, and Tuba City; *B*, data from Natural Bridge, Jerome, and Keams Canyon—Jeddito.

DROUGHT FREQUENCIES IN THE SOUTHWEST

In most of the Southwest, less than 1 day in 6 is rainy and in the arid parts of the region the rainy days may not average more than 1 in 30. At Fort Mohave the average annual number of days with rain is 15. There is considerable monthly as well as annual variation in the number of days on which precipitation occurs. In figure 20, the average number of days of rain in each month is shown for Natural Bridge, Keams Canyon, and Leupp; and also the actual number of days with rain at Natural Bridge in each month during 1903, 1904, and 1905. By comparing the graphs of Natural Bridge in this figure with figures 9, 10, and 13, it can be seen that a rough parallelism exists between the number of storms and the monthly and annual amounts of precipitation.

TABLE 8.—*Frequency of 24-hour precipitation amounts, Keams Canyon—Jeddito, Ariz.*

Month	24-hour amounts of rainfall occurring once in—								
	30 years	25 years	20 years	15 years	10 years	5 years	3 years	2 years	1 years
	Inches	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*
January	1.30	1.20	1.12	1.00	0.87	0.68	0.56	0.40	0.38
February	1.12	1.03	.96	.86	.74	.57	.47	.41	.32
March	1.22	1.14	1.06	.95	.82	.64	.53	.46	.36
April	1.22	1.14	1.06	.95	.82	.64	.53	.46	.36
May	.98	.90	.81	.70	.56	.39	.30	.25	.17
June	1.20	1.07	.94	.79	.62	.42	.30	.24	.16
July	1.98	1.90	1.82	1.70	1.56	1.33	1.18	1.08	.94
August	2.30	2.10	1.90	1.65	1.35	.96	.75	.62	.44
September	1.48	1.35	1.22	1.05	.86	.62	.48	.39	.28
October	1.30	1.22	1.14	1.04	.91	.73	.62	.54	.44
November	1.16	1.06	.96	.84	.69	.50	.39	.32	.23
December	1.85	1.70	1.52	1.32	1.08	.77	.60	.48	.35

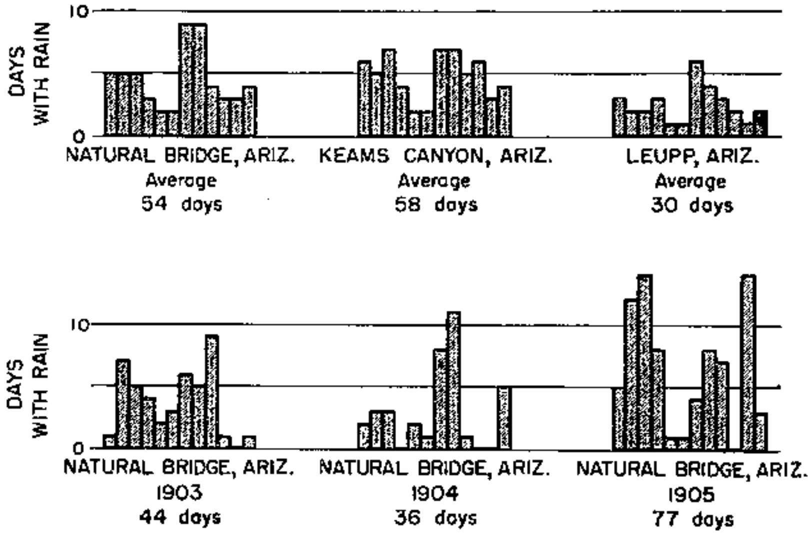

FIGURE 20.—Average number of days with rain in each month at Natural Bridge, Keams Canyon, and Leupp, and actual number of days with rain at Natural Bridge in each month in 1903, 1904, and 1905. The years of record for Natural Bridge, Keams Canyon, and Leupp are respectively 38, 12, and 9.

Since there is no regularity in the occurrence of rainfall there can be none in the intervening periods of drought. Periods lacking in rainfall are brought about by specific meteorological conditions just as are storm periods and are equally important elements of the climate of the Southwest. Absence of sharp frontal passages and of vigorous invasions of moist unstable air results in drought. Hence, droughts, like large storms, do not occur with any regularity but are associated with nonrhythmic occurrences of air-mass invasions. Despite the great irregularity in the occurrence and length of drought periods, much useful information can be secured through analysis of mean drought frequencies.

There is a minimum amount of precipitation which may be said to break a drought period. This varies from one region to another and from season to season. Thus, any uniform definition of drought is necessarily more or less arbitrary. On the basis of experimental work, Shreve (*94, p. 134*) determined that under desert conditions rains of less than 0.15 inch are without influence on soil moisture at a depth of 15 cm. except under special conditions. Other workers have observed that small amounts of precipitation are of slight value to crops unless they follow larger amounts.

On the other hand, as little as 0.10 inch in 48 hours may represent meteorologic conditions which would terminate a drought on the western grazing ranges. Cloudiness and high atmospheric humidity may cut daytime evaporation losses and bring about condensation and direct absorption at night so that the effectiveness of the actual rainfall is greater than it would be otherwise. No quantitive measurements of condensation or absorption are available, and it is therefore impossible to say what is the minimum amount of rainfall which could be utilized by the range grasses. In the analysis which follows, drought periods are considered to be terminated by rains totaling 0.10 inch in 48 hours.

Drought frequencies for the four seasons and the year at four Arizona stations are given in figure 21. At Yuma, drought periods of 120 days duration may be expected every year, and once in a 10-year period a drought may exceed 220 days. Every one of the seasons may be entirely rainless. Occasionally, a drought period may extend through two consecutive seasons and sometimes through three. Spring drought may extend through the entire 90 days 2 years out of 4; autumn drought, 2 years out of 5; summer drought, 2 years out of 7; and winter drought, 2 years out of 9. At the other stations droughts are shorter. At Jerome, as at Yuma, drought periods are longer in spring and autumn than in summer or winter. In Phoenix and Tuba City, however, the autumn droughts occurring once in 10 years are shorter than those of summer or winter.

In figure 22, the length of the drought period to be expected once in 5 years in each of the four seasons is shown for the Southwest. The period varies in the different parts of the region and with the season. The minimum drought period shown, less than 30 days, appears in the mountainous parts of New Mexico and Colorado in all but the autumn season. In some part of the region droughts of 90 days duration are experienced in every season once in 5 years on the average. The shifting seasonal drought pattern is the obverse of the pattern of rainfall distribution, as may be seen by comparing figure 22 with figure 11. Excluding the arid areas, summer droughts are longest to the west and winter droughts are longest to the east of the region. Summer droughts reach 90 days in western Arizona, in virtually all of California, most of Nevada, and parts of Oregon, Washington, Idaho, and Utah. Winter droughts reach 90 days in western Kansas and eastern Colorado and exceed 70 days in the

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entire southern Great Plains. Longer droughts are experienced in the Southwest 1 year in 10, on the average, but the seasonal variations in pattern of distribution are similar to those of the 5-year frequency.

Throughout most of the Southwest, drought periods are shorter in summer than in any other season. In most of the region, spring is the season of maximum length of drought and autumn stands

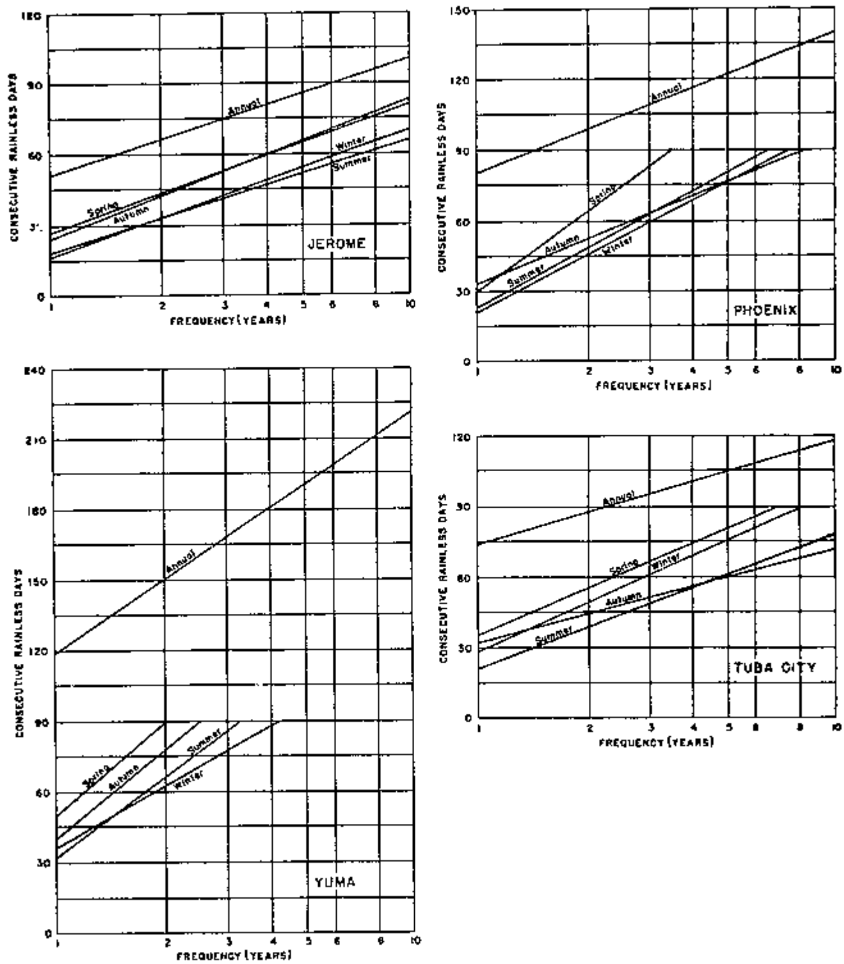


FIGURE 21.—Annual and seasonal drought frequencies at Yuma, Jerome, Phoenix, and Tuba City, Ariz.

second. In the eastern part of the area, however, winter is the season of longest drought periods, since the winter invasions of Polar Pacific air, bringing precipitation to the Southwest, fall off in frequency and become progressively drier from west to east. In the extreme western part of the region summer droughts are the longest. This is also related to the incidence of air masses, in this instance the relative infrequency of invasion of moist unstable Tropical Atlantic air into the western part of the region.

The occurrence of a prolonged drought does not preclude the possibility of having annual or monthly rainfall totals which are equal to or above normal. In 1909, at Keams Canyon, only 0.15 inch of rain fell between March 31 and July 2. On July 3, 1.01 inches fell. No rain fell between September 13 and November 12, but on November 13 and 14 there was a storm which brought a total of 0.60 inch of precipitation. The total rainfall for 1909 was above the normal. An abnormally wet month or year may reflect mainly the occurrence of a few large storms, and low totals do not necessarily indicate that droughts have been frequent or long.

There is every reason to expect at long intervals in the Southwest a drought extending through most of a year. Occasionally such droughts may follow each other in successive years. Such dry periods are normal features of the climate of the Southwest.

The Climatic Pattern in the Southwest

A DEFINITION OF CLIMATE

Climate is an integration of the climatic or meteorological elements or factors which combine within a region to give it its character and individuality. The catalog of the elements is familiar, consisting of temperature, wind, precipitation, atmospheric humidity, evaporation, sunshine, cloudiness, and several others. These elements are extremely diverse, temperature being merely a form of molecular energy, wind a form of momentum, and precipitation a material which collects on the land in varied forms (rain, snow, hail), in various amounts, and at varying rates. Drought is an absence of precipitation, and evaporation a rate of loss of precipitation. All are complexly interrelated: each is dependent on the others, and all are expressions of the operation of meteorological forces world wide in their scope.

Ingenious and accurate instruments have been developed for measuring and recording the elements of weather and climate. There are, however, no instruments for measuring the climatic complex. For the characterization of climate it is necessary to select measured values of the individual elements in an effort to arrive at those which are correlated with the significant physical and biological features of the different parts of the earth. To obtain this end, attention has at different times been focused on different sets of elements.

A climatic index that has been proved to be highly significant is the relation of precipitation to evaporation, but it is one that is extremely difficult to determine. Present measures of both precipitation and evaporation are grossly inadequate. The analysis of precipitation in earlier pages has shown that total precipitation expressed numerically has little significance since all precipitation is included, regardless of the conditions under which it falls. The rainfall of a crop season is a composite made up of a series of rains, each possessing an individual pattern of distribution. The rains may be gentle showers or downpours, long or short in duration. Periods without rain may last for a few days or for several months. The measurements of evaporation are even less satisfactory than those of precipitation, and it is only within the past 2 years that

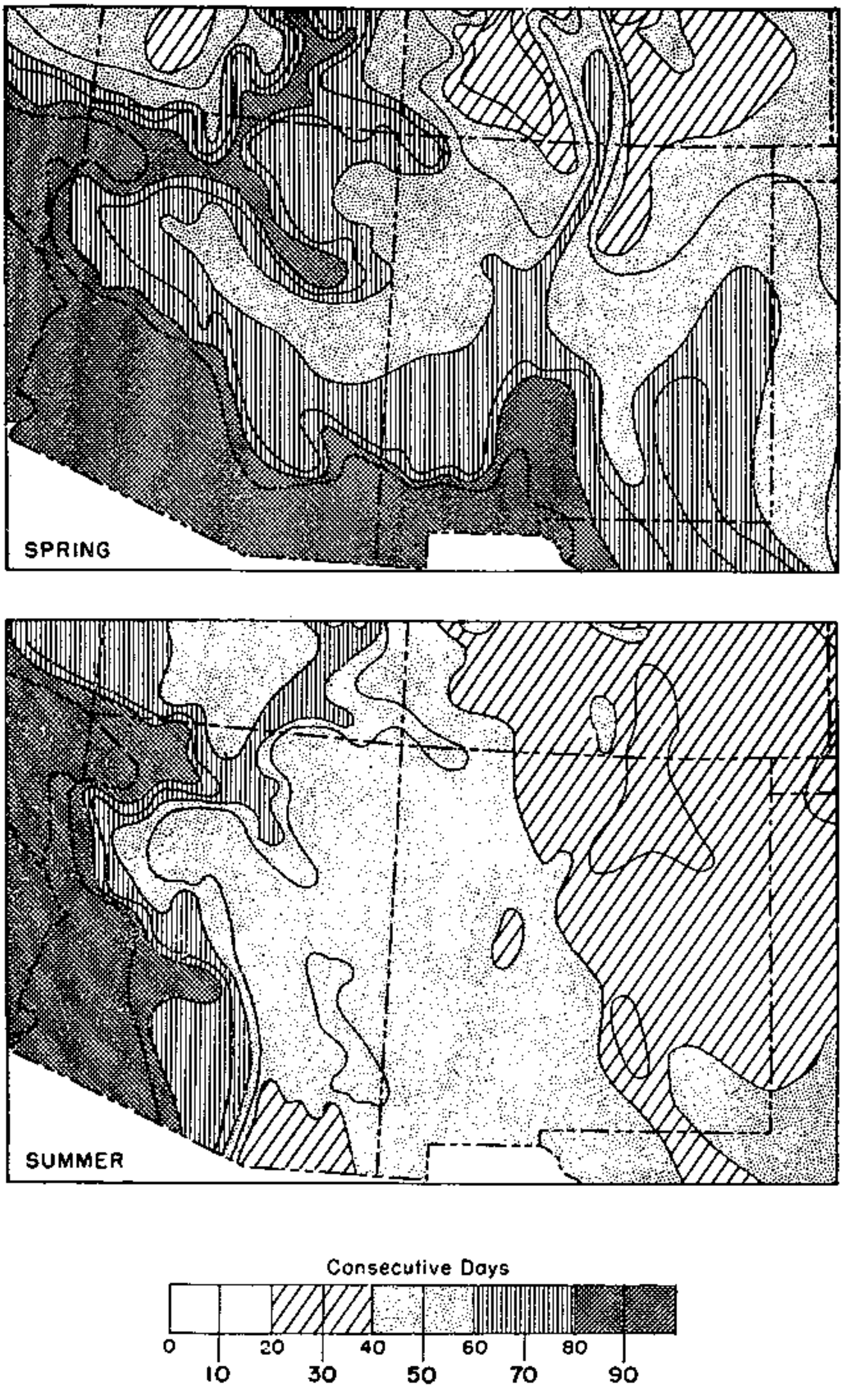
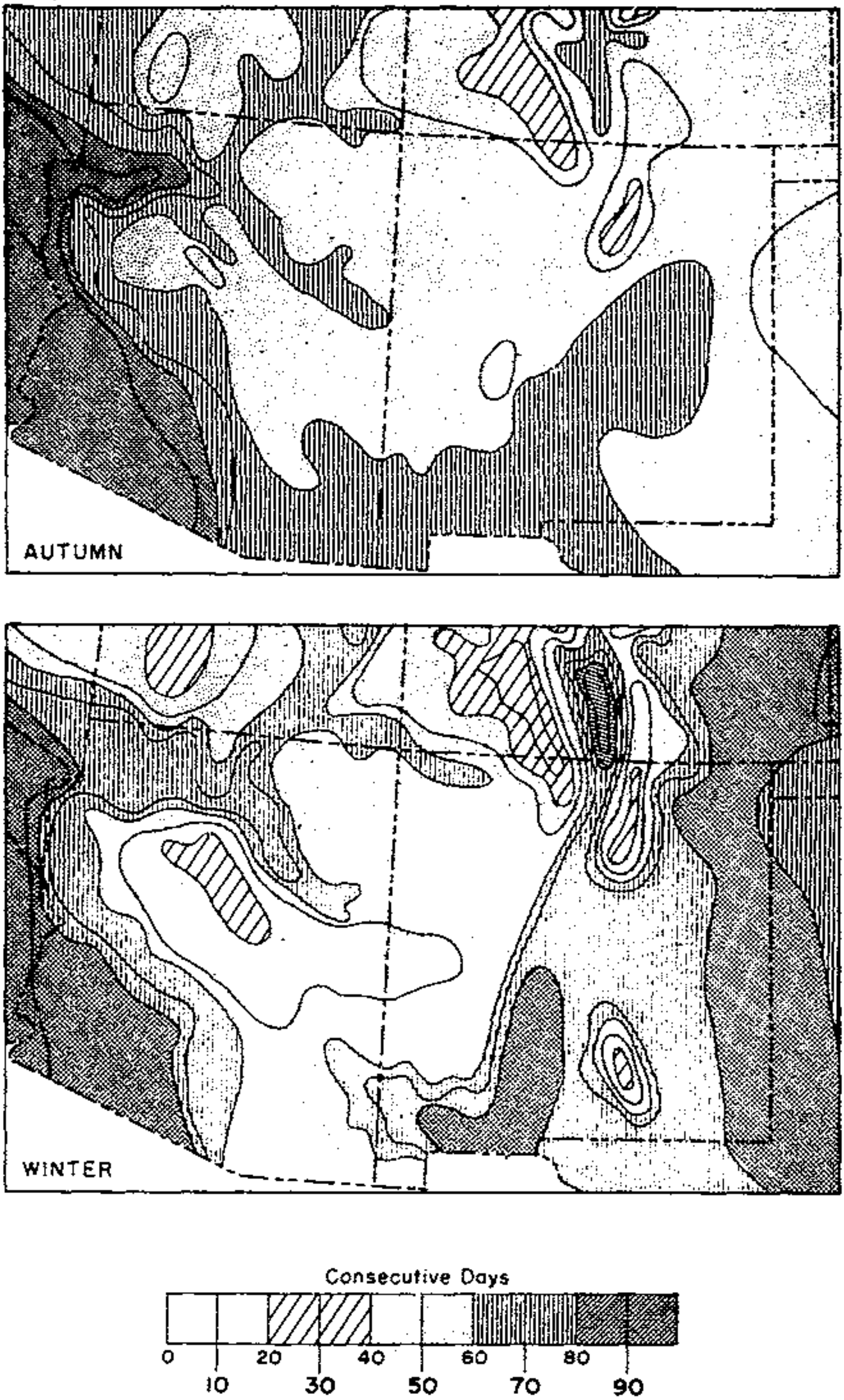


FIGURE 22.—Consecutive days of drought to be expected once



in 5 years in each of the four seasons in the Southwest.

direct means of measuring the actual amount of water lost from a land surface through evaporation and transpiration has been found.

