EROSION AND SEDIMENTATION IN THE PAPAGO COUNTRY, ARIZONA,

WITH A SKETCH OF THE GEOLOGY.

By Kirk Bryan.

INTRODUCTION.

The Papago country, as the term is used in this paper, is a region of about 13,000 square miles in southwestern Arizona. As shown on Plate IX (in pocket), it is bounded on the north by Gila River, on the east and west by Santa Cruz and Colorado rivers, respectively, and on the south by the boundary between the United States and Mexico. It is a part of the vast region of northern Sonora and southern Arizona which was known to the early Spanish explorers as the Pimería Alta, but which later, when the Spaniards came to distinguish the Papagos or nomadic agriculturists of this region from the more sedentary Sobaipuris and Pimas of the Santa Cruz and Gila valleys, they called the Papagueria.

The mean annual rainfall of the Papago country ranges from 3½ to 11 inches. The mean annual temperature at Tucson is 67° F. and at Yuma 72° F. The mean temperature at Ajo in 1919 was 70° F. The small rainfall and high temperature with consequent excessive evaporation combine to make the region one of the driest parts of the United States, and much of it is, in fact, true desert. The climatic conditions have produced a striking assemblage of plants, in which large cacti, numerous trees, and woody shrubs are characteristic.[1] This arboreal desert has a deceiving verdure that is in great contrast to the scarcity of watering places.

The broad expanse of desert has a characteristic topography. Small and large groups of mountains are separated by broad basins or valleys. The mountains are so arranged that the valleys have a general north-south trend, but the parallelism of the ranges is by no means so complete as indicated on earlier maps. From the southeast corner, near Nogales, where the valleys have elevations that range from 3,200 to 3,500 feet, there is a general slope to the north

[1] MacDougal, D. T., Botanical features of North American deserts: Carnegie Inst. Washington Pub. 99, 1908. Spaulding, V. M., Distribution and movements of desert plants: Carnegie Inst. Washington Pub. 113, 1909. Mearns, E. A., Mammals of the Mexican boundary of the United States, part 1: U. S. Nat. Mus. Bull. 56, 1907.

and west, each valley to the west being lower than that to the east, until on the western edge of the region the Yuma Desert, bordering Colorado River, has a general elevation of 250 feet.

The field work of which the present paper is a by-product was begun September 4 and continued to December 23, 1917. The primary object of the investigation was to prepare a guide to the desert watering places of the Papago country.

To the intelligent and observing traveler the surface features of a desert region like the Papago country are a constant source of enjoyment and interest. The bold slopes of the mountains, brown and desolate if composed of schist or gneiss, variegated, cliffed, and pinnacled if composed of thick and massive lava flows, present a remarkable contrast to the generally smooth and verdant slopes of mountains in more humid lands. The broad plains, which support orchard-like forests of strange trees and cultivated fields yet contain no watering places, impress him with the majesty and mystery of the desert. These land forms, interesting in themselves and exercising complete control over the lives of the Papagos and the movements of travelers, are the result in large part of processes peculiar to a desert region. The object of this paper is to describe these land forms and to discuss their probable mode of origin. The rock framework is briefly described in a sketch of the geology of the region in order to form a setting for a discussion of processes that have been active in the production of the desert landscape.

The investigation was conducted under the direction of O. E. Meinzer, geologist in charge of the division of ground water, and to him the author is indebted for a free hand in developing the problems discovered in the course of the work. C. P. Ross, who conducted a similar investigation north of Gila River, has cooperated harmoniously along an extensive boundary line. C. G. Puffer, field assistant, contributed largely to the success of the work by his ability to make desert travel easy if not luxurious. The writer is indebted for generous criticism to Dr. H. H. Robinson and Prof. Chester R. Longwell. M. R. Campbell and other members of the physiographic committee of the United States Geological Survey have been most helpful in the critical reading of the text.

GEOLOGY.

STRATIGRAPHY.

The rocks of the Papago country consist of pre-Cambrian schist, gneisses, and intrusive rocks, Paleozoic limestones and quartzites,

[2] Bryan, Kirk, Routes to desert watering places in the Papago country, Ariz.: U. S. Geol. Survey Water-Supply Paper 490–D, 1922; The Papago country, a geographic, geologic, and hydrologic reconnaissance: U. S. Geol. Survey Water-Supply Paper — (in preparation; contains detailed descriptions of the mountains and valleys).

Mesozoic clastic rocks and granitic intrusives, Tertiary conglomerates and volcanic rocks, and Quaternary alluvium.

The pre-Cambrian rocks are a basal complex whose history is as yet unraveled and which is separated by a great unconformity from the succeeding rocks. The Paleozoic rocks now exist as scattered patches infaulted into the pre-Cambrian or embedded in later Mesozoic intrusive rocks. The Mesozoic clastic rocks are arkosic sandstones and shales, which are separated from the Paleozoic limestones and quartzites by an unconformity. The Mesozoic igneous rocks occupy large areas, but the granitic intrusives and more or less metamorphosed lava flows are not easily distinguished from the pre-Cambrian, and the undifferentiated rocks of both ages are referred to as the crystalline complex. The Tertiary conglomerates and lava flows are separated from all the rocks previously formed by an unconformity that represents a desert surface in the old age of erosion. The pre-Tertiary and Tertiary rocks form the mountains and hills, but in the valleys lies a great mantle of alluvium, composed of débris derived from the destruction of the older formations. The general distribution of these rocks is shown on the geologic map (Pl. IX) and is more particularly described below.

PRE-CAMBRIAN BASAL COMPLEX.

The pre-Cambrian rocks of the region form a highly metamorphosed complex consisting largely of schists and gneisses. No sequence of pre-Cambrian sedimentary rocks such as have been found north of Gila River[3] has yet been determined, but doubtless some of the schists and gneisses are metamorphosed sedimentary rocks. In the northern part of the Salt River Mountains the complex is mostly chloritic schist. In the Sand Tank Mountains chloritic schists have been feldspathized, and there are many transitions from schist to gneiss. Fine-grained biotite granite and phyllite occur also. The northern parts of the Gila Mountains are composed mostly of coarse biotite granite and micaceous and hornblende schist and gneiss. As noted by Blake,[4] near the Fortuna mine the schistosity dips 45° to the south and west and is very even and regular. There hornblende schist predominates, and parallel to the schistosity are quartzose beds in which gold occurs. Blake noted also feldspathic dikes that intersect the schistosity and seem to be connected with great intrusions of pinkish granite, which form the higher peaks.

The older gneisses, which are of pre-Cambrian age, in many localities have a very definite sheeting that divides them into layers from

[3] Ross, C. P., Geology of the lower Gila River region, Ariz.: U. S. Geol. Survey Prof. Paper 129, pp. 153–181, 1922.

[4] Blake, W. P., Geology of the Gila Range: Governor of Arizona Rept., 1898, p. 25.

2 to 4 feet thick. Such gneisses, which are easily distinguished from the later intrusive rocks of supposed Mesozoic age, were observed near Tule Tank, in the Cabeza Prieta Range, and in the Baker Peaks, Sierra Blanca, and Coyote Mountains. In the Coyote Mountains the almost perfect sheeting controls the erosion of the mountain, which has the topographic form of a monoclinal block of sedimentary rock.