It was the inability to measure precipitation effectiveness directly that led to the development of the many empirical formulas for expressing the effectiveness of precipitation. All are only approximations. In the present study the precipitation effectiveness (P–E) index from the Thornthwaite classification of climates (*105, 106*) is used. It is determined by evaluating the monthly totals of precipitation in terms of the temperature of the month in which it falls. The terms "arid," "semiarid," "dry subhumid," "moist subhumid," "humid," and "superhumid" refer to moisture provinces delimited by means of precipitation-effectiveness indices. The term "superhumid" has been substituted for the less specific term "wet," which was originally employed.

THE NORMAL CLIMATIC PATTERN

The climates of the Southwestern States are prevailingly arid and semiarid. Areas of extreme aridity are relatively limited and cover only small parts of southern California, Nevada, Arizona, New Mexico, and Utah. Semiarid conditions cover most of the remainder of these States and extend eastward through the Great Plains and northward into Canada (*88, 105*). The climate is more humid where mountains and high mesas and plateaus rise as islands above the general level. Some of these higher elevations exceed 12,000 feet and are superhumid.

The climatic pattern in the Southwestern States can best be understood by considering it with reference to the general pattern of climates over the earth. The deserts of North America, comprising portions of northern Mexico, southern California, Arizona, New Mexico, Nevada, and Utah, as well as small areas in several other Western States, are a shrunken and foreshortened counterpart of the great arid regions of Eurasia and North Africa, which include the Sahara, the Arabian deserts, the deserts of Iran and Turkestan, the Thar of India, and the Gobi Desert of Mongolia. Continental west coasts between 20° and 30° north of the Equator are arid. Similarly located arid regions in the Southern Hemisphere include the Atacama Desert of South America, the Kalahari Desert of South Africa, and the Great Desert of Australia.

The other extreme, the superhumid climate, appears on equatorial coasts and islands and on continental west coasts between 40° and 60° both north and south of the Equator. The Pacific coast of North America from northern California to Alaska is superhumid. In Europe this climate is found in the northwest corner of Spain and the western coastal parts of Ireland, Scotland, and Norway.

Between the arid and superhumid regions are belts of semiarid, subhumid, and humid climates of greater or less width. The subhumid climate is subdivided into moist subhumid and dry subhumid. The generalized normal distribution of these six principal climatic types in the United States is shown in figure 23 (*105, 106, 108*).

VARIATIONS IN THE CLIMATIC PATTERN

Much emphasis has been placed on the variability of the elements that combine to make climate. Precipitation and temperature have

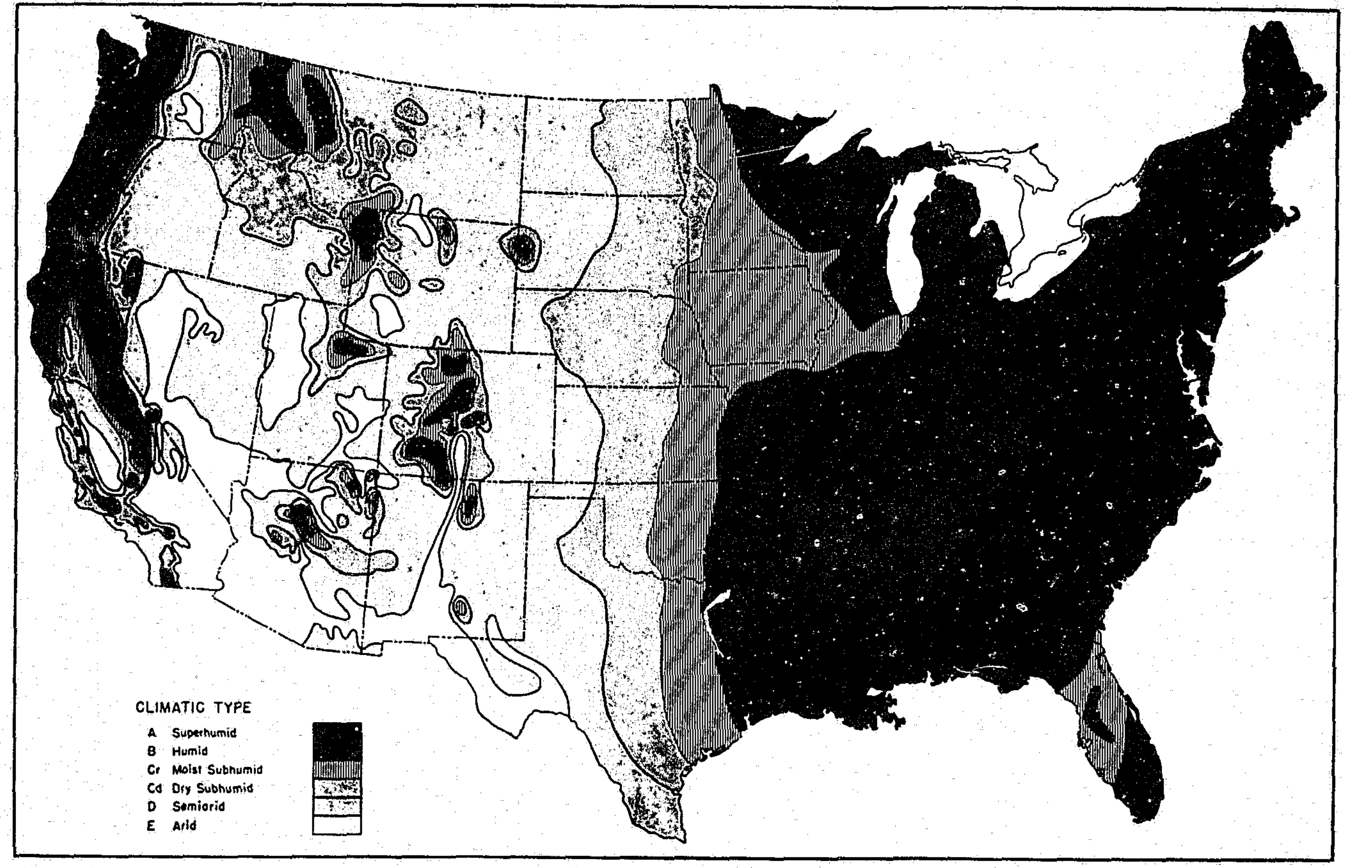


FIGURE 23.—Generalized normal distribution of the principal climatic types in the United States.

been shown to vary greatly from day to day, from one month to another, and from one year to another as a result of variations in air-mass interactions (pp. 5–11). Wind velocity, cloudiness, and evaporation are likewise known to vary with air masses (*60*). Since climate is an integration of these many complexly varying elements, it is obvious that climate must also vary from one year to another. Variation may be thought of as an element of climate, equal in rank with precipitation, temperature, or any of the others.

The extent of the climatic variations in the Southwest is illustrated by maps of two extreme years, 1905 and 1934 (fig. 24), both of which show distributions in marked contrast to the normal pattern shown in figure 23. In 1905, both arid and semiarid climates,[11] which ordinarily occupy most of these States, were virtually absent. A large area extending from the vicinity of Williams, Ariz., southeastward into New Mexico was humid. Other smaller humid areas appeared in Northern Arizona and in New Mexico. In 1934, nearly two-thirds of New Mexico and almost as large a part of Arizona were arid, and practically the entire remainder of the two States was semiarid. Only small, high areas had dry subhumid climate.

Table 9 shows the range of variations in climate from one year to another for a number of stations in Arizona. No Arizona station has experienced a superhumid year since weather observations have been made, although several stations in New Mexico have. A few stations have experienced humid years, but only Fort Valley and a few other mountain stations have humid climates. At Fort Valley, 16 out of 24 years were humid, 6 were moist subhumid, and the other 2 were dry subhumid. At Williams, although the climate is moist subhumid, only 7 out of 32 years were moist subhumid, 8 were dry subhumid, 15 were humid, and 2 were semiarid. A few stations experienced a range in climatic years from humid to arid. Jerome, for instance, a dry subhumid station, experienced 1 humid year and 1 arid year in the 37 for which there is a record.

It may be that frequency distributions for a limited number of years will fail to reveal the true nature of the climate. For example, the frequency distribution for Miami and Oracle, Ariz., are very similar and are close to the dry subhumid-semiarid boundary, Miami being dry subhumid and Oracle semiarid. It is quite possible that as data for additional years become available Miami will prove to be semiarid or Oracle will be dry subhumid. Of course, this would not constitute a change in climate but rather merely an adjustment to bring about greater accuracy in the designation of the existing climate.

Both Prescott and Jerome are dry subhumid, yet there is a distinct difference in the frequency distributions at the two places. In the 37 years of record, 18 years were humid or moist subhumid at Prescott, whereas at Jerome there were only 4 such years. At Jerome, 14 years were semiarid or arid and at Prescott only 6. If it could be assumed that these frequency distributions correctly describe the climates of the two places then the climate of Jerome would change if it were

[11] The word "climate" is employed to express two meanings. Climate is the integration of the weather from day to day in a single year: thus we speak of the climate experienced in a given year. It is also the integration of the climates of a series of years. Although the word is used in both ways in the discussion that follows, no confusion should result, because one can always readily see whether the normal climate or the climate of a year is meant.

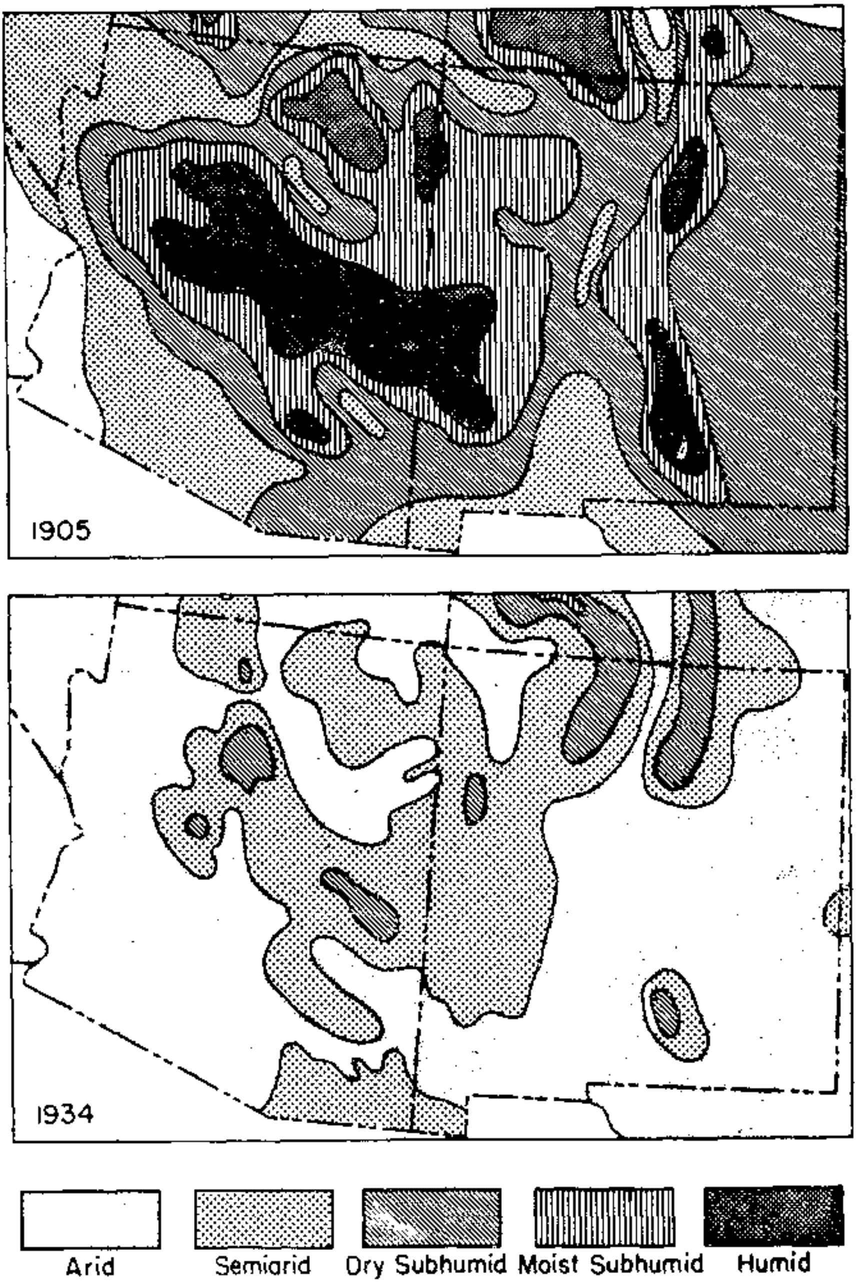


FIGURE 24.—The distribution of climates in Arizona and New Mexico, 1905 and 1934.

to become like that of Prescott. The climatic change would involve an increased frequency of humid and moist subhumid years and a decreased frequency of semiarid and arid years.

There is a slight difference in the annual precipitation at the two stations. The average through 1930 at Prescott is 18.53 inches and at Jerome 19.20 inches. The tendency for greater frequency of semiarid and arid years at the station with greater rainfall is a result of higher temperatures and greater consequent evaporation losses.

Table 9.—*Frequency distribution of climatic years for the period of record at 33 stations in Arizona, 1900–1939*

Station	Climate for the period of record	Years of record	Number of occurrences[1] of a—				
			Humid year	Moist subhumid year	Dry subhumid year	Semiarid year	Arid year
Fort Valley	Humid	24	16	6	2	0	0
Williams	Moist subhumid	32	15	7	8	2	0
Flagstaff	do	39	13	14	10	2	0
Natural Bridge	do	24	7	7	7	3	0
Prescott	Dry subhumid	37	4	14	13	6	0
Grand Canyon	do	31	3	8	13	7	0
Pinedale	do	22	3	7	11	1	0
Jerome	do	37	1	3	19	13	1
Fort Apache	do	32	1	3	13	15	0
Miami	do	26	0	3	11	12	0
Oracle	Semiarid	29	1	3	10	15	0
Fort Defiance	do	14	1	0	6	4	3
Fort Huachuca	do	17	1	0	3	12	1
Snowflake	do	28	0	1	3	21	3
Bisbee	do	36	0	0	11	23	2
Globe	do	34	0	0	12	17	5
St. Michaels	do	17	0	0	6	10	1
Keams Canyon	do	10	0	0	3	0	1
Tombstone	do	35	0	0	3	23	9
Holbrook	do	33	0	0	1	17	15
Douglass	do	36	0	0	2	18	16
Clifton	do	31	0	0	0	17	14
Fort Mohave	Arid	13	0	0	1	4	8
Benson	do	39	0	0	1	17	21
Casa Grande	do	29	0	0	1	7	21
Chin Lee	do	18	0	0	0	7	11
Tuba City	do	28	0	0	0	8	20
Parker	do	34	0	0	0	2	32
Maricopa	do	38	0	0	0	4	34
Phoenix	do	38	0	0	0	3	35
Yuma	do	38	0	0	0	1	37
Lee's Ferry	do	14	0	0	0	0	14
Mohawk	do	30	0	0	0	0	30

[1] No Arizona station has experienced a superhumid year since weather observations began.

There is, also, a very significant difference in storm frequency[12] (table 10). A storm of 4.00 inches or more in 24 hours may be expected once in 13 years on the average at Prescott, but only once in 50 years at Jerome; whereas a 1.50-inch storm will occur equally often at both places. It would require a considerable increase in annual rainfall or a change in meteorological conditions for large storms at Jerome to become as frequent as at Prescott.

An increase in average annual precipitation might result from an increase in the frequency of rainstorms, an increase in size of individual storms, or an increase in the proportion of large storms to small ones. An increase in the number of storms would require a

[12] It must be remembered that the reliability of these storm-frequency determinations are subject to serious question because of the extremely small number of cases. They should therefore be considered merely as illustrative of the point that climatic change is an extremely complex phenomenon.

speeding up of the general circulation of the atmosphere such that more frequent interchanges of air masses occurred. An increase in the size of storms would require increases in the moisture content of air masses and in the vigor of their interaction. A change in the proportion of intense storms could be brought about by a change in the local surface configuration. Since none of these changes can take place except very slowly, it appears that what have sometimes been called climatic changes in the Southwest are in reality merely the normal, more or less random, variations characteristic of all climates.