PALEOZOIC ROCKS.

The Paleozoic rocks occur in two situations—as plates or blocks resting on the eroded surface of the pre-Cambrian complex, or as blocks more or less engulfed and metamorphosed by later intrusions.

In the western part of the Tucson Mountains, beneath a blanket of lava, mostly Tertiary rhyolite,[5] lie limestone and quartzite of Cambrian and Carboniferous age.[6] At Snyders Hill, just west of Robles Pass, blue limestone has been quarried for burning lime, and also for road metal. Fossils collected at this locality have been identified by G. H. Girty as follows:

Zaphrentis? sp.
Pustula aff. P. porrecta.
Productus aff. P. subhorridus.
Rhynchopora? n. sp.
Squamularia perplexa.
Composita mexicana.

Mr. Girty considers that this fauna is probably younger than that found at the Vekol mine and indicates upper Pennsylvanian, perhaps even Permian time.

South of this locality, on the east side of the Sierrita Mountains, limestones and shales, partly metamorphosed and containing copper, occur at Mineral Hill and Twin Butte.[7]

The ore deposits of Silver Bell occur in blocks of limestone embedded in post-Paleozoic intrusive rocks.[8] In the near-by Silver Bell Mountains Tolman [9] found 3,700 feet of alternating quartzite, shaly quartzite, and limestone, of which the massive limestone contains Carboniferous fossils.

North of Pozo Blanco, at the east foot of the Sierra Blanca, the galena ore of the Black Prince mine is found in blocks of blue lime-

[5] Tolman, C. F., The geology of the vicinity of the Tumamoc Hills: Carnegie Inst. Washington Pub. 113, p. 76, 1909.

[6] Blake, W. P., Geologic sketch of the region of Tucson, Ariz.: Carnegie Inst. Washington Pub. 99, pp. 45–68, 1908. Jenkins, O. P., and Wilson, E. D., A geological reconnaissance of the Tucson and Amole mountains: Arizona Univ. Bur. Mines Bull., Geol. Ser., No. 2, p. 11, 1920.

[7] Blake, W. P., op. cit., p. 53.

[8] Stewart, C. A., The geology and ore deposits of the Silver Bell mining district, Ariz.: Am. Inst. Min. Eng. Trans., vol. 43, pp. 240–290, 1913.

[9] Tolman, C. F., Copper deposits of Silverbell, Ariz.: Min. and Sci. Press, vol. 99, pp. 710–712, 1909.

stone which, with some red shale, are embedded in intrusive rocks. No fossils were found at this locality.

The northern part of the Vekol Mountains consists of a monocline of limestone, quartzite, and shale, extending from the Vekol mine to the Reward mine. These sedimentary rocks rest on a basal complex of schist, granite, and diorite and have been faulted and intruded by granitic masses and later siliceous porphyry dikes and plugs.[10] On the south side of the monocline, near the Vekol mine, fossils were collected in three lots from a thickness of about 200 feet of thick-bedded gray limestone. The surface of this limestone is marked by brown siliceous concretions, and the lower beds are cherty. Near the mine the same limestone is red. The fossils were submitted to G. H. Girty, who reports the following combined list:

Cladochonus sp.
Campophyllum torquium.
Rhombopora lepidodendroides.
Schizophoria? sp.
Chonetes verneuilianus.
Productus semireticulatus.
Marginifera splendens.
Spirifer cameratus.
Spirifer rockymontanus.
Composita subtilita.

Mr. Girty states that the beds are "Pennsylvanian, apparently lower Pennsylvanian." They thus correspond in age to the lower part of the Naco limestone of the Bisbee district.[11]

About 14 miles northwest of the Vekol mine and 3 miles east of Stouts Well is a small hill composed of massive gray limestone, which dips gently to the southeast. About 100 feet of limestone is exposed. This mass appears to be an infaulted fragment of the great limestone series exposed in the Vekol Mountains. A few fossils were collected and submitted to Edwin Kirk, who reports as follows:

There are no determinable fossils in the lot that definitely fix the stratigraphic horizon. The crinoid fragments, however, are of such a nature that they could not be older than Devonian nor younger than Carboniferous. There is little doubt in my mind that the material is of Carboniferous age.

West of this hill only one other outcrop of limestone was found. At the east side of Growler Pass is a high, irregular hill composed of limestone and quartzite which appear to have been mashed and the limestones later silicified. Because of this alteration fossils seem to be rare, and none were found by the writer in the short time available.

The remnants of Paleozoic rocks occurring at widely scattered places in the Papago country indicate that the Paleozoic seas were

[10] Higgins, Edwin, Vekol copper deposits (Pinal County, Ariz.): Eng. and Min. Jour., vol. 91, pp. 473–474, 1911.

[11] Ransome, F. L., Some Paleozoic sections in Arizona and their correlation: U. S. Geol. Survey Prof. Paper 98, p. 148, 1916.

limited on the west by land. The Cambrian and Devonian rocks extend no farther west than the Santa Rita and Tucson mountains; the later Paleozoic (Pennsylvanian) has a wider extent. Earth movements following the Paleozoic era, with consequent erosion, contributed the clastic materials that now form the Mesozoic sedimentary rocks and destroyed a large part of the previously deposited Paleozoic rocks. Similarly uplift and subsequent erosion which were incident to the Mesozoic period of igneous activity further diminished the volume of Paleozoic rock, which now forms isolated blocks that are separated by great distances and are preserved largely because they are infaulted and protected by other formations.

MESOZOIC ROCKS.

SEDIMENTARY ROCKS.

In the Santa Rita and Patagonia mountains, small portions of which are shown on the geologic map (Pl. IX), Schrader and Hill found a great series of shale, sandstone, and conglomerate, with calcareous layers, aggregating about 6,000 feet in thickness.[12] Fossils found in a thin-bedded arenaceous limestone near Mowry indicate, according to T. W. Stanton, that the beds are of Lower Cretaceous (Comanche) age. Because of faunal and lithologic similarities Schrader[13] considers that the Mesozoic rocks of the Santa Rita and Patagonia mountains are equivalent to the Comanche series ("Bisbee group") of the Bisbee quadrangle.[14] At Bisbee there are numerous beds of limestone with a well-developed marine fauna. In the Patagonia region, however, the calcareous layers are few, and the greater part of the beds are red sandstone and shale.

What seem to be the same rocks are found in the Tumacacori Mountains. Just east of the Montana mine is a great mass of red sandstone, conglomerate, and shale, dipping to the west at high angles and unconformably overlain by tuff. Both east and west of Arivaca are red and green shales with incipient slaty cleavage, which may be part of the same formation. Red sandy shale and arkosic gray sandstone of a total thickness of 2,140 feet, attributed to Mesozoic time, have been found in the Tucson Mountains.[14a]

West of the Tumacacori Mountains red shale and arkose sandstone were seen at Agua la Vara, faulted against the gneiss of the Coyote Mountains, and again at Pozo Blanco associated with the limestone

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[12] Schrader, F. C., and Hill, J. M., Mineral deposits of the Santa Rita and Patagonia mountains, Ariz.: U. S. Geol. Survey Bull. 582, p. 53, 1915.

[13] Idem, p. 53.

[14] Ransome, F. L., The geology and ore deposits of the Bisbee quadrangle, Ariz.: U. S. Geol. Survey Prof. Paper 21, pp. 51 et seq., 1904.

[14a] Jenkins, O. P., and Wilson, E. D., op. cit., p. 11.

already mentioned. In these small outcrops no fossils were seen, but it seems not unlikely, because of lithologic similarity, that they are westward remnants of the Mesozoic formations.

IGNEOUS ROCKS.

The igneous rocks which are thought to be Mesozoic are difficult to distinguish from the pre-Cambrian rocks without detailed study. In general they are characterized by lack of sheeting and gneissoid structure, and by the fact that many of the granitic types have both orthoclase and plagioclase feldspars.

In the Santa Rita and Patagonia mountains the Mesozoic igneous rocks, consisting of granite, granite porphyry, quartz monzonite, quartz diorite, aplitic and lamprophyric dike rocks, syenite, and gabbro, are intruded into the Paleozoic sedimentary rocks but nowhere cut the Mesozoic sedimentary rocks. The period of igneous intrusion is therefore thought to be pre-Cretaceous, or at the latest very early Cretaceous.[15]

At Silver Bell the Mesozoic intrusive rocks consist of alaskite, alaskite porphyry, biotite granite, andesite, and quartz porphyry.[16]

In the Sierra Estrella Schrader found biotite granite, granitic aplite, and pegmatite, which intrude older gneisses and schists. In the Sacaton Mountains he found mica diorite similarly intruded. These rocks he considers Mesozoic.[17]

The copper ores of Ajo occur as disseminated deposits in monzonite, or as vein deposits in rhyolite lava and tuff into which the monzonite is intruded.[18] These two types of rock make up the eastern portion of the main part of the Little Ajo Mountains and are older than the conglomerate of the Ajo Peaks and the lava flows of Black Mountain. Older gneiss and schist which resemble the pre-Cambrian complex form the western part of the mountains. The igneous rocks that contain the ores, both the monzonite and the rhyolite, into which the monzonite is intruded, seem, because of their lack of intense dynamic metamorphism and their relation to the older crystalline rocks, to belong to the Mesozoic period of igneous activity.

In a number of localities in the Papago country were observed granitic and granitoid rocks containing both plagioclase and orthoclase feldspars, which probably belong to the same period of igneous activity. These localities are the Palo Verde Mountains, the mountains in the pass north of Table Top Mountains, the Maricopa Mountains near Estrella, O'Neills Hills, the Tule Mountains, and the

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[15] Schrader, F. C., and Hill, J. M., op. cit., p. 57.

[16] Stewart, C. A., op. cit., p. 246.

[17] Schrader, F. C., unpublished report on the Gila River Indian Reservation, Ariz.

[18] Joralemon, I. B., The Ajo copper-mining district, Ariz.: Am. Inst. Min. Eng. Bull. 92, pp. 2011–2028, 1914.

Tinajas Altas Mountains. Fractured and altered porphyritic felsite of pre-Tertiary age was seen in the Papago Saguaro National Monument north of Tempe and in Growler Pass

TERTIARY ROCKS.

SEDIMENTARY ROCKS.

The sandstone and conglomerate found at a number of localities in this region are thought to be of Tertiary age. The evidence for their age is not definite but consists in their stratigraphic position and their similarity to rocks in the lower Gila region that are associated with calcareous beds from which Tertiary fossils have been collected.[19] The close association of the conglomerate with the great sequence of lavas is probably the best evidence of its Tertiary age.

The beds included in this group are probably not strictly synchronous. Wherever their lower members were observed they rest on the eroded surface of the older rocks and are made up of angular débris derived from those rocks. In general the Tertiary sedimentary rocks are composed of coarse, poorly sorted arkosic material, such as is deposited by ephemeral streams in the same region to-day.

They are thus typical fanglomerates as defined by Lawson.[20] In some localities so much tuffaceous material is included that it is evident that they were deposited during the volcanic period. Outcrops of the rocks were studied at nine localities, which are shown upon the geologic map (Pl. IX). The beds range in thickness from 50 feet to more than 1,000 feet and are, without exception, dislocated and extensively eroded.

VOLCANIC ROCKS.

Distributed throughout the Papago country is a great series of volcanic rocks which range in chemical composition from siliceous rhyolite to olivine basalt. In some localities, as in the Sand Tank and Sauceda mountains, they formed a great mantle of flows and tuffs which almost completely buried all the preexistent rocks. In the Growler, Ajo, Sauceda, Quijotoa, and Sand Tank mountains the thickness of lava is commonly 1,200 to 1,500 feet and may reach 2,000 feet. In other localities the lava is thin or lacking, and in the Tumacacori Mountains tuffs predominate over lava flows. All these lavas have been dislocated and dissected. The dissected slopes merge with the mountain pediment (see pp. 52–53) or are buried in alluvium, and this characteristic indicates that all the lavas are probably older than the Pleistocene. In contrast to them the Pleistocene basalt lies on top of the alluvium in the valleys and is but little dissected.

[19] Ross, C. P., op. cit., pp. 188–190.

[20] Lawson, A. C., The petrographic designation of alluvial-fan formations: California Univ. Dept. Geology Bull. 7, pp. 325–334, 1913.

Most of the centers of eruption from which the Tertiary volcanic material emerged are either concealed by later flows or removed by erosion. Much of the lava may have been extruded from fissures, and volcanoes may never have been prominent features of the Tertiary landscape. However, Batamote Mountain has the form of a slightly dissected volcano, and the mountain south of Kaka appears also to be an old volcano.

The variety of rocks included in this series is illustrated by the work of Guild in the Tucson Mountains.[21] He found rhyolite, rhyolite tuff, biotite-hornblende andesite, pyroxene andesite, pyroxene-mica andesite, and several basalts.

In the Tumamoc Hills Tolman[22] found the following succession, beginning with the youngest: (1) Basalt flows and intrusions, (2) rhyolite tuff, (3) two basalt flows, (4) andesite flows. These rocks he considered to be of Pleistocene age, but because they are uplifted, faulted, and dissected they are here mapped with the Tertiary.

In the Santan Mountains Schrader[23] found 100 feet of olivine basalt overlying 200 feet of latite, which in turn rests on granite of the crystalline complex. These rocks increase in thickness toward the center of the Malpais Hills, in which they occupy an area of about 9 square miles. Basalt also occurs at Walker Butte and in Poston Butte and other outliers of the Santan Mountains.

South of the Salt River Mountains lies Jackson Butte, separated from the mountains by a plain more than 2 miles wide, mantled by alluvium. The top of the butte is a bed of agglomeratic vesicular basalt about 20 feet thick. The lower part of the butte, which is masked by a talus of large blocks of basalt, is composed of unconsolidated gravel and sand. There is no near-by source of the basalt, and it is possible that the gravel conceals the plug that occupies the neck through which the basalt rose. The gravel also is much less consolidated than most of the Tertiary formations. The basalt of Jackson Butte may easily be of early Quaternary age.