TABLE 10.—*Frequency of 24-hour precipitation amounts at Prescott and Jerome, Ariz.*

Station	Frequency of 24-hour precipitation amounts of—						
	1.5 inches	2.0 inches	2.5 inches	3.0 inches	3.5 inches	4.0 inches	4.5 inches
	Years	*Years*	*Years*	*Years*	*Years*	*Years*	*Years*
Prescott	0.6	1.5	3.0	5.3	8.3	13.0	19.0
Jerome	.6	2.1	5.8	13.0	27.0	50.0	84.0

This distinction is extremely important because climatic change involves a significant change in the frequency distribution of climatic years, whereas variation from one year to another within the limits set by the frequency distribution must be accepted as an attribute of every climate. To prove the existence of climatic change it is necessary to show that differences in frequency distributions derived from two parts of the same record could not result solely from sampling error. Unless this can be done climatic change in the Southwest in the last 2,000 years cannot be established.

CLIMATIC FLUCTUATIONS IN THE PAST

In the Southwest there have been, without doubt, wide fluctuations in climate during the past several centuries. It is known that the climate of the Southwest, as everywhere in the United States, has changed since the Pleistocene, but the change has been very gradual, occupying at least 25,000 years, and has not been very great in this region.

In the absence of rainfall records of sufficient length many indirect lines of evidence have been examined to determine whether there has been any progressive climatic change in the Southwest during the last 2,000 years. In 1913, Henderson and Robbins (*59, p. 68*) summarized the evidence from archaeology, history, botany, and geology available at that time and stated that it was not conclusive; but they expressed the "opinion" that there had been "progressive desiccation of the region since the beginning of the cliff-dwelling period."

Reexamination of the evidence from these fields suggests that it shows merely the existence of climatic fluctuations in the past similar to those of today and does not demonstrate progressive change in any direction.

In recent years the science of dendrochronology, developed in the Southwest by Prof. A. E. Douglass and his students, has accumulated evidence which has been used variously to prove and to disprove the existence of climatic change. A statement made only recently by one of the students of tree rings claims that they are indicative of climatic fluctuations rather than climatic changes (*58, pp. 67–68*).

> Most important conclusion of the new science amounts to a certainty. The trees say the same thing over and over: The climate of the United States is not changing.
>
> Trees say that there has been no change in the amount of precipitation certainly for 650 years and probably for 2,000 years. The trees record droughts centuries ago that lasted longer and were drier than anything this generation has known, for all our dram..ic dust storms. But the droughts were always followed by plentiful rainfall.
>
> * * * * * * *
>
> The popular notion that the drought-rainfall cycle is regular is exploded by the tree-ring calendar.

Lake levels in the Great Basin have constantly risen and fallen and have been studied for evidence of climatic fluctuations and progressive changes. According to Antevs (*72, p. 71*) the expansion of the Pleistocene lakes in the Great Basin corresponded to the maximum extension of glaciers in the neighboring mountain ranges and of ice sheets over the northern part of the continent. He places the last major lake expansion at 30,000 to 35,000 years ago. The well-developed shore lines and the lack of deltas indicate that diminished evaporation rather than increased precipitation and run-off was the main factor in the rise of lake levels.

Jones (*72, p. 47*), on the other hand, concludes on the basis of mineral concentration in the water that Lake Lahontan originated not more than 2,000 to 4,000 years ago and reached its maximum depth and extent only about 1,000 years ago. He states that in order to support Lake Lahontan at the high-water mark, 2½ times the present rainfall throughout the drainage basin would be required. Such a change in average precipitation in 1,000 years would have meant a tremendous climatic change, a change that would have been reflected over the entire western half of the continent. Under the conditions postulated by Jones the climate of Reno and Carson City, now semiarid, would have been humid and the more elevated portions of the area would have been superhumid.

Powell (*81, p. lxxii*), in 1898 cited archaeological evidence for the opinion that the cultures of the Southwest were developed under conditions approximately as adverse as they are at present.

> The Pueblo peoples, ancient and modern, grew up under hard environment; shadowed ever by the specters of thirst and famine, they were exceptionally impressed by the potencies of pitiless nature and the impotency of their own puny power; and like other desert peoples, seafarers, and risk-haunted folk generally, they developed an elaborate system of ceremonies and symbols designed to placate the mysterious powers. * * *
>
> Occupying an arid region in which water is the most precious of all commodities, the Pueblo peoples early acquired skill in the manufacture of utensils adapted to the conservation of water, and eventually became the potters par excellence of aboriginal America.

Thus a climatic change of the magnitude indicated by Jones is altogether improbable.

There is historical evidence of large changes of lake levels in the Great Basin during the last century. That these rises and declines of water level are associated with fluctuations of precipitation is shown by the rainfall records themselves and by supplementary tree-ring records (*19*).

In recent years Bryan and his students have presented a great many physiographic observations which they interpret as being indicative of climatic change. Bryan has traced buried channels upward of one-third of a mile in length in the fill in the valleys of Arizona and New Mexico. Bryan (*25, 30*), Hack (*55*), and others have found that in some of the valleys of the Southwest there have been at least three past periods of increased erosion separated by times of dominant deposition. Albritton and Bryan, for example, consider that the alternate filling and channeling in the Davis Mountains, Trans-Pecos, Texas is due to climatic changes.[13] They say (*11, p. 1472*):

> It is a well-established working hypothesis that in an arid climate and in areas of ephemeral and intermittent streams aggradation of valley floors occurs in periods of relative humidity and erosion by channeling occurs in periods of relative aridity.

On a table giving a tentative correlation of the stages of filling and eroding in valleys of western Texas with those of the Jadito Wash described by Hack, each period of aggradation is indicated as "more humid" and each time of erosion, represented in the sedimentary record by disconformities, is shown as "less humid" (*11, p. 1468*). Huntington (*66, pp. 31–36*) also attributes alternate filling and cutting in the valleys of the Southwest to climatic change but he believes that aggradation is due to greater aridity and cutting to increased rainfall (p. 109).

In the physiographic studies of Bryan the nature of the postulated climatic changes is vague and no clear-cut distinction is made between progressive climatic changes and climatic fluctuations. Presumably "relative humidity" and "relative aridity" are equivalent to "more humid" and "less humid," but what is implied by these terms is never indicated. Probably they refer to the normal fluctuations in the existing climate and not to climatic changes (pp. 88–89).

Bryan recognizes the importance of the occasional intense storm (*24, p. 31*).

> So far as erosion and sedimentation are concerned, the rate of rainfall and fluctuations in rainfall are perhaps more important than the average amount. Yuma has had as little as 0.6 inch in 1899 and as high as 11.41 inches in 1905. The highest monthly rainfall in 51 years occurred in August 1909, when 6.25 inches fell—nearly twice the normal annual rainfall. On September 30, 1921, 3.63 inches of rain fell in 24 hours, an amount exceeding the normal annual rainfall for the station by 0.3 inch. On August 16, 1909, 3.33 inches fell. The effect of such storms in erosion and in the transportation of débris by floods on ephemeral streams is obvious.

In recent years, however, Bryan has insisted that gullying in the Southwest, although contemporaneous with settlement and its attendant overgrazing, was actually independent of it and was caused by progressive desiccation of the region. In an address in 1939,[14] he concluded that the alternate cutting down and building up of streams record minor fluctuations in climate, running over hundreds or even thousands of years. The most recent cutting down, he said, is independent of the animals that roam the country and their effect on the vegetation. It was imminent at the time when cattle were introduced into the country and the coincidence in time between the introduction

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[13] On pp. 88–89 these physiographic observations are interpreted in terms of normal physiographic processes, and it is shown that they do not constitute positive evidence of climatic change.

[14] Great Plains Conference, Flagstaff, Ariz., Sept. 3, 1939.

of the cattle and the cutting of the channels is the same coincidence as that between the pulling of the trigger and the explosion of the cartridge.

It is hard to reconcile this statement with the known fact that a land surface which has been irritated by overgrazing and livestock and wagon trails will be gullied by a less intense rainstorm than one which has suffered no such irritation. Bryan goes on to say that gully cutting might have been initiated in the Southwest by 1940 or 1950 even had the country never been settled or overgrazed. This is true, but it would have required a series of much larger storms than those that caused the extensive gullying during the last half century. The probability of the occurrence of such a series of intense storms is far less than that of the occurrence of the moderately intense ones that have brought about the existing gullies. There is at present no possible means of forecasting such series of intense rains.

The evidence from history, botany, archaeology, and geology, relating to the last 2,000 years is indicative of climatic fluctuations such as those we experience today and confirms the meteorological axiom that the more or less random interactions of air masses that determine present climatic variations are the same as those of the past. Evidence for or against long-period climatic changes must necessarily be indirect or circumstantial and it is impossible to identify the variations as climatic changes. If there has been any progressive climatic change in either direction in the last 2,000 years in the Southwest, it is so small as to be completely obscured or overshadowed by the fluctuations introduced by air-mass activity.

EROSION IN THE POLACCA WASH

The general characteristics of the climate of the Southwest have been considered. The following pages present a picture of the relation of climate and other basic factors to the action and effects of accelerated erosion in the Polacca Wash drainage basin, which is typical of much of the Southwest. The discussion deals first with the basic conditions governing erosion in the area, second, with the present state of the erosion, and third, with the characteristic processes of normal and accelerated erosion and their effects.

Rising in a number of fingerlike headwaters near the northeastern rim of Black Mesa 100 miles north of Holbrook, the Polacca Wash extends in a general southwesterly direction to its mouth at Leupp, Ariz. The upper half of its course lies in canyons deeply carved in the Mesa (fig. 25). The lower half is more open and traverses a broad plain and shallow basins. Other similar and more or less parallel washes, including Moenkopi Wash, Dinnebito Wash, Oraibi Wash, and Jadito Wash, drain the remainder of Black Mesa.

Basic Conditions Governing Erosion

CLIMATE OF THE POLACCA WASH

In the Navajo country, in northeastern Arizona, and extending into adjoining States, the wide range of elevations, from near 4,700 feet in the canyons and major valleys to almost 10,500 feet on Navajo Mountain, causes a wide range of climate. Along the Polacca Wash,

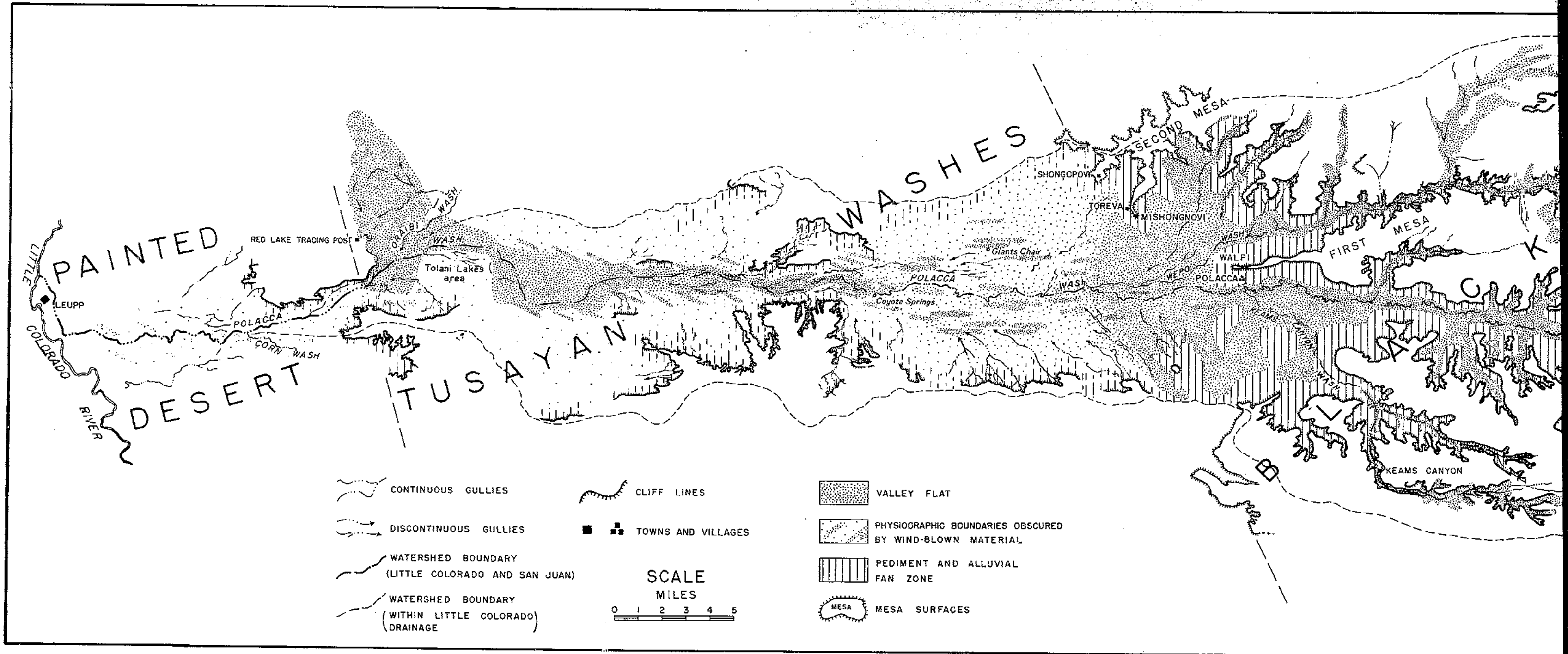
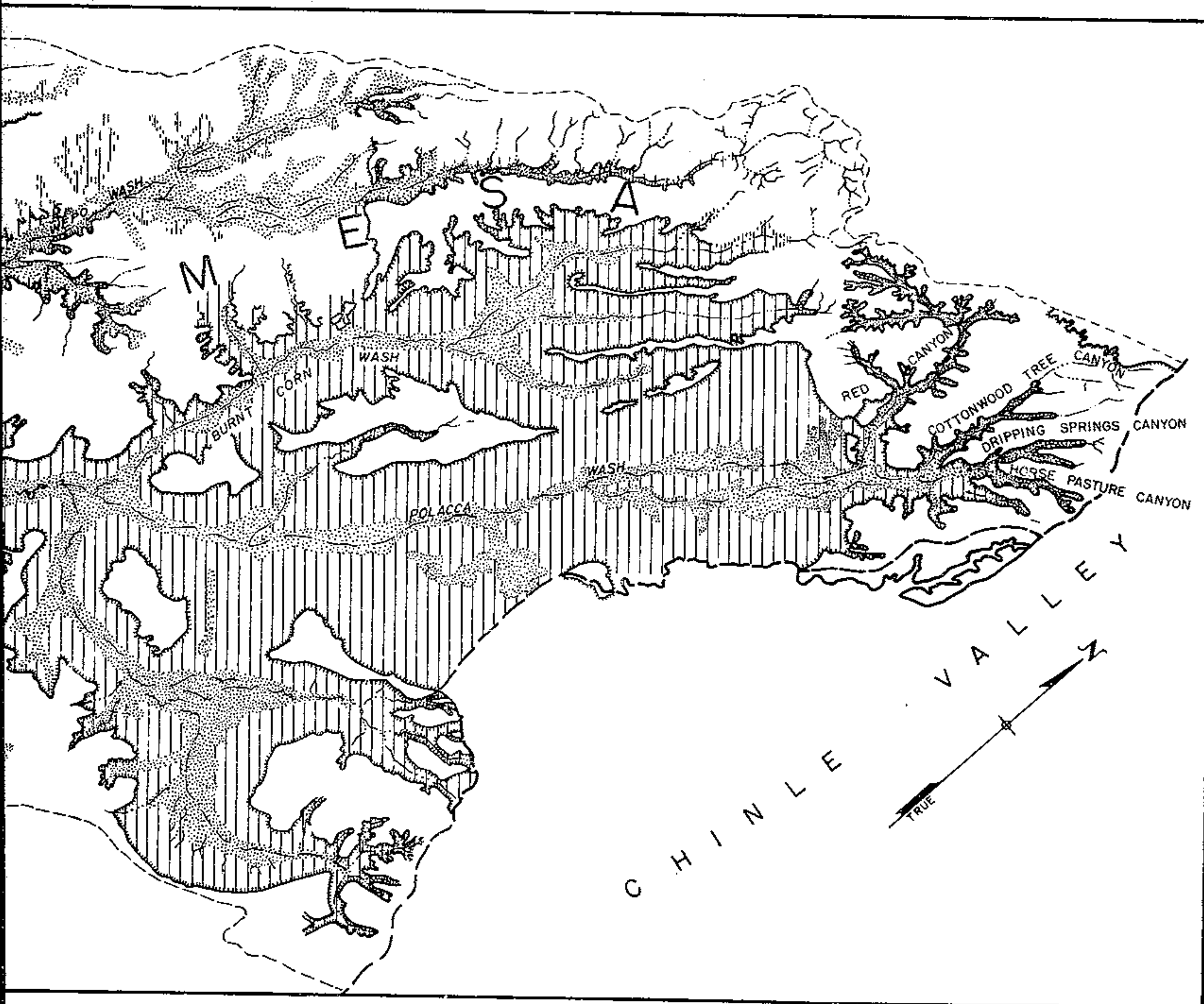


FIGURE 25.—Physiographic map of the Polacca Wash drainage basin, Arizona. Base compiled from field reconnaissance maps and aerial photographs.



WASH
M
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CANYON
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HORSE PASTURE CANYON
POLACCA
CHINLE VALLEY
N
TRUE

(Faces p. 46)

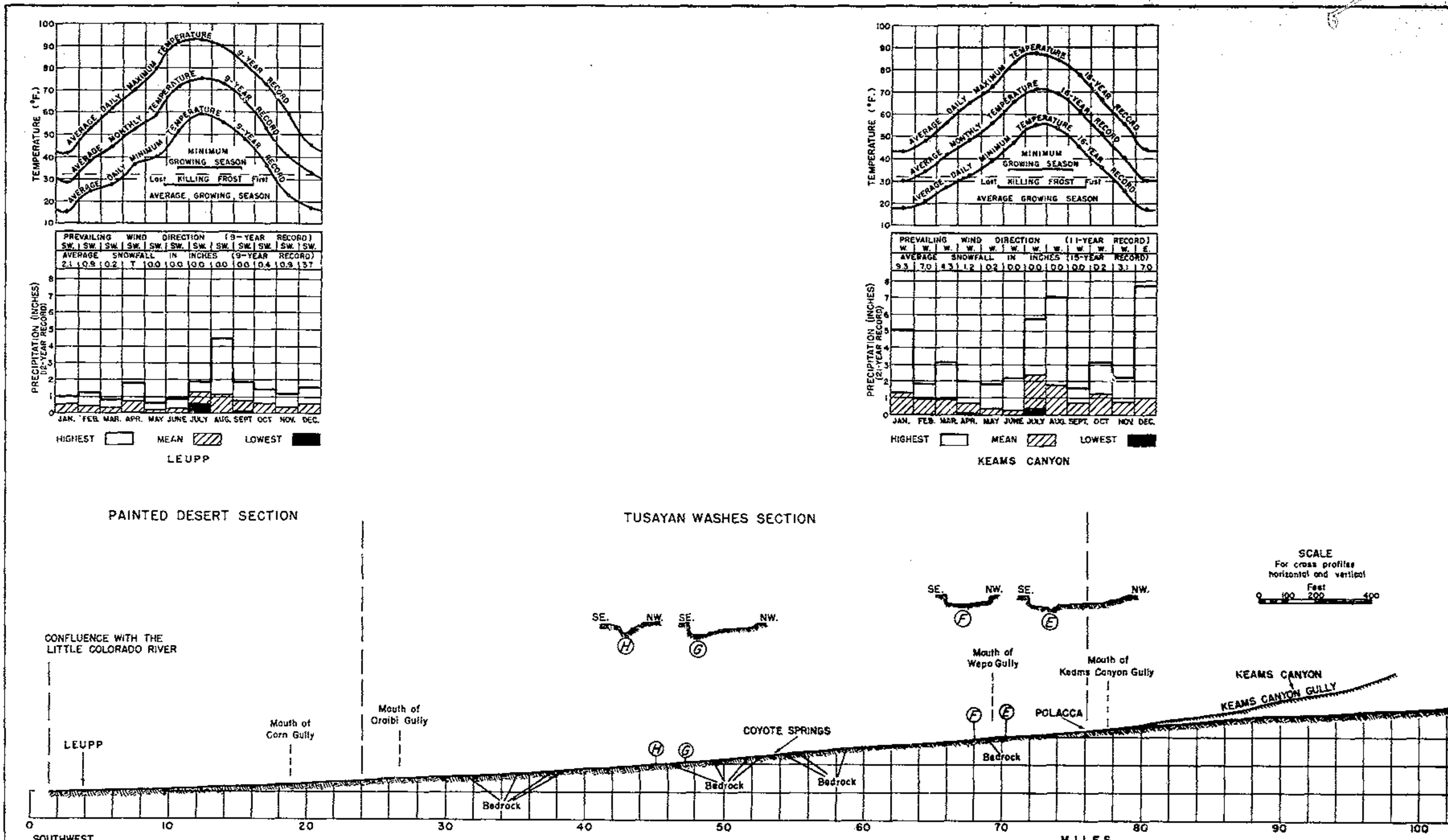
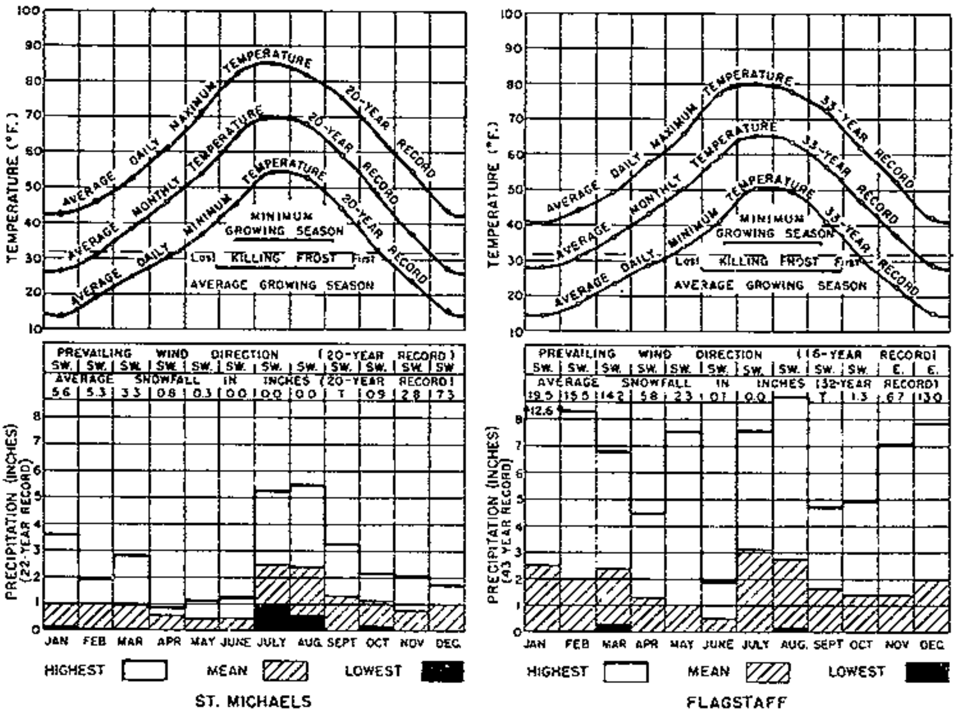
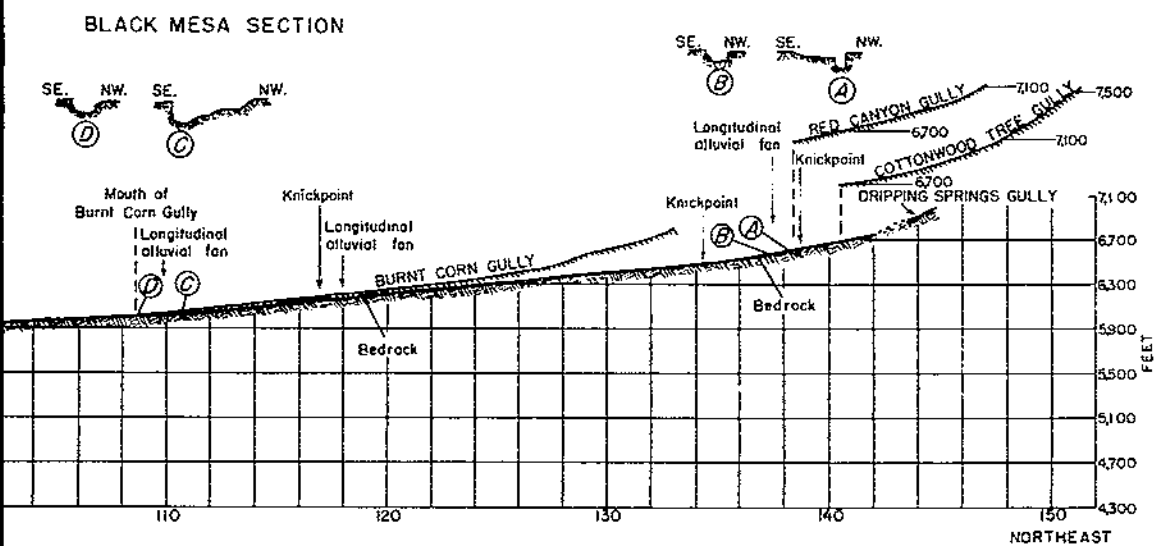


FIGURE 26.—Longitudinal profile of the Polacca Gully from its head to the Little Colorado River at Leupp, b
5-mile intervals. Longitudinal profiles of important tributaries, selected cross-profiles, and locations of kn
alluvial fans are shown. Climatic summaries from Weather Bureau stations at Keams Canyon and Leupp
in the middle and at the lower end of the Polacca. There is no meteorological station in the headwaters a
vegetation seem to indicate that climatic conditions there are intermediate between those at Flagstaff and





ased on average grades of
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(Faces p. 46)

the climate varies from humid or moist subhumid to arid. In most years only the highest parts of the headwaters area are sufficiently humid to have precipitation adequate for a good range.

Weather records are available for only a few stations in the Polacca drainage, but by examining in addition the climate at other stations in this area a fair picture of the conditions for a period of 12 to 43 years can be obtained, depending on the local length of record (fig. 26). Temperature for the lower parts of the area averages above 70° F. for June, July, and August: the highest monthly average in the Polacca drainage is 76.4° for July at Leupp (fig. 26). Maximum temperatures range upward to 104° or 105° but are well below the records of 112° to 127° in the southwestern part of the State.

Precipitation at stations in the Polacca drainage ranges from an annual average of 7.07 inches at Leupp (4,700 feet elevation) to 11.87 inches at Keams Canyon—Jeddito (6,200–6,700 feet elevation) and is believed to be considerably greater on the high mesas in the headwaters. Rain is received throughout the year, but there is a well-defined summer maximum and a secondary peak in winter. About one-eighth to one-quarter of the precipitation falls as snow, which in the Polacca drainage has been recorded for all months except June, July, August, and September. Nearby stations have received snow in all months except July and August. Precipitation increases with increase in elevation away from the Little Colorado; whereas temperature tends to decrease.

The summer rains, which are convective or frontal-convective, are usually of high intensity and short duration, in contrast to the widespread, more gentle winter rains. The degree of contrast in rainfall characteristics from month to month is brought out in the chart for Keams Canyon showing mean monthly amounts of precipitation falling at specified 24-hour intensities (fig. 27). July stands out as the month experiencing the most intense downpours. No data were available for the computation of short-period intensities, but it is certain that the summer rains fall at much higher short-time rates than do those of winter (table 8). High 24-hour amounts occurring during winter are nearly always of several hours duration, whereas in the summer it is not unusual for more than an inch to fall in less than 2 hours.

Intense storms are much more frequent in the headwaters of the Polacca Wash than near its mouth. It is probable that 24-hour storm amounts of precipitation that might be expected annually in the headwaters would occur not oftener than once in 5 years in the vicinity of Keams Canyon or once in 30 years at Leupp, where the Polacca joins the Little Colorado. The frequency of larger storms is proportionately diminished down the valley.

The erosional effects of precipitation are closely related to the seasonal distribution and intensity of the individual rains. Rainfall in months when the ground is moderately well protected by vegetation is obviously less likely to cause erosion than is rain falling during colder or drier months, when the cover of vegetation is sparse. At most of the stations in the vicinity of the Polacca Wash, July is the rainiest month, with August a close second (fig. 26). The intense, local summer storms tend to be roughly oval in form and may measure only a few hundred feet across and less than one-quarter of a mile in length, but they range upward in size to several hundred miles in diameter (fig. 28).

The extent of a summer storm, in one dimension, at least, as measured by the odometer on an automobile traversing the rain area, is usually not over 6 miles. Larger storms are occasionally encountered.

Winter precipitation, heaviest from December to March, is usually of the warm-front type and is of low intensity, wide extent, and long duration.

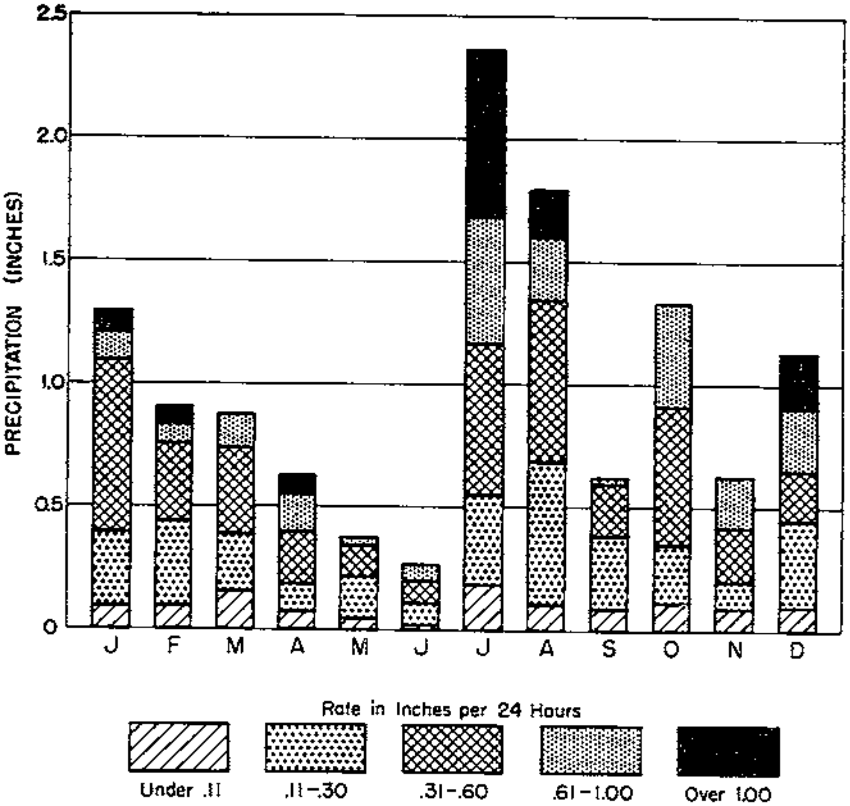


FIGURE 27.—Mean monthly amounts of precipitation falling at specified intensities, Keams Canyon, Ariz.

Owing to the seasonal differences in type of precipitation, daily incidence of rainfall and cloudiness are both greater in summer months, as shown in table 11.

During the period from June to mid-October 1936, a number of rain gages were operated between the village of Polacca and the head of the south fork of Keams Canyon to secure data on the intensity, internal structure, and migration of the rainstorms of that area. At first 1 recording gage and 24 of the standard type were used, but in late July and early August the number in use was increased to 6 recording and 36 standard gages. The distance between gages did not exceed 2 miles and averaged about 1 mile (fig. 29).

TABLE 11.—*Average number of days clear, cloudy, or with precipitation of 0.01 inch or more in a summer and a winter month in the vicinity of Polacca Wash, Ariz.*

Season	Clear	Partly cloudy	Cloudy or overcast	0.01 inch or more of precipitation
	Days	*Days*	*Days*	*Days*
Summer month	13	12	6	7
Winter month [1]	18	7	6	4

[1] December or January.

In the season studied, August had the most days of rain and the largest catch, 5.52 inches. September came second in total rainfall and July second in number of days on which rain was received (table 12). Continuous rainfall at any one spot usually lasted less than 1 hour, although one rain of slightly over 3 hours' duration was recorded (fig. 30). Rainfall periods, lasting several hours, with rains of short duration separated by short rainless intervals, were found to occur, especially in late summer and in the fall.

FIGURE 28.—View northwest from Second Mesa showing local summer rain over Oraibi Mesa.

The rainfall graphs for August 2 and September 1-2 (fig. 30) illustrate these types of storms and show the essential differences between typical summer and winter precipitation. The storm of August 2 was of a convective nature, having a rather high intensity and a short duration. The release of the convective energy in the prevailing Tropical Maritime air mass was brought about by the invasion of

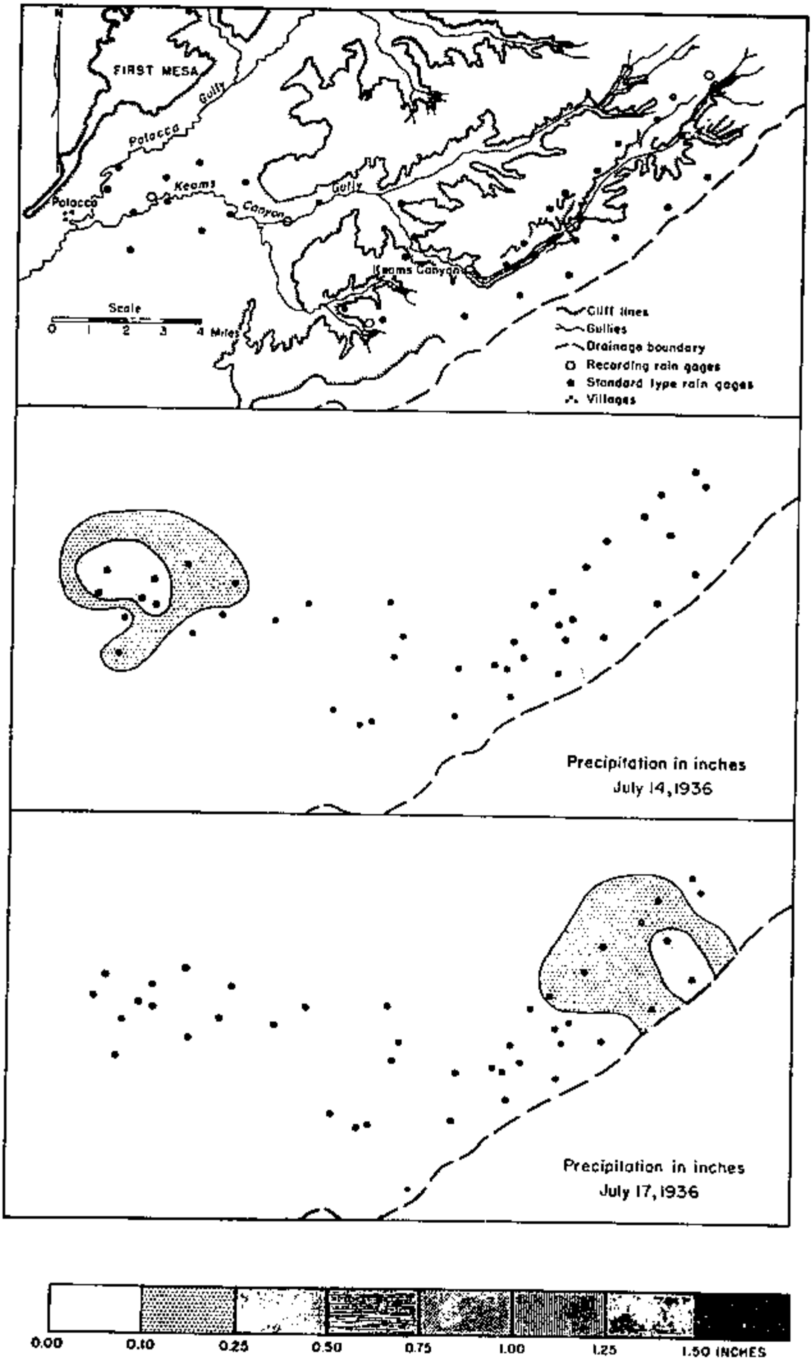
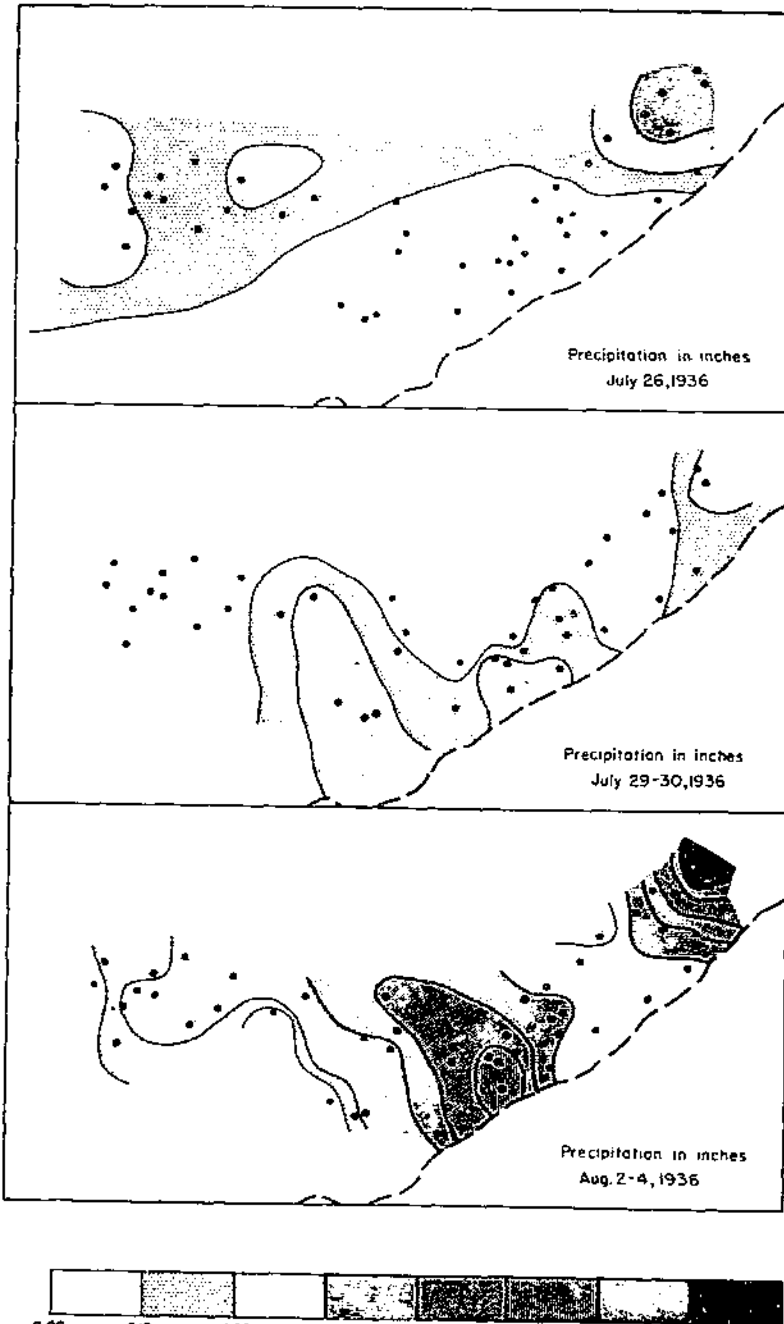