The same remarks apply equally to a somewhat similar outlier on the east side of the Maricopa Mountains 1 mile north of Estrella station (Pl. XIII, *B*). This outlier consists of two small hills capped with 20 to 30 feet of dull-red felsite, which rests on arkosic gravel that separates it from the underlying crystalline rocks. The felsite forms beds 2 to 3 feet thick, of which the upper one is full of holes, like a vesicular basalt. The holes, however, are probably not due to the expansion of gases while the rock was hot but to the solution by

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[21] Guild, F. N., Petrography of the Tucson Mountains, Pima County, Ariz.: Am. Jour. Sci., 4th ser., vol. 20, pp. 313–318, 1905.

[22] Tolman, C. F., Geology of the vicinity of the Tumamoc Hills: Carnegie Inst. Washington Pub. 113, pp. 67–82, 1909.

[23] Schrader, F. C., unpublished report on the Gila River Indian Reservation, Ariz.

weathering of some constituent of the rock. The gravel is similar to that of the present streams and is but a thin coating on an old surface of erosion that has been uplifted and now stands above the level of the adjacent pediment.

QUATERNARY DEPOSITS.

ALLUVIAL MATERIALS.

GENERAL CHARACTER.

The Pleistocene and Recent materials have been derived from the erosion of the present mountains and laid down by existing streams or their counterparts. The climate of Quaternary time has not been uniform, though doubtless it has been throughout of the arid type. Variations in climate may be assumed because of the known fluctuations throughout the world shown by the glaciation of large areas, and also because in Arizona there were permanent lakes where now there are only temporary lakes.[24] The fluctuations in this region were, however, not so great as to bring about a humid climate. The change was only in the degree of aridity.

Thus the deposits of the different stages of Quaternary time are similar to one another and vary chiefly according to their topographic position. Near the mountains ephemeral streams build up alluvial fans of coarse, poorly assorted gravel. Farther down the slopes the same streams deposit finer débris as sandy clay and fine gravel and sand. Near the middle of the valleys clay or sandy clay may predominate, though wind-blown sand and lenses of sand or gravel are also deposited, the material being dependent on the type of the axial stream. Thus if materials of one of the older Quaternary stages originally laid down near the mountains are exposed near recent deposits of streams at a distance from the mountains the contrast between the two deposits is great. But if deposits of the two stages were both laid down by essentially similar streams in corresponding portions of their courses they may be so similar that it is impossible to tell them apart. In general those beds of alluvial material which stand above the general level and are now being eroded are regarded as belonging to the earlier stages, and these beds are commonly cemented with caliche. Much larger amounts of the older deposits must be buried under the modern alluvial plains, however, and concerning these deposits little is known except such facts as are disclosed by well records.

The Quaternary deposits fall into three divisions—older alluvium, younger alluvium, and Recent deposits. These divisions can not be

[24] Meinzer, O. E., and Kelton, F. C., Geology and water resources of Sulphur Spring Valley, Ariz.: U. S. Geol. Survey Water-Supply Paper 320, p. 34, 1913.

definitely correlated with divisions of the Quaternary in other regions, however, nor can rigid application of these divisions be made within the Papago country.

OLDER ALLUVIUM.

The older alluvium is exposed at only a few widely separated localities, largely around the borders of the Papago country, though doubtless it lies buried beneath younger deposits in the greater part of the valley region.

Near Tucson red and partly cemented older alluvium is exposed near the base of the Santa Catalina Mountains at the mouth of Sabino Canyon. It is tilted and eroded, and on it rests the younger alluvium.[25] Field work by the writer in 1920 and 1921 indicates that this red material should be correlated with similar fanglomerates in the San Pedro Valley, which are of Pliocene age. Farther south, near Tubac, the bluffs along Santa Cruz Valley are doubly terraced, as shown in figure 23 and described on page 75. The gravelly deposits of the upper level seem to belong to the older alluvium; the lower terraces can be correlated with a part of the terrace and flanking stream-built slopes near Tucson. Similarly near Nogales the rock plains which border both Santa Cruz River and Nogales Wash, especially on their lower portions, are mantled with gravel. Near the streams these plains stand as bluffs about 150 feet high. The gravel that caps the bluff probably belongs to the older alluvium, whereas that on the rock bench about halfway down the bluff belongs to the younger alluvium.

On Gila River, east of the junction with the Salt, no outcrops of the older alluvium were found, but west of this point Ross[26] found only small areas of tilted gravel in the margins of the Gila Bend Mountains.

South of Wellton, lying against the northern border of the Wellton Hills, is a small tract of gravelly alluvium, which forms a plain about 50 feet above the alluvial slope. The slope is graded with respect to the base-level of the terrace about 100 feet above the flood plains at Wellton. The tract of alluvium is obviously older than the slope, and the slope seems to be of the same age as the terrace, which is regarded as part of the younger alluvium (p. 30).

North of Blaisdell and associated with an outcrop of red sandstone and clay of probable Tertiary age, is a deposit of gravel composed of rudely sorted materials with pebbles 1 to 2 inches in diameter in beds that dip about 10° W. The gravel has been bev-

[25] Smith, G. E. P., Ground-water supply and irrigation in the Rillito Valley: Arizona Univ. Agr. Exper. Sta. Bull. 64, pp. 89–90, fig. 57, 1910.

[26] Ross, C. P., op. cit.

eled and more or less concealed by the outwash from the north end of the Gila Mountains. This outwash was deposited when Gila River stood at the level of the terrace of younger alluvium, and therefore the tilted alluvium must be older than the younger alluvium. It is, however, closely associated with the red sandstone and clay, and further work may show that both are Tertiary or perhaps that both belong to the older alluvium.

In the interior valleys of the Papago country the older alluvium can be identified positively only in Altar Valley. In these valleys the mountain pediments have a thin coating of alluvium, part of which is still being augmented by streams, but some of it lies above the present streams and is partly consolidated. Along the axial stream and the main tributary of Altar Valley, however, it seems possible to distinguish the older alluvium, as is more fully discussed on page 73.

YOUNGER ALLUVIUM.

Along Gila River there is a more or less continuous terrace from Gila Bend to Yuma. This terrace, cut into promontories by tributary streams, stands about 75 feet above the river. The surface is mantled with a coating of pebbles, in places only one pebble deep. Below the pebbles the terrace is composed of alternating beds of sand, clay, and gravel very similar to those laid down by the present river. The terrace, therefore, represents a period of aggrading of Gila River, at the conclusion of which the river stood at least 75 feet higher than it does now. All the tributaries were adjusted to this grade, and consequently the stream-built slopes of the adjacent mountains of the interior valleys slope to the top of the terrace. The cutting down of Gila River to or perhaps below its present level changed the base-level of the tributary streams, which with increased grade have cut valleys through the terrace. This headward cutting has been very effective on some of the tributaries north of Gila River,[27] but the tributaries on the south have been too feeble to dissect to any large extent the valleys which they drain. (See p. 68.)