FIGURE 29.—Locations of rain gages operated in the vicinity of Keams Canyon
five characteristic storms. These should be compared with the large storms



and Polacca village in the summer of 1936 and distribution of precipitation in shown in figure 6.

a Polar Pacific air mass, which forced the tropical air to ascend aloft and condense its moisture. The storm of September 1–2 had an entirely different meteorological genesis. The rainfall, which was gentle and continued for approximately 15 hours, was caused by a warm-front type of occlusion. A well-modified type of Polar Pacific air advanced aloft over the prevailing polar air that occupied the southwestern United States at this time, and a gentle continuous rain was produced in advance of the invading upper front.

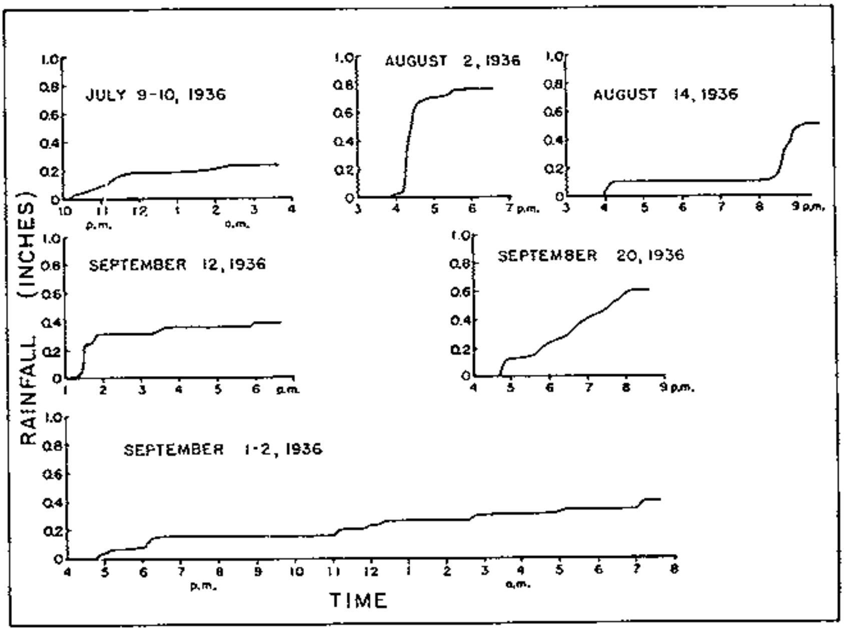


FIGURE 30.—Rainfall graphs from recording rain gages in the vicinity of Keams Canyon and Polacca village, July, August, and September 1936.

TABLE 12.—*Maximum monthly precipitation recorded at gages in the vicinity of Keams Canyon, Ariz., June to October 1936*

Month	Days of rain	Maximum monthly total	Month	Days of rain	Maximum monthly total
	Number	*Inches*		*Number*	*Inches*
June	6	0.74	September	9	3.24
July	11	1.51	October [1]	4	.59
August	17	5.52			

[1] Period of record, October 1–20; on October 21, the rain gages were removed.

The maximum short-period intensities shown by the recording gages from June to the middle of October 1936 were:

Maximum precipitation in—	*Inches*
5 minutes	0.20
10 minutes	.34
20 minutes	.57
30 minutes	.63

The absence of any very high intensities may be attributed in part to the shortness of the period of observation but is also in agreement with general meteorological conditions of the area.

One of the largest storms reported by the cooperative Weather Bureau observer at Keams Canyon continued from July 21 through July 24, 1915. The total precipitation of the storm was 4.38 inches. Three of the 20 rainiest days of record occurred during this storm. It brought 35 percent of the average annual rainfall and approximately 25 percent of the total rainfall received that year. During the 62 days preceding the storm, only 0.05 inch of rain fell, and following it no rain fell for a period of 27 days.

In spite of the small area of the Polacca Wash drainage as compared with the area of the Southwest, year-to-year variations in climate cover a wide range of climatic types. The range of variation during 40 years of record is illustrated by the climatic maps of the Southwest for 1905 and 1934 (fig. 24). Extensive upland areas which were humid in 1905 were dry subhumid or even semiarid in 1934. On the other hand, the widespread arid region appearing on the 1934 map is entirely missing from the map of the earlier year.

The magnitude of the variations from year to year is best brought out by the chart showing fluctuations from the headwaters down to the foot of the wash at Leupp (fig. 31). During the 30 years shown, the climate at the headwaters has ranged from humid to dry subhumid; at Keams Canyon, from humid to semiarid; at the point of confluence with the Little Colorado, from arid to semiarid. There is little doubt that if the record were longer the range would be even greater.

GEOLOGY

PHYSIOGRAPHY

The Colorado Plateaus of Arizona, New Mexico, Utah, and Colorado, comprising a large region of essentially horizontal rocks, are noted for their many broad mesas and deep canyons. In the center of the Navajo section of this physiographic province stands Black Mesa, approximately 55 miles wide and 65 to 70 miles from north to south (fig. 1). In the eastern part of the Mesa, the gathering ground for the waters of the Polacca Wash, the elevation ranges from nearly 8,000 feet close to Yale Point to approximately 6,200 feet at the pueblos on First Mesa. The margins of Black Mesa drop away in cliffs many hundreds of feet high to the Chinle Valley on the east and by somewhat lower cliffs to the basin of the Tusayan Washes on the south (fig. 25).

Owing to the alternation of resistant sandstones and weaker shales in the bedrock of this region, Black Mesa and its projecting tongues are not all formed of one individual rock surface but of many different beds. The escarpments, which at first glance seem to rise perpendicularly from the valley, when seen in profile are revealed as a series of steps extending to the mesa tops (fig. 32). Each of these steps or benches is separated from those adjacent to it by cliffs, the height and steepness of which depend on the thickness and resistance of the sandstones or other beds from which they are formed. Four levels are recognized, of which the lower two are by far the most extensive (figs. 32, 33, and 34).

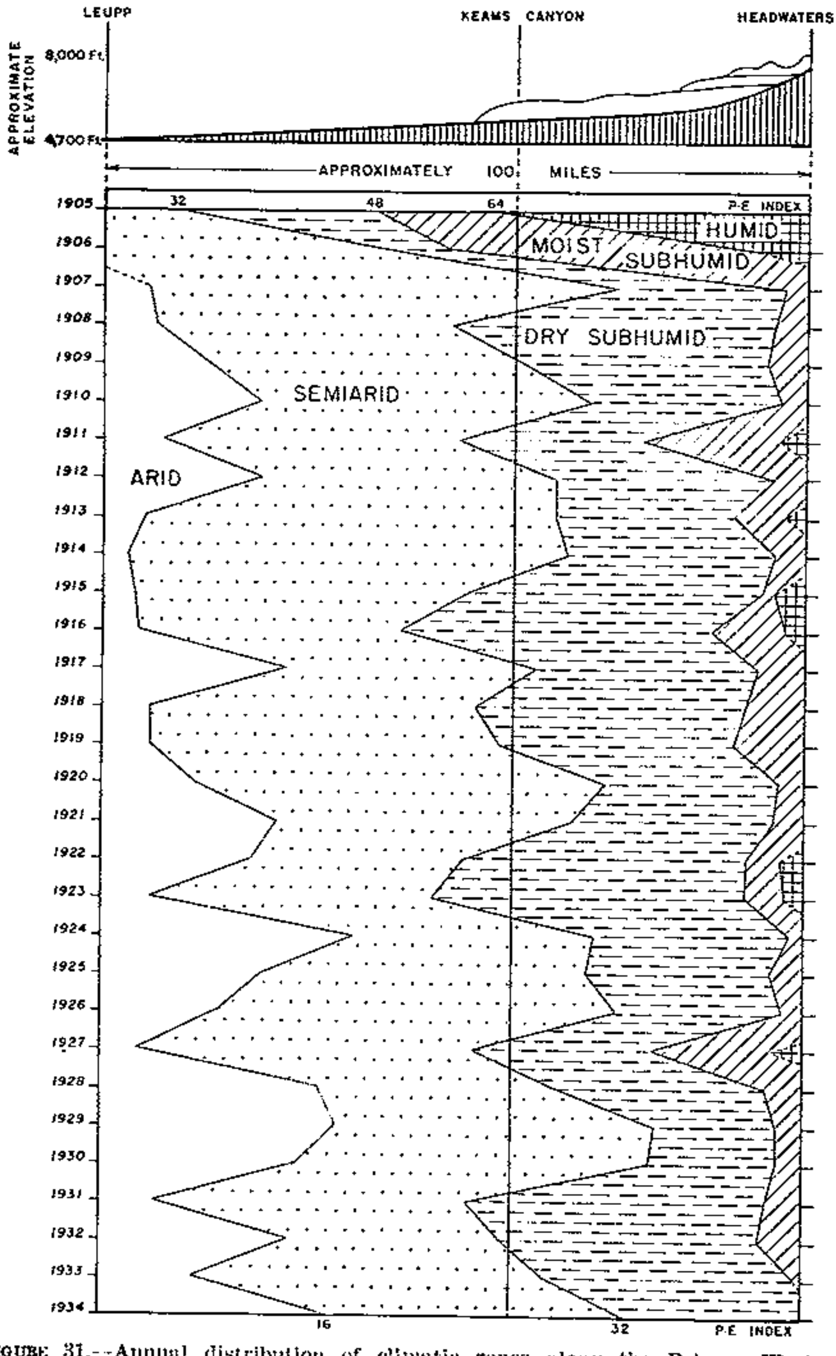


FIGURE 31.—Annual distribution of climatic zones along the Polacca Wash 1905–1934, based on a series of precipitation-effectiveness maps for northeastern Arizona.

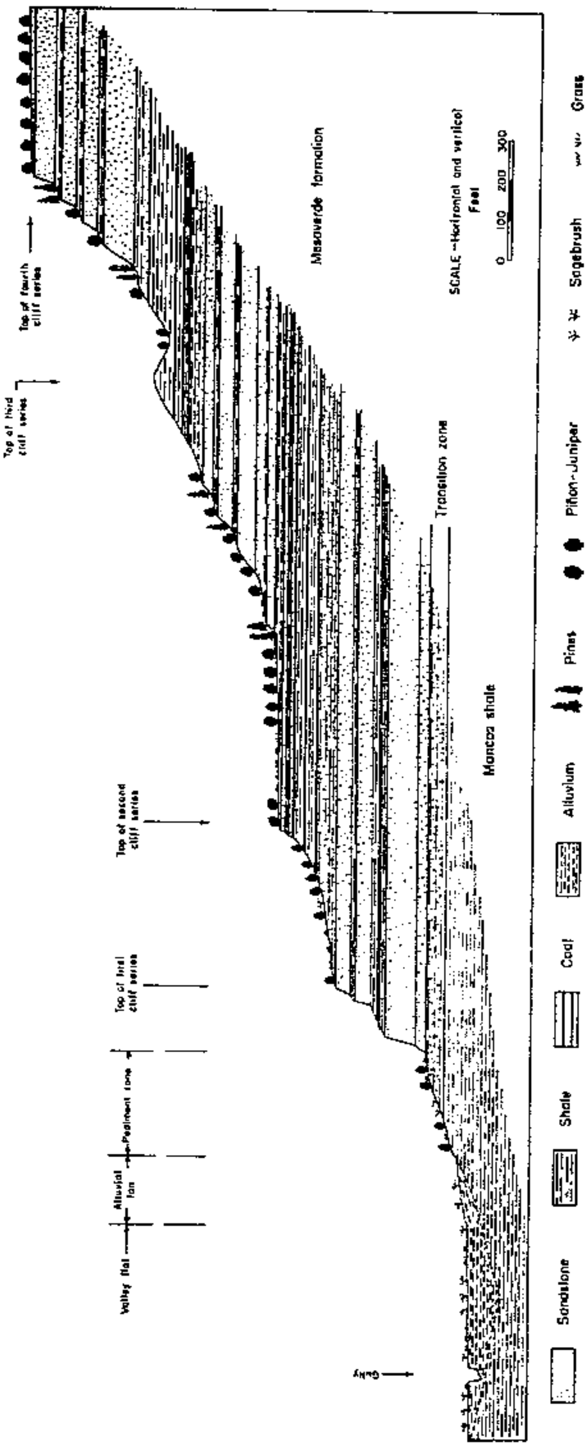


FIGURE 32. Generalized section from valley floor to highest mesa in the headwaters of the Polacca Wash.

FIGURE 33.—Rolling hills characteristic of the second highest surface, seen from the forks of Cottonwood Tree Canyon, looking southwest. Piñon and scattered juniper cover most of this upland area.

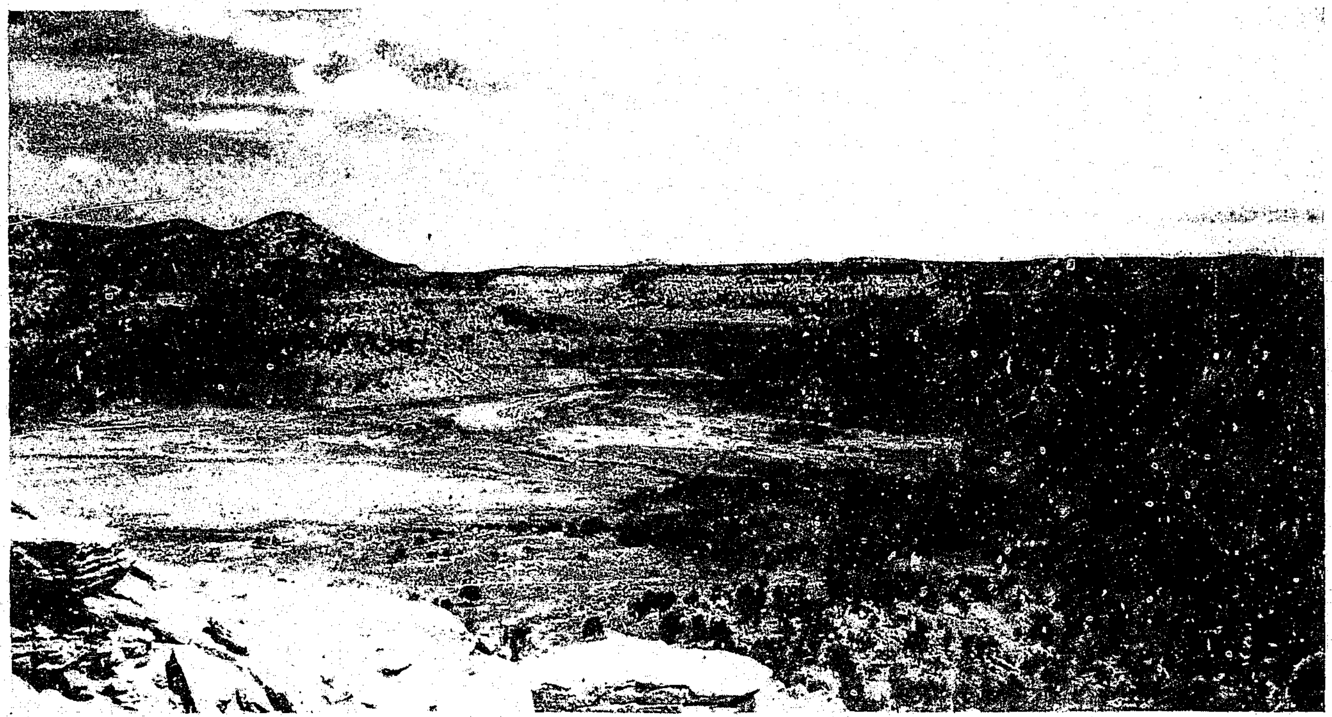


FIGURE 34.—Junction of Red Canyon, left, and the Polacca Wash, as seen from the butte west of the mouth of Red Canyon. Rounded hills of the second highest surface form the skyline at the left of the view. Below a narrow bench are the cliffs of the second series. Cliffs of the first, or lowest, bench form the major wall along both sides of the Wash.

Along the northeastern half of the Polacca Wash the land bordering the foot of the lowest cliff series slopes downward to the flat valley floor. The upper part of the slope, through most of this area, is a pediment (figs. 32 and 34) which projects irregularly into the valley, as if composed of a series of spurs. Large sandstone masses that have slumped from the cliffs interrupt the slope of the pediment zone in many areas. Soil and vegetation are meager on much of the pediment area. The soil thickens at the lower end of the slope, where the pediment characteristically gives way to an alluvial fan or an almost continuous alluvial apron.

The valley floor in the upper Polacca is in general broad and flat (fig. 34) and is covered with a deep alluvium which supports vegetation in abundance wherever sufficient water is available during the growing season.

Below the village of Polacca, the wash leaves the Mesa area, the high cliffs disappear, and the stream channel traverses a series of shallow basins (fig. 25). Over much of the area, normal development of surface drainage is hindered by low dunes and ridges of windblown sand. Small streams survive for only short distances before being absorbed in the surface sand.

Numerous abandoned channels and distributaries mark former courses of the Polacca, but the present channel is deeply entrenched in the valley fill. On the flood plain of the Little Colorado the Polacca turns westward for nearly 3 miles and joins the river west of Leupp.

STRUCTURE AND STRATIGRAPHY

The entire Polacca drainage is included in what Gregory has called the Tusayan downwarp (*51, p. 112*), a broad synclinal structure centering in the vicinity of Polacca village and Coyote Springs. In the headwaters area of the Polacca Wash the regional dip is to the west and southwest and attains a maximum of about 3 degrees. Locally

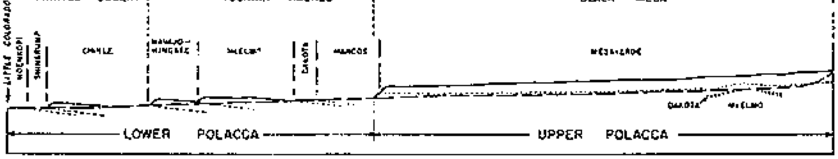


FIGURE 35.—Diagrammatic profile showing the relation of geologic structure to physiography along the Polacca Wash.

the major structure is complicated by minor flexures, the most prominent of which is an anticlinal or domed area 2 to 3 miles south of the mouth of Red Canyon, where the valley widens into a broad topographic basin (figs. 25 and 35). South of Black Mesa along the Polacca the rocks dip gently to the northeast and the wash passes through the dissected rims of successively lower formations (fig. 35).

The rocks of the Polacca Wash drainage, largely sandstones and shales, range in age from the Cretaceous Mesaverde formation in the headwaters to the Moenkopi shales of the Triassic along the Little

Colorado River at Leupp (*51, 52*) (fig. 35). Not only the topography, but vegetation and land use are closely related to rock structure and stratigraphy.

According to Gregory (*51, p. 75*):

> The Mesaverde of the Navajo country differs in no essential respect from strata of this age at the type locality in Colorado. At its base are one or more heavy beds of sandstone 30 to 50 feet thick; these are succeeded by strata consisting of about equal amounts of thin sandstone and shale with many beds of coal. The top of the formation includes three or more beds of massive sandstone attaining thicknesses of 40 to 100 feet. It is a prominent cliff maker.

Figure 32 represents the Mesaverde as it is exposed in the headwaters area of the Polacca Wash in the vicinity of Cottonwood Tree Canyon, where the formation is exceptionally thick. Marked lateral gradations in resistance and lithology are common and are reflected directly in the geomorphic forms of the area.

Conformably beneath the Mesaverde formation and usually separated from it by transition beds lies the Mancos shale, consisting largely of drab sandy clay shales and containing a relatively small percentage of sandstone, impure limestone, and coal. The beds are gypsiferous (*51, p. 73*). The gently sloping but irregular pediment zone of the upper Polacca Wash is developed on the Mancos shale. Height and width of the zone depend in large part on the stratigraphic depth to which the canyon has been cut. Where the canyon floor is in the Mesaverde-Mancos transition the pediment is small or absent, but where erosion has cut downward into the Mancos shale the pediment usually is broader.

Beneath the Mancos are the sandstones, conglomerates, shales, and coal beds of the Dakota formation, which in the Polacca drainage is seldom more than 25 to 30 feet thick. They outcrop locally on both limbs of the structural arch in the floor of the upper valley and again come to the surface in the lower valley south of Polacca village.

The McElmo formation lies unconformably below the Dakota sandstone. It outcrops on the limbs of the arch in the upper valley, and is also exposed in a broad band extending from about 7 miles below Polacca village to the vicinity of Coyote Springs. The shales and weaker sandstone members of this formation develop broad topographic flats or basins. The more massive sandstones, commonly cross-bedded, outcrop as cliffs, and in this area they form a rim on the southeast side of the Coyote Springs basin.

The McElmo formation grades downward through a thickness of as much as 100 feet to the rocks of the Glen Canyon group of probable Jurassic age. Elsewhere in the Navajo country and Grand Canyon area, these beds, the Navajo sandstone, Todilto shale, and Wingate sandstone, are prominent cliff formers, but such cliffs are only moderately developed in the Polacca drainage. They border the Polacca Wash irregularly from about 2 miles to 6 miles below Coyote Springs.

Beneath the Wingate sandstone, lowest member of the Glen Canyon group, lie the many-colored marls and shales of the Chinle formation of Triassic age. Most of the beds of this formation erode readily to an irregular badland topography. A few of the more resistant sandstone, limestone, and conglomerate beds form buttes, mesas, or long cliff lines such as those along the Polacca between the Tolani Lakes area and the point of entrance of Corn Wash (fig. 25).

The Shinarump conglomerate lies between the Chinle shales above and the Moenkopi shales below but in the Polacca drainage is not a prominent cliff former.

The Moenkopi shale, the lowest formation represented in the Polacca drainage, is of Triassic age and consists of highly colored platy sandstones and shales, which weather to low irregular badlands with scattered small buttes. The formation is largely nonresistant to erosion and forms the weak zone followed by the Little Colorado River from Holbrook northwestward for more than 80 miles.

Volcanic rocks of Tertiary age form irregular hills and mesas in the Hopi buttes area southeast of the Polacca drainage (*51*). The Giant's Chair (fig. 25), a prominent landmark on the west side of the Polacca Wash between Coyote Springs and Toreva, is an eroded volcanic plug probably connected with the rocks of the Hopi volcanic field.

SOIL

No detailed maps or descriptions of the soils of the Navajo and Hopi Indian reservations have yet been published. The Soil Survey of the Winslow Area, Arizona (*102*), the only bulletin discussing soil types close to the reservation area, covers part of the valley of the Little Colorado River for about 18 miles east and 14 miles north of Winslow but does not include any of the Polacca Wash drainage. A few reconnaissance surveys and detailed maps of special areas on the reservation have been made by Government agencies.

In general the soils vary with the underlying rock and local physiographic history. The three main groupings used in the Winslow area are applicable to the Polacca Valley. These are: (1) Residual soils, (2) old valley-fill soils, and (3) recent alluvial soils (*102, p. 162*). Residual soils are restricted largely to mesa surfaces and to marginal slopes on pediments. The valley flats and active fans comprise the other two soil groupings.

As the soils of the Southwest are in general thin and poorly formed, the residual soils relate closely to the underlying parent materials in water properties and in resistance to erosion. Residual soils on areas of sandstone and shale, for example, may support altogether different kinds of vegetation and respond quite differently to erosion, although lying within the same climatic region. The area underlain by Mancos shale in the Polacca Wash drainage basin is one of the critical soil areas of the watershed.

The bottom soils are in general heavier than the sandy soils of the uplands, the flat alluvial benches, and the colluvial slopes. Alkali conditions are generally not unfavorable on the higher lying soils but make some of the lower lying, poorly drained soils less suitable for agricultural use. Wind blowing has modified almost all the soils. In general, however, the heavier textured soils are less affected than those that are loose and sandy.

VEGETATION

NATURAL VEGETATION

The natural vegetation of the Navajo country ranges from desert to subalpine types and correlates closely with local climatic conditions. Soil and drainage are important in determining the vegetal pattern within individual climatic zones.

Five main climax types are present. Lowest of these is the sagebrush climax or northern desert shrub (fig. 36), found in parts of the valley of the Little Colorado, the Painted Desert, and the southern edge of the Tusayan Washes. Next higher is the grassland climax or short-grass zone, extending from the sagebrush area to the mesa borders and occupying elevations of roughly 5,300 to 6,000 feet. The lower mesa levels, from about 6,000 to 6,700 or 6,800 feet, bear the woodland-climax or piñon-juniper association. Above 6,800 feet the montane-forest climax dominates and continues to an elevation of more than 8,000 feet. The subalpine climax, characterized by Englemann spruce, extends from the upper limit of the montane forest to the top of Navajo Mountain, about 10,416 feet, the highest elevation in the Navajo country. The same general zonal plan is found through most of the arid to semiarid lands of the Southwest but is extended to include a still more xerophytic desert flora at the lower elevations and on the highest peaks in northern Arizona, above 11,000 or 11,500 feet, an alpine meadow climax (*56, 78*). The zonal boundaries are not sharply drawn. Members of each climax extend in lesser abundance into adjoining zones.

In the Polacca Wash drainage basin, elevation restricts the vegetation to the montane-forest, piñon-juniper, short-grass, and sagebrush zones. In general the vegetation range from the mesa top to the valley floor closely resembles the climatic range from the cooler, moister headwaters of the Polacca Wash to its warmer, drier lower course. The boundary between the montane-forest and piñon-juniper zones is several hundred feet higher in the Polacca drainage on the eastern part of the Black Mesa than elsewhere in the Navajo country. Piñon-juniper here grows profusely on the mesa to altitudes of almost 8,000 feet (fig. 33). Small groves of yellow pine and climatically associated montane-forest types, such as Douglas fir and aspen, are present in the coolest and most humid areas, as in the upper ends of Cottonwood Tree Canyon and Red Canyon, and on the divide between (fig. 37). Piñon-juniper is common in the pediment zone, especially in the headwaters, but is present only locally on the canyon floors (fig. 34).

On the southern part of the mesa surface, within 25 miles up valley from Polacca village, piñon-juniper grows less thickly on the mesa top. Areas of grass and sagebrush are more common (figs. 38 and 39). Trees are much less abundant in the cliff and pediment zones here and are rare on the canyon floors.

On the wooded mesas in the headwaters country remnants of parklike areas of grassland are found in shallow basins or flats where colluvial material from gentle side slopes has accumulated to form a thicker soil mantle. Large areas of this sort, separated by low divides which support a growth of piñon-juniper, are present on the mesas bordering the wash below the mouth of the Burnt Corn (figs. 38 and 39). Much of the mesa-top grassland, however, has been lost. The remaining growth is sparse and its place is gradually being taken by brush and weeds and by expansion of the area of piñon-

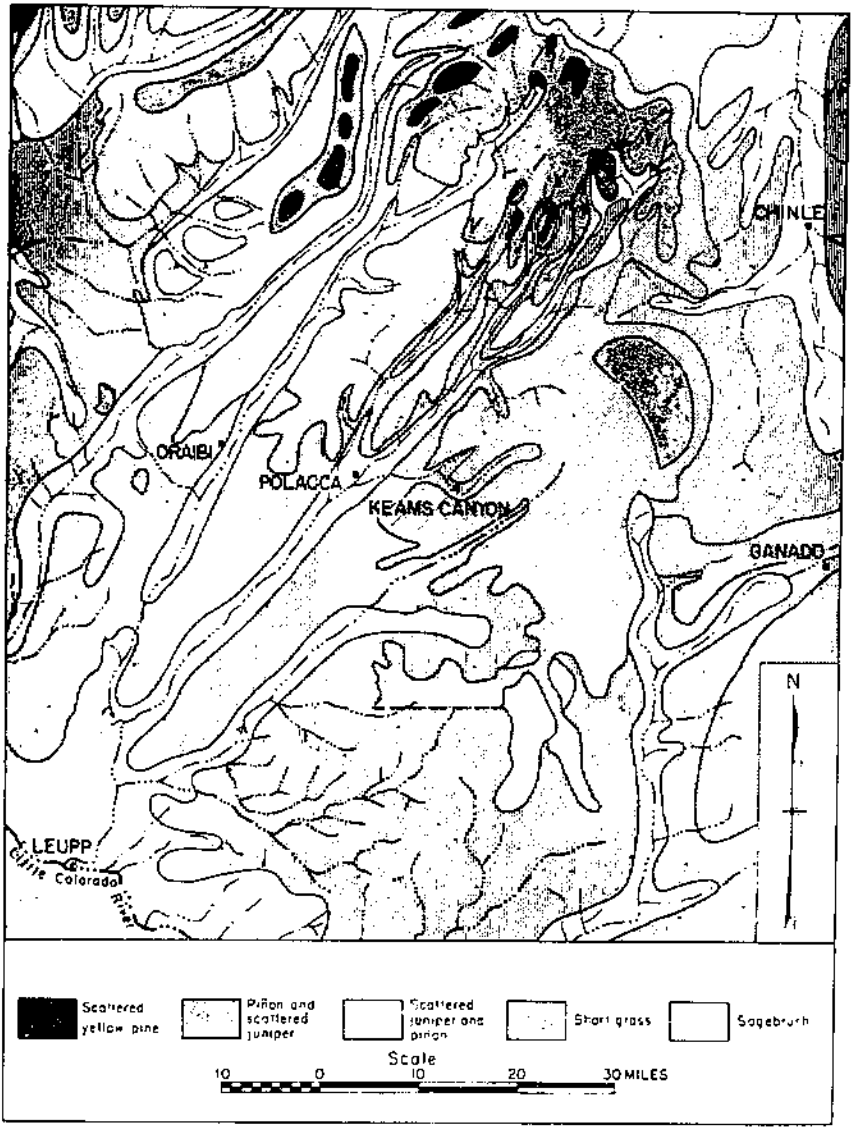


FIGURE 36.—Generalized natural vegetation in the Polacca Wash region, Arizona. (After Gregory (50), A. A. Nichol (78), and others.)

juniper. In places the loss of grass sod has resulted in soil removal and the exposure of large areas of bare rock.

Short grass with a minor amount of sagebrush was formerly the characteristic vegetation of the valley floors. In recent years this

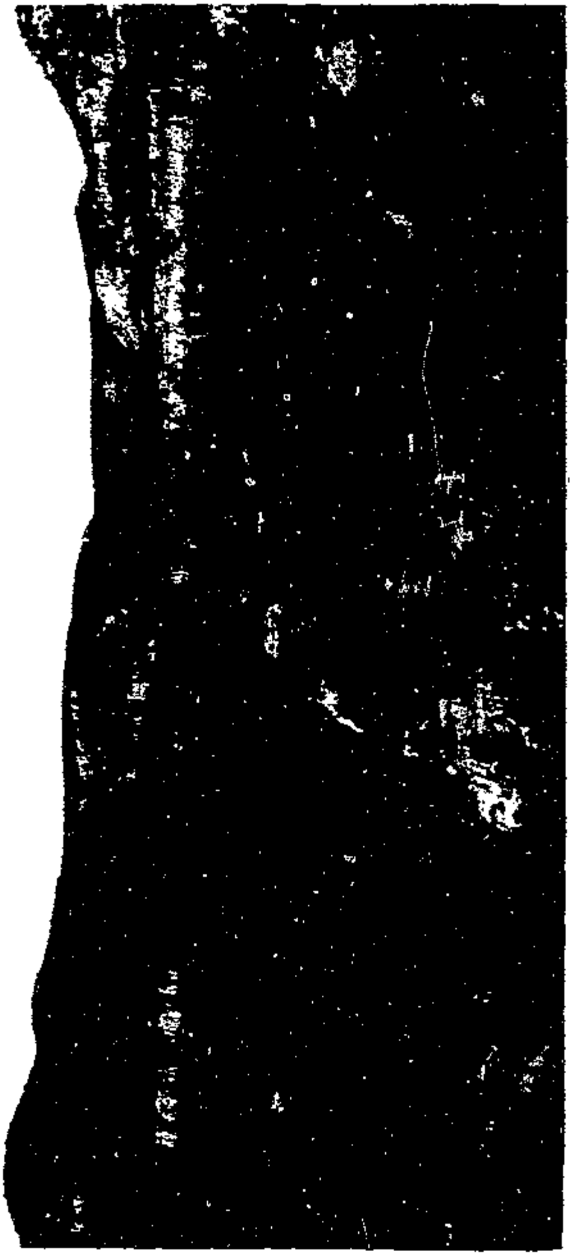


FIGURE 37.—View headward up Cottonwood Tree Canyon from about one-quarter mile above the fork. Most of the cover is piñon and juniper, but scattered pines are present in the steep walled canyon at the left.

FIGURE 38.—Badly overgrazed grassland on the mesa top 5 miles southeast of Keams Canyon. Piñon-juniper occupies the divide in the background.

FIGURE 39.—Sagebrush flat invaded by some juniper on the mesa surface 2 miles northeast of Keams Canyon.

cover has gradually diminished. Gully cutting has lowered the water table. Drought has reduced the ability of the grass to regenerate after the heavy grazing of Navajo and Hopi sheep and ponies. As a result more xerophytic plants have gained ascendancy.

In general, depletion of vegetation has been less in the valley floor of the lower Polacca than in the upper valley. Because of its drier and warmer climate the lower area had a more xerophytic natural vegetation. Sand dunes in the lower valley have retarded run-off and conserved moisture. In spite of these conditions, however, many of the more palatable plants have been displaced by less desirable types.

HISTORICAL EVIDENCE OF DEPLETION OF VEGETATION

Conversation with Indians and traders and inspection of old records give a variety of opinions as to the former vegetal cover of the Hopi and Navajo country. There is evidence that the grass cover was once more nearly complete, but it is certain that the abundance of grass varied considerably from place to place. Local areas probably have always been barren.