Near Ligurta, 7 miles east of Dome, fossil bones were found on two promontories of the terrace that project into the flood plain of the river. The bones lay on the surface as part of the layer of pebbles resulting from the erosion of the materials which form the terrace. Near the river underlying beds are exposed in the bluff and consist of brown sand, gravel, and sandy clay similar to material now carried by Gila River. The clay has round, smooth concretions 3 to 12 inches in diameter. The brown sand has also many concretions, but they are rough on the surface and irregular in shape.

[27] Ross, C. P., op. cit.

A small sliver of bone was found in place in the brown sand, so that the bones are undoubtedly derived from it and probably are inclosed in the concretions. The bones were probably transported some distance before deposition, but it seems most reasonable to assume that the animals died on the river flood plain during the period of deposition of the brown sand.

A small collection of these bones was referred to J. W. Gidley, who identified the phalanx of a horse (*Equus* sp.) and the basal portion of the antler of a deer probably belonging to the genus *Odocoileus*. According to Dr. Gidley, "These fossils do not determine the age more closely than that they are Pleistocene, though the presence of horse remains suggests one of the older phases of the Pleistocene." The importance of even this indefinite dating is great, for it affords the first positive evidence of the Pleistocene age of the gravel of Gila Valley and establishes a datum point for the complex sequence of events worked out by Lee[28] and Ross.[29]

In 1921 waterworn fragments of bone were found three-quarters of a mile east of Comobabi. (See map, Pl. IX.) At this locality the mountain pediment is developed on tilted fanglomerate similar to the Tertiary conglomerate of other localities. Resting unconformably on this conglomerate is a bed of gravel about 10 feet thick, which lies about 30 feet above present stream grades and perhaps belongs to the older alluvium. The gravel contains boulders of all sizes up to 3 feet in diameter and is similar to the channel gravels in the present streams. The upper 2 feet is thoroughly cemented with calcium carbonate (caliche). Below this part the cementation is less, and iron oxides are nearly as abundant as lime. The bones all occur in the lower 4 feet, and most of them were found in the lower 2 feet. The gravel was evidently deposited by the stream that eroded the pediment and presumably was deposited at or near the end of the period of erosion.

The fossils have been referred to J. W. Gidley, who reports as follows:

> In the lot of fragmentary remains obtained 55 miles west of Tucson the only determinable material consists of portions of three teeth representing the genus *Equus*. One of these, a nearly complete upper molar of the right side (catalogue No. 10443, U. S. Nat. Mus.), I refer provisionally to *Equus occidentalis*, a species described by Leidy in 1865,[30] from Tuolumne County, Calif. The specimens are too incomplete and the species too little known to make this determination positive, but in size and general characters the Arizona tooth agrees very closely with the type of the California species.

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[28] Lee, W. T., Underground waters of Salt River Valley, Ariz.: U. S. Geol. Survey Water-Supply Paper 136, p. 112, 1905; Geologic reconnaissance of a part of western Arizona: U. S. Geol. Survey Bull. 352, p. 67, 1908.

[29] Ross, C. P., op. cit.

[30] Leidy, Joseph, Acad. Nat. Sci. Philadelphia Proc., 1865, p. 94. Gidley, J. W., Am. Mus. Nat. Hist. Bull., vol. 14, pp. 14–16, fig. 10, 1901.

On the basis of this material no positive statement can be made regarding the possible age of the beds from which it came, for two reasons: First, although *Equus occidentalis* is usually considered a Pleistocene species, the fact, so far as Mr. Gidley is aware, has never been proved; second, there is no good reason why this particular species may not have found its way into the southwestern United States in Pliocene time and continued its existence there into the Pleistocene. It follows, therefore, that the paleontologic evidence regarding the age of the alluvium is at present of little value.

A small rodent jaw from Robles Well, on the Ajo road 25 miles west of Tucson, said to have come from a depth of 212 feet below the surface, Mr. Gidley has carefully studied and finds it can not be distinguished from similar jaws of *Neotoma albigulus*, a species of wood rat now living in that general region. He therefore concludes that it must have fallen into the well by accident from the surface.

The Gila Valley east of the Sierra Estrella is bounded by bluffs 25 to 50 feet high which, though not so high as those farther west, seem, like similar terraces on Salt River, to correspond to the 75-foot terrace of the lower part of the river.

Near Tucson a large part of the dissected stream-built slopes which terminate at the flood plain of Santa Cruz River belong to the younger alluvium. Farther south the lower terraces at Tubac and the gravel on the lower bench in the vicinity of Nogales may be correlated with it.

In the interior valleys the same difficulties of correlation exist for the younger alluvium as for the older alluvium. There are at a number of points, however, low terraces which probably belong with this formation. These terraces are described in the section on the valleys (p. 80), where such explanations as suggest themselves are offered.

RECENT DEPOSITS.

The Recent deposits comprise the sand and gravel in stream beds, the flood-plain deposits of the larger streams, and the deposits on the great flats of the interior valleys. These materials are all unconsolidated alluvium with minor amounts of wind-blown sand. They are more particularly described under the heading "Valleys," (p. 65).

BASALT.

Two flows of basalt covering extensive areas were poured out of low cones during Quaternary time. The great flow at Sentinel largely rests upon and protects the terrace of younger alluvium along Gila River and has been described by Ross.[31] The other large area

[31] Ross, C. P., op. cit.

lies in the southern part of the Tule Desert just west of Las Playas. It is a northern extension of the volcanic plateau surrounding the Sierra del Pinacate of Sonora and like that plateau appears to be of relatively recent geologic date. The volcanic character of the Sierra del Pinacate was first recognized by Father Eusebio Kino in his journey to the region in 1701.[32] A biologic exploring party under the leadership of D. T. MacDougal mapped and described the region in November, 1907. Godfrey Sykes made a map of the region, showing the boundaries of the lava fields and the position of the principal craters.[33] Lumholtz, whose explorations in southwestern Arizona and Sonora resulted in an excellent map, found a legend among the Papagos referring to eruptions and ash showers from the two higher peaks.[34]

The portion of the Pinacate lava flow which extends across the international boundary is a low mesa about 6 miles from north to south and 5 miles from east to west. The mesa rises from 50 to 100 feet above the Tule Desert, and this elevation seems to measure the thickness of the olivine basalt of which it is composed. The margins are but little dissected and seem to be near or at the original limits of the flow. Small cones and craters dot the surface. One of the cinder cones, a crescent-shaped ridge about 50 feet high, is composed of very fresh-looking reddish slag, much of which was thrown out still molten and fell in pasty masses. Volcanic bombs are numerous. Though the bombs seem very fresh, the under side, where they lie on the surface of the ground, is covered by a film of calcium carbonate obviously derived from the weathering of the bomb. This coating or patina is thicker than that found on Papago artifacts in the neighborhood and may indicate that the Pinacate flows of basalt do not belong within the period during which the Papagos have lived in the region. Some weight, however, may be given to Papago tradition with respect to Recent eruptions in the Sierra del Pinacate.