One of the earliest accounts of the vegetation of this region is given by Lieutenant Edward F. Beale, who, under commission from the War Department, surveyed a wagon road from Fort Defiance, Ariz., to the Colorado River (*15*). He passed westward down the valley of the Little Colorado River through the Navajo country early in September 1857 and returned up the valley shortly before the middle of February 1858. His route through this area did not traverse the Polacca drainage basin but lay along the upland south of the Little Colorado and within 5 miles of the river. Beale's journal gives a glowing account of excellent and abundant grass between Holbrook and the mouth of Canyon Diablo, of fertile soil, and of plenty of water. He describes a luxuriant crop of grama grass on the mesa near Leupp, Ariz., and states of one day's travel near there that nothing had impeded their progress but the grass. This region, he predicted, would become as good a livestock country as any in the United States and would undoubtedly be heavily settled by whites once the Indians were held in check (*15, pp. 44–48*).

The contrast between the conditions described by Lieutenant Beale and those of the present day has been shown in a publication of the Office of Indian Affairs (*75*). Recent photographs of the approximate localities described by Beale suggest a notable depletion of the vegetal cover.

In 1858, the year of Beale's eastward trip, Lieutenant Joseph C. Ives' expedition, which had been exploring the Colorado River, entered the Navajo-Hopi country from the southwest. After a difficult trip on which he and his party were seriously short of water they reached the pueblos on the Hopi mesas (*70, p. 119*). When the party arrived at "Mooshahneh" (Mishongnovi), on Second Mesa, May 11, the Hopis guided them to a camp ground of which Ives says (*70, pp. 120–121*):

> In ten minutes a spot was reached which all agreed was the best grazing camp the country afforded. I no longer wondered that their one horse looked so thin. A single animal could scarcely have existed for three days upon all the grass in the neighborhood.

Because of exhaustion of the mules and because of the poor prospect of finding water the party abandoned their plan to travel northward from Oraibi when they had gone only about 30 miles.

Returning southward they crossed the neck of Second Mesa and on May 17 camped in the Wepo Valley along the trail from Oraibi to First Mesa. Ives records that "the valley was well covered with grass. Large flocks of sheep attested the wealth of the citizens of this department of Moquis" (*70, p. 126*). The "department of Moquis" to which he refers is the group of Hopis on First Mesa, and Wepo Valley is one of the best watered of the entire area. It has been cultivated extensively by the Hopis in recent decades.

Kit Carson visited the Hopi pueblos on October 21, 1863, to obtain their assistance in a campaign. In his report on the action he noted (*43, p. 34*):

> . . . these people, numbering some 4,000 souls, are in a most deplorable condition, from the fact that the country for several miles around their village is quite barren and is entirely destitute of vegetation.
>
> They have no water for purposes of irrigation, and their only dependence for subsistence is on the little corn they raise when the weather is propitious, which is not always the case in this latitude.

Crop failures in 1864 and 1865 bore out Carson's statement of the peoples' dependence on weather and were in part responsible for a severe famine. As Colonel Carson's observations were made in October it is obvious that he would not have seen the grasses and crops at their best.

Almost 20 years later John G. Bourke, captain in the United States Cavalry, made a journey to the Hopi pueblos to observe the traditional snake dance. He left Santa Fe early in August 1881 and spent the night of August 7 at Fort Defiance, Ariz. His route from there lay west across the Defiance Plateau and Pueblo Colorado Wash to Keams Canyon and the Hopi mesas. After the dances he returned to Keams Canyon for a short sojourn. He and his party started their return to the line of the railroad on August 19. From Mishongnovi their trail led through the Hopi butte country to the Mormon settlement of Sunset, along the Little Colorado about 3 miles northeast of Winslow.

Bourke's special interest in ethnology did not prevent his making full and apparently accurate notes on the natural history of the region the party traversed. Observations on the abundance of grama grass are particularly pertinent. About 16 miles west of Fort Defiance he notes that the pine woods gave way to piñon and cedar as the road descended the slope of the plateau. There was much large sagebrush and Spanish bayonet, and "grama grass, in thick bunches, filled all the ground not covered, or too deeply shadowed, by other vegetation" (*17, p. 66*). In the valley he found little piñon. Sagebrush was more abundant. "The grass still remained excellent" (*17, p. 66*). On August 9, riding from Pueblo Colorado Wash to Keams Canyon, Bourke notes that the vegetation in the valleys was almost exclusively grama. He refers to an absence of flowing water but says that grama grass of the finest kind was growing luxuriantly everywhere (*17, p. 72*).

The valley of the Polacca Wash was far less hospitable. Bourke describes it (*17, p. 96*) as a plain of heavy sand.

For the whole fourteen miles [down Keams Canyon and across the Polacca Wash to First Mesa] one had to bear with patience the intense heat of the sun's rays, reflected back with increased power by the minute crystals of sand. Progress over such a trail is at all times difficult * * *.

The difficulty the mules had in traversing the high sand dunes southwest of the end of First Mesa and the presence of shifting sand, thinly grassed, in the valley between Mishongnovi and Shongopovi are mentioned. Of this area he says (*17, p. 312*):

The grass and cedar, which were very poor near the towns, improved in quantity and quality as we receded from them. The herds and flocks had, beyond question, eaten and stamped out the herbage, and the demand for fuel had caused the cutting down of much timber.

On August 19, the party turned southeast from Mishongnovi and after crossing the Polacca Wash continued southward apparently along the eastern side of the valley (*17, p. 343*).

* * * the trail ran through a fine pasture-land, mantled with vernel green. We saw on all sides a broad grassy plain, sloping back towards the Moqui villages. This plain we estimated to be seven miles broad, covered in its whole extent with the choicest "black grama" grass, and in area could not have been less than 20,000 acres.

The grassy plain was succeeded southward by a hilly area and buttes of odd and picturesque shapes, obviously the Hopi Buttes. Sagebrush and greasewood took the place of grass in this rugged country, but beyond the first range of hills the party descended into a—

second broad expanse of refreshing green grass running for miles in every direction. * * * sheep trails without number, leading hither and thither, showed unmistakably that the Navajoes were sensible of the value of this grand pasturage. [(See *17, p. 344*).]

In contrast to these garden spots of the reservation the breaks of the Little Colorado extending 15 miles back from the river were described (*17, pp. 346–347*) as of unsurpassed aridity.

A few shrivelled sprigs of grease-wood, a speck or so of sage-brush seen at great intervals, and in one or two shady nooks a solitary leaflet of green which may be grass, or something else, constitute the sole verdure, the sole covering for these hills of burnt, baked clay and sand.

Ten years later, on November 1, 1891, Julian Scott, a special agent for the Eleventh Census, visited the Hopi villages. He says (*43, p. 52*) that from the mouth of Keams Canyon:

* * * our road lay across what seemed almost a desert waste. * * * Bunches of amoli (soapweed), wild sage, yucca (Spanish bayonet), sweet grass, and cacti relieve the monotony the sandy stretches would otherwise have presented.

Bowman, in 1911, says of the vegetation of the Navajo-Hopi country as a whole (*18, p. 276*):

The extent of bare rock and sand floor is very great, and probably not more than 10% of the Navajo-Moki region is actually covered with vegetation. In fact it is possible to walk from Gallup, New Mexico, to Tanner's Crossing on the Little Colorado, or from the Carrisos Mountains to Lee's Ferry, without stepping on a twig or a spear of grass.

From these accounts it is apparent that even 80 years ago grass was scarce in the vicinity of the Hopi villages. In favorable locations far from the pueblos, however, there was good grass cover at least as late as Bourke's visit in 1881. The estimates the various travelers give of the vegetation depend not only on the particular area observed but on the season and year in which they saw it. Beale's impressions gained in September and February, months following wet seasons of the year (figs. 12, 13, and 26), are in strong contrast to those of Ives, who saw the Navajo-Hopi country in May, one of the two driest months. Vegetation receiving water from melting winter snows or permanent springs, as along the Wepo Wash, would be green in May and June, but vegetation dependent on summer rains of July and August for its growth would not be much in evidence. Colonel Carson's visit in October 1863 and Scott's in November 1891 were at a time of year when the grasses would not have been at their best. Carson's statement that the country around the villages was barren, however, would probably be almost equally true in summer and Scott's description of the Polacca Valley as "almost a desert waste" agrees with Bourke's earlier observations made in August, a month when summer rains are usually plentiful in that region and vegetation should be at the height of its growth.

Similar differences in condition of vegetation arise from the wide yearly variations in climate. However, total annual precipitation and average temperatures are less significant than the distribution of individual rains and droughts (pp. 31–35). That August 1881 must have had rather favorable precipitation is shown by the accounts in Bourke's journal (pp. 113–114). His party was rained on or saw rain near them almost daily for 2 weeks.

The fine plains of choice grama grass described by Bourke are now gone from the Navajo country. Where grama grass is present at all, it grows as scattered individual plants rather than in thick clumps.

LAND USE: PAST AND PRESENT

EARLY RECORDS

Our first knowledge of northeastern Arizona comes from the journals of Coronado's expedition, a party from which explored the area in 1540. At that time the country was inhabited by Pueblo Indians and had not yet been occupied by the Navajos. The Pueblo economy was agricultural, and the Indians had no livestock until sheep and horses were introduced by Coronado.

By the early seventeenth century the Navajos had entered the territory of the Pueblo dwellers, and within the next 100 years had made themselves dreaded enemies of the Pueblo peoples. The warlike invaders attacked the Spaniards and Pueblo dwellers alike, and in these raids obtained the first of the sheep which have since become so important in Navajo life. Amsden (*12, p. 129*) thinks it probable that weaving was established among the Navajos at the time of the Pueblo Rebellion of 1680, when the Spaniards were driven from many of their holdings, particularly in the northern part of what is now New Mexico. In 1692, the Spaniards fought their way back into that area, and permanent settlements were established.

Herding and weaving became more and more important among the Navajos, and according to Amsden (*12, p. 133*) these people had gained a recognized supremacy in native weaving of wool in the Southwest as early as the beginning of the nineteenth century. Until at least the time of the Civil War, the concentration of human and domestic animal population of the Navajo and other tribes of this area of northeastern Arizona was relatively low, and their use of the land could have changed it but little from the natural condition.

The Navajo Reservation was created in 1868, when the tribe was released from Fort Sumner, N. Mex., after the Navajo uprisings had been put down by Kit Carson. It was estimated that 8,000 Indians (*38*) and livestock consisting of 1,550 horses, 20 mules, 940 sheep, and 1,025 goats (*41*) were placed on the reservation at that time. Amsden states (*12, pp. 198–199*) that 30,000 sheep and 2,000 goats were distributed to these Indians in 1869, and 3 years later 10,000 more were brought in. Although these figures are low in comparison to the 48,000 Navajos (*109, table 1*) and 800,000 (*109, table 13*) to more than 1 million sheep and goats[15] reported on the reservation in recent years, it is evident that the period following 1868 marked a great increase in grazing and was the beginning of a critical time in the erosion history of the area.

Additions to the Navajo Reservation changed its boundaries but did not greatly lighten the grazing load.

CHARACTERISTICS AND EFFECTS OF NATIVE LAND USE

Most of the villages of the Hopi Indians in northeastern Arizona long antedate the founding of the Hopi Reservation in 1882, and the agricultural practices of these people have changed but little from contact with the white man. They are essentially tillers of the soil rather than stockmen, and their traditional methods of tillage—hoeing or weeding by hand—the small size and number of their fields, and the location of fields on flat or nearly flat surfaces, have combined to keep to a minimum soil erosion from agricultural causes.

Archaeological evidence indicates that at one time small-house villages, cliff-houses, and pueblos were numerous in the Black Mesa country. Reagan states that they were more closely spaced than farmhouses are in central Iowa today (*84, pp. 144–147*). Each little wash and flat had its village, and water was so carefully gathered and husbanded that none was allowed to escape down the drainageways (*85, p. 240*). Dams and ditches diverted the water of side canyons and made it available for irrigation and village supply. This abstraction of water by man would have the same general effect on valley gradation as would a reduction in rainfall, but without the corresponding general depletion of vegetation. Traces of the dams and other structures can still be found locally (*100, 101*). Whether these works were as numerous at any one time as Reagan suggests is open to question. Most of them have long been in disrepair. If the dams and ditches of these early agriculturists played even a minor part in bringing about aggradation of the valley floors, as a corollary, abandonment and disintegration of the structures, through increase in run-off, might have furthered to a small extent the recent acceleration of erosion.

The Navajos, originally hunters and warriors, are partly nomadic and in general are little inclined to raising cultivated crops. Some have departed from this tradition, however, and the Indian Service

[15] The dipping records of the Bureau of Animal Industry show 1,013,696 sheep units (lambs, rams, goats, and kids) for 1933.

Figure 40. Polacca Gully and a small tributary 9 miles southwest of Coyote Springs. Eroding livestock trails radiate from a watering place at the right. Longitudinal sand dunes parallel the main channel. (Scale approximately 2 inches to 1 mile.)

reports that in the calendar year 1938, 42.5 percent of the Navajo families planted gardens, as compared with 82.8 percent of the Hopis (*109, table 13*).

For the majority of Navajos, who are primarily herdsmen, scarcity of forage, firewood, and water forces a change of abode seasonally or oftener. According to Hoover (*63, p. 432*), pressure of increasing population now confines most families to particular grazing areas within which their movements follow more or less regular routes. Many of the Navajos have definite summer and winter ranges, a few miles to 60 miles apart, to which they return and in which they occupy the same hogan each year. In the Black Mesa area the best watered lands for farming are along and at the mouths of arroyos, so there is a general move to the valley bottoms in summer. In winter the mesas are more hospitable. Pasturage then is good in the juniper zone. Juniper and piñon are available for firewood, and melting snow provides water. Snowfall is not excessive, and the trees catch much of the snow and provide shelter for the livestock (*63, p. 437*).

Although the Navajo herder may cover a wide summer circuit and return to the same hogan on the mesa in winter, he does not move constantly but lives for many days or weeks in each of several homes. These Indians do not drift with the sheep from day to day, as do most herdsmen, but bring them to the corral each night and drive them out again in the morning. Intense utilization of a restricted radius results. When a section of the range no longer affords subsistence the sheep are driven to a new area, a new hogan and corral are built, and the process is repeated. The Navajos are not village dwellers. Though several hogans may be built together in some favored location, they are more commonly widely scattered.

With the large increase in Navajo population and the corresponding growth in size of the flocks, the carrying capacity of the reservation has been strained to the limit. Concentration of corrals, and hence of grazing and trampling, in areas of the best grass or close to the few watering places (fig. 40) has denuded the soil and induced sheet and gully erosion. Grass is rapidly giving way to bare ground or is being replaced by Russian-thistle, snakeweed, rabbitbrush, and other unpalatable shrubs and weeds. In some localities hauling of wood, water, and other supplies has developed ruts which serve to concentrate the run-off. As the ruts enlarge to channels the old wagon trails are abandoned and new routes are chosen, usually only a few feet to the side. Series of nearly parallel linear gullies commonly result (fig. 41).

Present Erosion Conditions [16]

The Polacca Wash, both in present condition and in physiographic history, is typical of the larger drainage basins of northeastern Arizona. Flow in the wash is intermittent and rarely is there a con-

[16] Field studies of erosion conditions in the Polacca Wash drainage were made under the direction of C. O. Sauer, head of the Department of Geography at the University of California and a collaborator of the Soil Conservation Service. The first field party working on the Polacca Wash included A. A. Normand, F. A. Johnson, and Parry Reiche. A. A. Normand's manuscript, a progress report on the Polacca Wash study, submitted February 23, 1935, has been utilized in the preparation of this bulletin. E. H. Roff, E. F. Dosch, and F. Robinson took part in later field work, with F. A. Johnson acting as party leader.

tinuous stream of water from headwaters to mouth. Through almost its entire length the Polacca contains a recently formed, deep, steep-walled channel or gully,[17] the cutting of which has destroyed large areas of the valley flat and, even more important, has brought about a marked lowering of the water table. Although accessible by car and truck, the Polacca Wash contains very few dams, bridges, or other engineering structures that might alter the natural drainage and is therefore especially suitable for study.

The Polacca drainage basin can be divided according to topography and erosion conditions into three main sections (figs. 25 and 26): The Black Mesa section, the Tusayan Washes section, and the Painted Desert section. Other washes draining southwestward from Black Mesa have similar divisions.

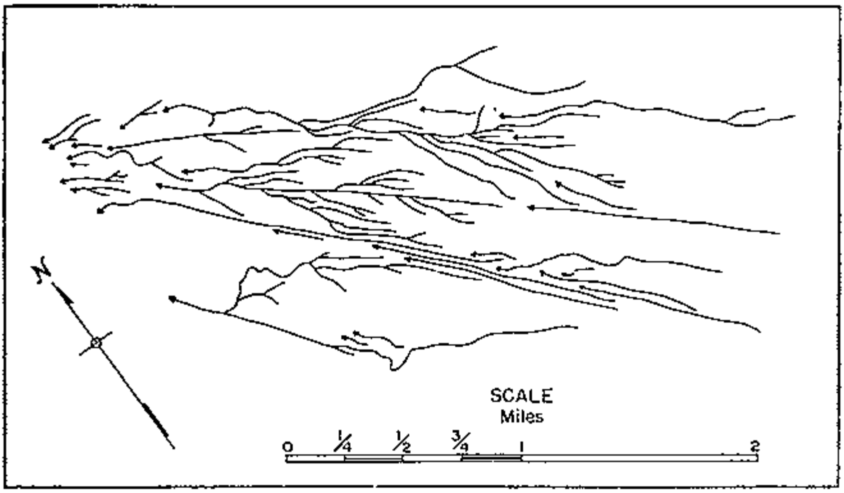


FIGURE 41.—Linear gullies, 4 miles southeast of Polacca village, formed by erosion of wheel ruts on wagon trails leading to a spring.

BLACK MESA SECTION

The Black Mesa section of Polacca Wash extends from the headwaters, near Yale Point, downstream about 45 miles to the vicinity of Polacca village (fig. 25). After traversing 10 or 11 miles of headwater canyons the wash passes through a broad, open basin for more than 20 miles. From there it is again confined in a canyon for about 15 miles before reaching the southern boundary of the mesa.

The relatively short courses of the headwater channels on the mesa surface are characteristically broad and shallow. After no more than 4 or 5 miles the washes descend from the upland into narrow rock-cut canyons, which gradually broaden downstream (figs. 37 and 42).

In the larger canyons pediments border the alluvial floors, but in the upper ends and in many of the smaller canyons the flat floors

[17] The term "gully" as used here is restricted to channels developed largely as a result of culturally accelerated erosion, in contrast to arroyos, which may be of similar size and shape, but are natural features.