STRUCTURE.

FAULTING.

The compressive movements of pre-Cambrian time can be recognized by the mashed condition of schists and phyllites, but the evidence of later folding has throughout the Papago country been de-

[32] Bolton, H. E., Kino's Historical memoir of the Pimería Alta, vol. 1, p. 283, 1919. Kino also visited the Sierra del Pinacate in 1698 (idem, vol. 1, p. 187) and in 1706 (idem, vol. 2, pp. 205 et seq.).

[33] MacDougal, D. T., Across Papaguería: Am. Geog. Soc. Bull., vol. 40, pp. 705–725, maps 1 and 2, 1908. Hornaday, W. T., Campfires on desert and lava, map opposite p. 110, New York, 1908.

[34] Lumholtz, Carl, New trails in Mexico, p. 203, New York, 1912.

stroyed by erosion. The scattered masses of Paleozoic rocks were disturbed, dislocated, and in part engulfed in Mesozoic intrusions, but post-Paleozoic folding has not been recognized. The Mesozoic sedimentary rocks are much disturbed in the Patagonia region,[35] where there is evidence of post-Cretaceous folding, but whether this movement extended westward into the Papago country is not known. Profound erosion had left a landscape of mountains of considerable elevation prior to the Tertiary lava flows, but the method of uplift of these mountains is not clear.

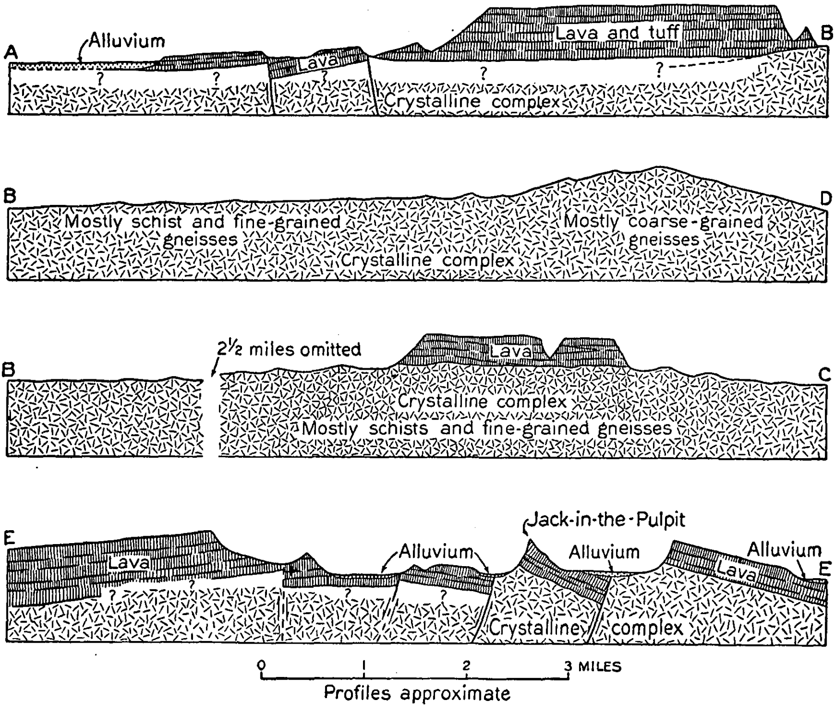


FIGURE 4.—Geologic cross sections in the western part of the Sand Tank Mountains, Ariz.

Faulting on a large scale, however, took place at the end of the Tertiary period of volcanism. To the movement which produced the faults of this period the present mountains owe their elevation, though there is evidence of Pleistocene movement along the same structural lines. The nature of the faults can best be illustrated by citing examples.

FAULTS IN THE SAND TANK MOUNTAINS.

The Tertiary lavas of the northwestern part of the Sand Tank Mountains are evenly bedded, and their whole thickness may be as much as 2,000 feet. The eroded surface of crystalline rocks appears

[35] Schrader, F. C., and Hill, J. M., op. cit., p. 77.

to have been fairly smooth, and consequently the lavas are immense plates of rock which, as at present broken by faults, resemble great flakes of ice stranded on a shore by the wind. Toward the east the lava flows are less continuous, the total thickness is more variable, and the individual fault blocks as revealed by the attitude of the lava plateaus stand out less clearly.

The faults are of the normal type and trend in two directions—north and east. The geologic map (Pl. IX) and the cross sections in

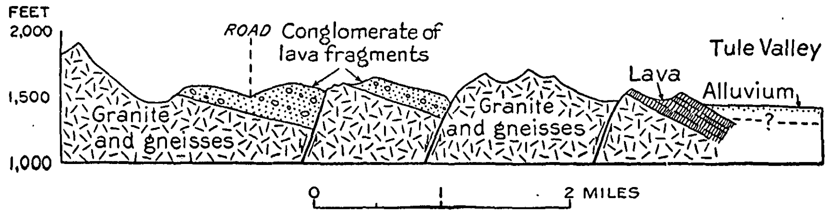


FIGURE 5.—Geologic cross section in the Tule Mountains, Ariz.

figure 4 show the effect of faulting on the distribution of the lavas and in the topography. Sections A–B, B–C, and B–D are arranged on a Y of which A–B is the stem. The faults shown in section A–B trend west of north and are marked by valleys. Along section B–D no lava appears, but a mountain of coarse-grained gneiss stands above the lavas which once covered it, at least in part. Along section B–C a lava plateau that has been uplifted, perhaps, but not tilted still resists erosion. Section E–E, at right angles to section A–B, shows the effect of the faults that have an easterly trend. Tilting of the

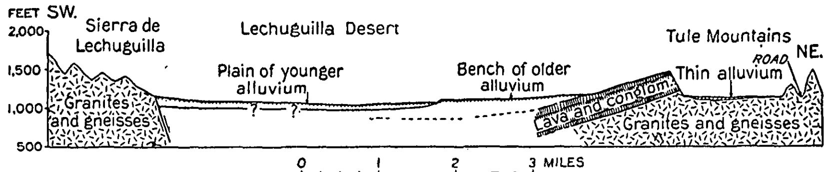


FIGURE 6.—Geologic cross section of the southern part of the Lechuguilla Desert, Ariz.

fault blocks is much more marked, and the underlying crystalline rocks are brought to the surface at the base of Jack-in-the-Pulpit and the plateau south of it.

FAULTS IN THE TULE MOUNTAINS.

In the pass southeast of Tule Well block faults are well shown by the tilted lavas and lava conglomerate which rest on a relatively smooth plain composed of the crystalline complex. The cross section in figure 5 brings out the character of these faults. On the west side of the same range and south of the road a great plate of lava and lava conglomerate about 750 feet thick dips westward under the Lechuguilla Desert (fig. 6). The contact with the crystalline complex is exposed along the eastern face of the ridge. Hills several hundred feet high project up into the lava and indicate the local irregularity of the surface over which the lava flowed. North of the road what seems to be the same lava caps the mountains at an elevation about 1,000 feet higher. (See Pl. XI, *B*.) As shown in figure 6, the westward-dipping block of lava is bordered by a bench of alluvium about 50 feet above the level of the main Lechuguilla Desert. This bench of older alluvium indicates renewed uplift of the Tule Mountains in Pleistocene time, probably accompanied by faulting along the east front of the Lechuguilla Mountains. On physiographic evidence the Tinajas Altas Mountains, near by, are thought to have been reelevated in Pleistocene time.[36]

FAULTS IN THE GROWLER MOUNTAINS.

The portion of the Growler Mountains north of Growler Pass is a rather simple monoclinal fault-block mountain trending northwestward and about 20 miles long. In the picturesque western escarpment are exposed between 1,200 and 1,500 feet of Tertiary lava, tuff, and conglomerate resting on the crystalline complex, which crops out in places at the foot of the mountain front. The eastern slope is gentle, almost without canyons, and conforms to the dip of the lava sheet.

In Growler Pass there are at least five faults that trend almost due north, but the intervening blocks are rotated in different directions. In the easternmost block the beds are horizontal. In the others the dips are easterly in two and westerly in two. The complex structure of Growler Pass continues in the southern part of the Growler Mountains, which consist of large lava plateaus, separated from one another by narrow canyons. The beds in each plateau dip at a different angle or in a different direction from those in neighboring plateaus, so that there must be a complicated system of faults.

GENERAL CHARACTER OF THE MOUNTAINS.

The mountains of the Papago country consist either of more or less isolated elevated regions separated by broad valleys underlain by alluvium, or of groups or chains of mountains separated by rather narrow alluvium-filled valleys or canyons. To the traveler crossing the country on the Southern Pacific Railroad the ranges appear to be rather monotonous in their characteristics, showing a recurrent sameness which implies a common geologic history. They seem to consist wholly of small detached sierras having very similar topographic forms, composed of granite and other coarse-grained crystalline rocks, and to be largely buried in alluvium. This appearance,

[36] Bryan, Kirk, Origin of rock tanks and charcos: Am. Jour. Sci., 4th ser., vol. 50 p. 199, 1920.

however, is the result of the accidental distribution of certain types of ranges along the route of travel. A further exploration of the Papago country shows that many of the mountains are capped with lava beds much younger than the granite and crystalline rocks already mentioned and have the typical fault-block form common to the ranges of Nevada. Other ranges consist of exceedingly complex plateaus, peaks, and pinnacles, generally carved from thick lava beds. The ranges are thus by no means uniform in their rock composition and topography and they may be separated into groups according to their composition and structure. There are 70 mountain ranges and groups of hills in the Papago country,[37] and 11 more that lie east of Santa Cruz River are represented on the geologic map (Pl. IX). Of these 81 ranges 17 can not be described, because they have not yet been sufficiently explored. Of the remaining 64 ranges 2 are old volcanoes; 12 are rather simple fault-block or horst mountains, composed mostly of lava beds; 11 are similar faulted mountains of more complex structure; 21, composed mostly of pre-Tertiary rocks, have large or small areas of Tertiary rocks so disposed that they show that the mountains have been elevated since the Tertiary volcanic period, and many of them were already in the old-age stage of erosion when the Tertiary deposits were laid down and have been revealed by removal of the cap, as well as rejuvenated by uplift; 18 ranges are not known to have outcrops of Tertiary rocks, but at least two of them, the Tinajas Altas Mountains and Sierra Estrella, have been reuplifted in Pleistocene time.

PHYSIOGRAPHY.

INFLUENCE OF ARIDITY.

Erosion and sedimentation, the active geologic processes of the Papago country, are affected in their degree, methods, and results by the intense aridity of the region. Temperature and insolation vary but little, but with respect to average annual precipitation the Papago country may be divided into three parts. West of the Growler Mountains the annual precipitation ranges from 3½ to 5 inches; between the Growler and Baboquivari mountains it ranges from 5 to 10 inches; east of the Baboquivari Mountains it is more than 10 inches, although not much more except in the Tumacacori Mountains. Though precipitation increases with altitude, the smaller mountains, averaging 2 to 4 miles in width and 1,000 to 1,500 feet in height, appear to have little effect on storms, and their vegetation does not indicate any large increase in effective rainfall over

[37] Bryan, Kirk, Geology and physiography of the Papago country, Ariz. (abstract): Washington Acad. Sci. Jour., vol. 10, pp. 52–53, 1920. Different figures are given because a smaller area was included in the "Papago country."

that of the adjacent plains. This is particularly true in the area west of the Growler Mountains. The mountainous district including the Sand Tank and Sauceda mountains probably receives a somewhat greater precipitation than the adjacent plains, as indicated by gramma grass and a slightly more luxuriant vegetation at the higher altitudes. In the same way greater precipitation on the Baboquivari Mountains is shown by scattered live oaks and other small trees not characteristic of the plain. Increase of rainfall due to increase of altitude is best shown in the Tumacacori Mountains, where there are orchard-like forests of live oak and a thick cover of perennial grasses. Even here the ease with which soil is formed on tuffaceous rocks and the consequent slow run-off may have as great an influence in producing the relatively heavy vegetative cover as increased precipitation.

MOUNTAIN SCULPTURE.

MOUNTAIN SLOPES.

The mountains of the Papago country rise from the surrounding plain with startling abruptness. To the traveler approaching them the mountain slopes stand like a wall, without transition from the plain on which he travels.[38] Only in a distant view is it possible to realize that the surrounding plain rises gradually on all sides toward the mountains, which stand up like jagged ornaments on the ridge-pole of a low-gabled roof.

This appearance is due to contrast in angle of slope between the mountains and the plain. The angles of the mountain slopes range from 15° to almost 90° with the horizontal; those of the plain from 1° to 6°. Between these slopes there is usually no region of transition, either of intermediate slopes or of low foothills. In many ranges slopes that average 25° to 30° rise directly from the plain to the crest of the mountains. The factors which produced the mountain slopes must then differ radically from those which produced the plain.

CONDITIONS DETERMINING MOUNTAIN SLOPES.

Mountains composed of rock of any one type have a relatively constant angle of slope, either at the mountain border or in the side walls of canyons. Even small isolated hills have similar slopes. These conditions have been stated by Lawson[39] as follows: "(1) That the hard-rock slopes of desert ranges which shed large spalls are steep, while those which shed small fragments have a low angle;

[38] Hornaday, W. T., op. cit., pp. 38–39 (a humorous statement of these facts).

[39] Lawson, A. C., The epigene profiles of the desert: California Univ. Dept. Geology Bull., vol. 9, p. 29, 1915.

(2) that ranges composed of hard rock, which are thus naturally steep, maintain their steepness as long as the rock slopes endure."

The resistance of rock to weathering is the dominating condition which determines the angle of slope, but the presence of large spalls is only one of the results of resistance to weathering, though in many types of rocks there is a significant relation between the size of spalls and the angle of slope, as noted hereafter. Resistance of rock to weathering seems to be divided into two phases—resistance to the detachment of large blocks and resistance to direct weathering into small particles. Both kinds of resistance involve mechanical and chemical processes of weathering, but in the Papago country, because of the arid climate, mechanical processes are dominant.