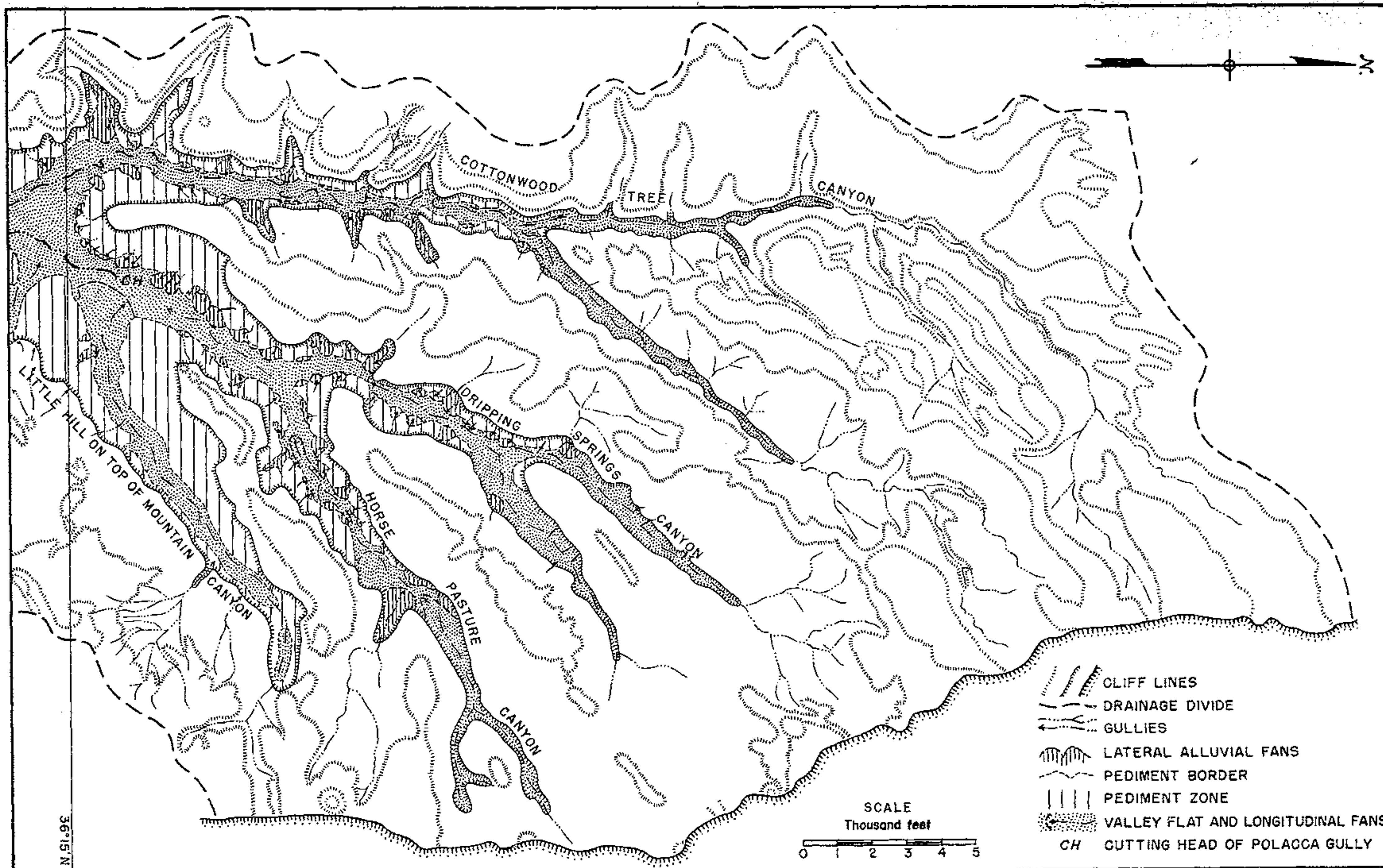


FIGURE 42.—Physiographic map of the eastern headwaters of the Polacca Wash, showing the mesas, cliff lines, pediments, alluvial fans, and valley floors.

(Faces p. 72)

abut directly against steep canyon walls, appearing almost as if the sediments had flowed in like water to seek their own level against the flanking slopes. The pediments are in large measure zones through which the cliffs have receded, but from which the products of recession have not been completely removed. Evidence for this is found in the presence of isolated "stacks," the position and structure of which indicate clearly that they are erosional remnants.

Accelerated sheet wash, rilling, and gullying are actively reducing the pediment surfaces, and deposition of the resulting debris is forming extensive alluvial fans a few hundred square feet to many acres in size extending onto the valley floor. Many recent deposits of this type have buried good grassland to a depth of several inches or more, as in the large longitudinal fan at the mouth of the Canyon of the Little Hill on Top of the Mountain (fig. 42). Where lateral fans are numerous they form more or less continuous aprons down both sides of the canyons and force the longitudinal drainage to the center. Irregular growth of lateral fans brings about periodic sideward shifting of the main drainage line.

In short reaches of the headwaters canyons the channels are essentially in their natural condition and show little sign of acceleration of erosion. Through most of the area, however, washing along the drainageways has been sufficient to cut away the protective vegetation and convert normal channels into active gullies. It is significant, in evaluating the present state of accelerated erosion in the headwaters, that the gullies in Dripping Springs, Horse Pasture, and Little Hill on Top of the Mountain Canyons end in fans and do not extend to the main Polacca Gully. Therefore, whatever sediments are now being carried out of these tributaries are carried by sheet wash and sheet flood. The absence of gully channels leading from the tributaries suggests that natural stabilization might still be attained if the causes of acceleration of erosion could be removed.

The cutting head of the Polacca Gully, when mapped in 1935, was about 0.8 mile above the mouth of Cottonwood Tree Canyon. This head was wide, shallow, and digitate (figs. 42 and 43), and it was advancing through a section of the valley that had a broad, smooth floor. Owing to the flatness of the floor the flow spread out and entered the head from many sides.

Opposite Red Canyon and for about a mile below its mouth, the floor of the main valley is made up of a large compound longitudinal fan consisting of three major lobes. Of these, the one across the mouth of Red Canyon and the long narrow lobe extending down into the basin area (fig. 44), and dissected by the present Polacca Gully, appear to be the youngest. Several secondary fans are also recognizable and suggest that the main fan was formed by coalescense of smaller ones. A few old drainageways, shallow and grass-covered (fig. 45), indicate former lines of longitudinal drainage through this reach and suggest the type of drainage line that may have been present before the acceleration of erosion. At present the convexity of the cross profile of the canyon floor is sufficient to cause a division of drainage, and gullies have developed along both sides of the canyon. The main gully follows the northwest side of the fan, and just upstream from the junction with the Red Canyon Gully it contains a knickpoint nearly 30 feet high.

FIGURE 43.—Cutting head of the Polacca Gully, 0.8 mile up valley from the junction of Cottonwood Tree Canyon Gully with the Polacca.

FIGURE 14. View southwest across the basin from the top of the mesa one-quarter mile west of the mouth of Red Canyon Gully. Long rock spurs of the pediment zone extend out into the valley floor in the foreground and at the right. The main lobe of the longitudinal fan, partially covered by light-colored dune sand, is in the left middle distance.

About 1 mile below the mouth of Red Canyon, the cliffs diverge sharply and the Polacca Valley expands to a broad basin more than 20 miles long. The semilunar arrangement of bedrock outcrops well out from the cliff face and the slight arch in the beds forming the cliffs to the north make it apparent that the upstream end of this basin has developed on an anticlinal structure of the Cretaceous beds.

The north and west sides of the basin are bounded by high cliffs, but to the southeast the cliffs are low or absent and the basin extends to the edge of an outward-facing rim overlooking the tributary drainage of the Chinle Valley. The divide between the Polacca and Chinle drainages is marked by an isolated butte or remnant mesa, Waterless Mountain, visible in figure 44. In this view, looking southwest from the northeast end of the basin, the rim of the basin formed

FIGURE 45.—Old distributary channel on the upper part of the longitudinal fan in the Polacca Wash opposite the mouth of Red Canyon, as seen looking southwest from the bank of the present Polacca Gully.

by the Chinle drainage can be seen at the extreme left, close to the horizon. The isolated butte is on the horizon, left of center, and from it long pediment slopes extend down to the main Polacca drainageway in the center of the view. Along the right horizon appear the cliffs bounding the valley on the northwest. The absence of cliffs along the southeast margin gives this basin somewhat the appearance of a gallery, facing out on the Chinle Valley.

A low bedrock ridge, extending down the center of the upper end of the basin for about 4 miles gives a somewhat convex cross section to the valley floor. This convexity is augmented by deposits of wind-blown sand. Drainage is imperfect except in the troughs along the two margins of the ridge, and small lakes are occasionally found among the sand hills and in depressions in the valley floor. The usefulness of these lakes for water storage is greatly increased by collecting ditches which lead water into them. It is thought that some of the depressions in the valley floor were once part of an old drainage system, but the great amount of sand that has shifted over the area has masked any definite relationships that otherwise might be established.

In the basin area, the fan zone is better developed than in the headwater canyons and forms an almost continuous alluvial apron. Only on the south, where the basin lies entirely within the Mancos shale beds, is the apron poorly developed or absent, and here a mantle of material more or less directly derived from the underlying bedrock merges with the alluvium of the valley floor. Gullies, most of which terminate down slope in fans, are abundant on the alluvial slopes.

Below the mouth of the Burnt Corn the Polacca drainage passes from the broad basinlike valley to the narrower canyon segment, which continues southwestward to the edge of Black Mesa.

In this part of the wash the cliff lines form a broken, irregular chain along both sides, and the pediment slopes stretch far out into the valley. The alluvial slopes here are relatively narrow and steep and are essentially continuous aprons formed of coalescing fans. Much wind-blown sand is present on the slopes (fig. 46), where it obscures surface features and interrupts drainage, so that only the larger tributaries reach the main wash. In spite of this covering the slopes are dissected by numerous gullies (fig. 47). Most of these terminate in alluvial fans, and whatever flow they carry sinks into the mantle of surface sand that becomes progressively thicker downstream.

The valley floor in this stretch is relatively narrow except where it broadens into local basins at the mouths of tributary drainages. It is noteworthy that every basin of any considerable size in the Black Mesa section of the wash has an extensive longitudinal fan in its upper end. There are several such basins in the upstream portion and one somewhat larger basinlike area at the mouth of Burnt Corn Wash. In the small basin along the Polacca Wash about 6 miles above the entrance of the Burnt Corn there is evidence of an old longitudinal alluvial fan that has given the valley floor a convex cross profile with marginal depressions. A large longitudinal fan has also been developed in the upper part of the basin formed at the mouth of Burnt Corn Wash (figs. 25 and 26). This distribution of longitudinal fans seems to indicate that before gullying began the Polacca contained a series of disconnected channels, each engaged in building a fan at its mouth. The location of the fans was probably determined by the low gradient of the basins, where spreading of the flow reduced the carrying power of the water and caused deposition of the load. Only exceptionally prolonged and widespread rains gave run-off sufficient to "run through" and carve a channel completely across the basin flats.

At many places in the deeper canyons of the Black Mesa section of the Polacca and along the southern margin of the Mesa large masses of the cliff, tens of feet to many hundreds of feet in length, have broken loose and have slid downward. This process is characteristic of areas where massive rocks such as the Mesaverde overlie the Mancos shale or other weak beds (54). Movement may be sudden or fairly slow, and displacement is generally small compared with the size of the block. The rock mass moves downward as a

FIGURE 16.—Sand dunes on the pediment slopes and valley floor about 7 miles above Polacca village.

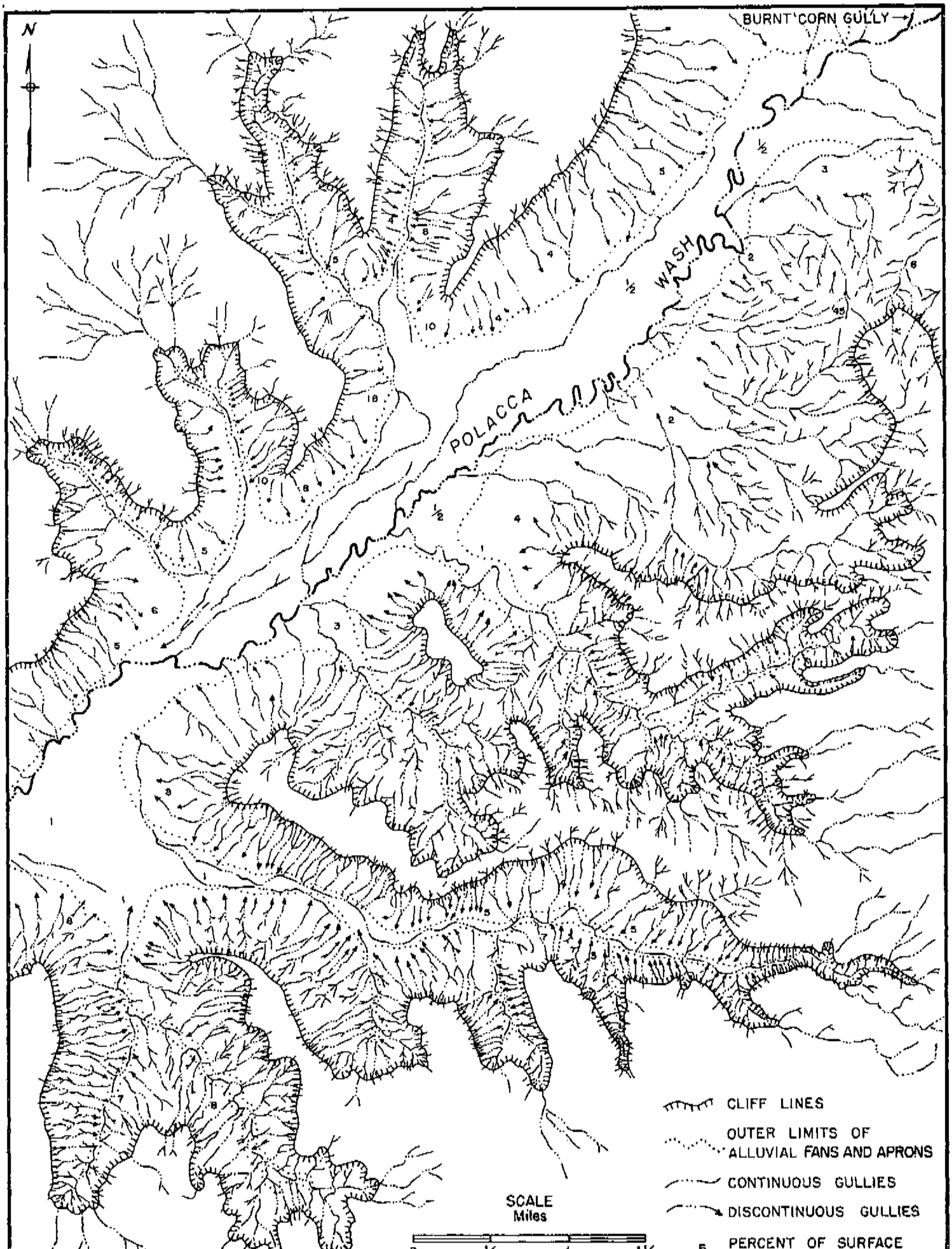


FIGURE 47.—Physiographic map of the Polacca Wash drainage from the mouth of the Burnt Corn downstream for 7.5 miles. The main, Polacca Gully, the secondary gullies in the tributary canyons, and the minute network of lateral gullies on pediment and fan slopes are shown.

(Faces p. 78)

unit or as several subsidiary units and rotates backward, sometimes as much as 50° or 60°, on an approximately horizontal axis parallel to the cliff from which it descends (fig. 48). Such movements usually are known as slumps (*93, pp. 65–68*), but owing to their abundance in the Navajo-Hopi country the local term Toreva-block, from the Hopi village of Toreva about 5 miles west of Polacca (fig. 25), has been applied to them by Reiche (*85*). Many of the blocks are more than 1,000 feet long, and some exceed 1,700 feet. In places, successive slumps from the same cliff have produced series of steplike rock benches.

That the process has been long continued is shown by the varied stages of disintegration of the blocks, by the location of man-made structures, and by accounts of local inhabitants. Ruins of thirteenth- and fourteenth-century pueblos on the crests of two of the largest and nearly last-formed slump blocks of a series near Chimopovi indicate the age of some of the movements. More recent slumps are known to have occurred near the Chimopovi Day School, about 1870, and approximately 6 miles north of Black Mountain Store in 1927 (*85, pp. 547–548*).

Where large slump blocks are abundant they add considerably to the available flat or gently sloping land in the pediment zone. The shallow sag between the displaced block and the parent cliff is a favored site for Navajo hogans. This may be attributed partly to the moderately good vegetal cover (usually grass and some sagebrush, indicative of favorable soil and moisture conditions), to protection from the wind, and to springs that issue nearby at the base of the slump blocks.

TUSAYAN WASHES SECTION

In the Black Mesa section of the Polacca (pp. 72–79) the longitudinal profile of the wash closely parallels the southwesterly dip of the Cretaceous rocks into which it has been cut. Evidence of this is noted in the uniformity of height of the cliffs along the valley and in the absence of bedrock outcrops in the wash except on the limbs of the anticline about 5 miles below the mouth of Red Canyon (fig. 25).

In the lower half of its course to the Little Colorado, instead of paralleling the dip of the geologic structure the wash cuts through the underlying rocks at a low angle, and the more resistant beds outcrop either in the bed of the wash or along the valley flanks, or both. Local steepening of the stream gradient and confining of the valley between low cliffs of the outcropping formations results. In localities where soft rocks formerly outcropped, erosion has worn them back to form broad basins, the size of which depends on the thickness of the soft beds. The schematic profile in figure 35 shows graphically the relation of the geologic formations to the stream profile.

The upper part of the Tusayan Washes section is a transition from the narrow valley above into the basin formed along the southern edge of Black Mesa. The confining cliff lines diverge rapidly, as the Polacca enters this broad basin. Keams Canyon Wash joins Polacca Wash from the east at the northeastern end of this section, and Wepo Wash enters from the north about 7 miles farther down the valley.

FIGURE 48.—Close view of a large slumped block of Mesaverde sandstone northeast of the mouth of Burnt Corn Canyon. The block has moved from left to right and has rotated to tilt steeply toward the cliff from which it was derived.