MECHANICAL PROCESSES OF EROSION

The mountain slopes are ordinarily barren of soil, the bedrock presenting an uneven surface, the lowest parts of which are covered by a layer of broken rock fragments but recently parted from the parent rock. The projections of the bedrock are large or small, according to the spacing of joints. Weathering proceeds along the joint planes, and the projections tend to be detached and then lie on the surface as blocks or boulders or, as Lawson speaks of them, "rock spalls." In many places the surface is completely mantled by blocks and boulders. The production of blocks of this character is accomplished in part by the weakening of cement and widening of joints by solution but largely by expansion and contraction of the rock under the influence of changes in temperature.

Daily as well as seasonal changes are very large, the mean daily air temperature in January, the coldest month, being 54.7° and that in August, the warmest month, being 90.1°. At mid-day the temperature of the soil and rock is frequently higher than that of the air, whereas at night the rock cools nearly to air temperature.

The depth to which changes in temperature are effective in disrupting rock can only be estimated. The water of wells dug wholly in rock has the temperature of the surrounding rock, from whose crevices and seams it seeps. Water standing only 59.5 feet from the surface in Al John's well at Gibson, on the east flank of the Little Ajo Mountains, had a temperature of 67.5° on October 10, 1917, and doubtless represents the mean annual air temperature for that locality, as it is only 1.6° below the mean annual air temperature at Ajo for the years 1915 to 1918. In the vicinity of this well seasonal changes of temperature do not penetrate perceptibly below 60 feet. However, the well is in an interstream area of gently rolling country, and it is not unlikely that on the crests of the ridges insolation is effective to greater depths. In the valleys, where the water table is nearer the surface, the reverse is probably true and insolation is effective to depths of about 25 feet, the depth at which water ordinarily stands in wells.

The daily changes in temperature produce effects much more striking and probably more effective in the breaking up of rock than seasonal changes. The effects may be summed up under three heads—rupture and spalling, exfoliation, and granular disintegration.

Rupture appears to be due to the expansion of rock under the influence of a rise in temperature beyond the elastic limit of the material, doubtless followed by sudden cooling as suggested by Walther.[40] It is most often observed in fine-grained brittle rock, such as siliceous lava. The action affects blocks of rock lying loose on the surface which are from 1 to 2 feet through in the direction of minimum thickness. The rupturing takes place on sharply defined but irregular planes and apparently in a single action, for the broken surfaces, though all manifestly younger than the exterior of the block, have a uniform color, corresponding to the time they have been exposed to the weather, but show no marks of weathering along initial cracks. Similar rocks suffer also from the spalling off of slivers, which in many places are scattered about like the quarry refuse left by Indians in making stone arrowheads. Though this process is most easily observed in loose blocks of rock, it undoubtedly affects the bedrock also, and thus in its ultimate effect it grades into exfoliation and serves to break up the plates formed by that process.

Exfoliation is a process by which successive surface sheets of rock are parted from the underlying mass. The surface of a rock mass, being in contact with the air, changes in temperature from hot to cold or from cold to hot more rapidly than the interior. As a consequence of the resultant changes in volume, the surface shell is either too large or too small for the interior. Shearing strains are set up between the shell and the interior and a crack forms. The thickness of the shell varies according to the area and form of the surface exposed to the air and the texture of the rock. When first exposed to this process rock masses are commonly angular and bounded by joint planes. The first places attacked are the corners and edges, where heat is most readily absorbed and radiated. The first parting plane is commonly 3 to 4 inches below a corner and thence approaches the surface in all directions, so that the first fragment to break off is a four-sided piece whose lower surface is concave. With the splitting off of successive sheets, each of which is slightly thicker at the protuberances of the rock, the remaining mass approaches a spherical shape. In the Papago country exfoliation sheets from one-fourth of an inch to 2 inches thick have

[40] Walther, Johannes, Das Gesetz der Wüstenbildung, p. 29, Berlin, 1900.

been observed on granite, from an inch to 2 feet thick on arkosic conglomerate, and of almost paper thinness on certain felsitic lavas. To exfoliation may be attributed the rounded bosslike forms that occur on most outcrops of the Tertiary arkosic conglomerates. Figure 11 (p. 50) shows the relation of these curved surfaces to joints, and the hill on the right in Plate X, *A*, shows both the bosslike surfaces and the niches mentioned on page 50.

Exfoliation sheets from 6 inches to 2 feet or more in thickness are recognized only on rocks that have few joints and very massive structure. It seems likely that these sheets are produced by seasonal changes in temperature. In rocks with more closely spaced joints yielding takes place along existing fractures or by the reopening of older lines of weakness. Thus in such rocks the curved forms of exfoliation are not produced.

Granular disintegration is due to the unequal rates of expansion of different minerals whereby a rock composed of more than one mineral is subject to internal strains with every change in temperature. These strains tend to separate the different mineral grains one from another and thus to reduce the rock to a loose rubble. The process is best observed in coarse-grained granite and is probably the most effective type of weathering in this rock.

CHEMICAL PROCESSES OF EROSION.

The freshness of rock débris, the lack of soil, and the absence of chemical deposits all testify to the preponderance of mechanical over chemical action in the Papago country. Though chemical action is not large in amount, however, evidence of its presence is widespread, and its total effect is likely to be underestimated.

Chemical action is dependent on the presence of water and is most active in regions of circulating water, abundant organic matter, and high temperature. Few of the rocks of this region are ever saturated with water or are even wet frequently, yet water circulates in the joints and adheres to the walls of all cavities and pore spaces for a considerable time after each wetting. It is also possible that moist air in the cracks of the rocks may be effective in chemical work on the side walls. Prospect holes and other excavations show few joints which are not widened by solution or along which rock decay is not evident. Even loose boulders are marked by concentric bands of color showing solution and redeposition, particularly of the iron minerals. In the mines at Ajo copper sulphides are oxidized to depths of 20 to 150 feet.[41]

[41] Joralemon, I. B., The Ajo copper-mining district, Ariz.: Am. Inst. Min. Eng. Bull. 92, pp. 2011–2028, 1914.

Rock débris seldom shows grains of hornblende or biotite mica, for these minerals are largely destroyed by chemical action before the rock breaks up. In certain localities in the Papago country granite surfaces are pitted by the removal of these minerals and subsequent mechanical disintegration is facilitated. The feldspars, on the other hand, are very fresh and clear and rarely have the dull-reddish opaque appearance which they assume in the residual soils of the Sierra Nevada and central New Mexico. Solution of the glassy matrix of lavas is also a fairly rapid process and probably plays a large part in the removal of lava blocks on talus slopes.

GRADES OF MOUNTAIN SLOPES.

Mountain slopes range in steepness from vertical cliffs to grades up which it is easy to ride a horse. Slopes can be divided into three groups—cliffy slopes, boulder-controlled slopes, and rain-washed slopes. The limiting angles and characteristic rocks of these groups are shown in figure 7. Each group has certain common characteristics, although the dividing lines between them are not very sharp.

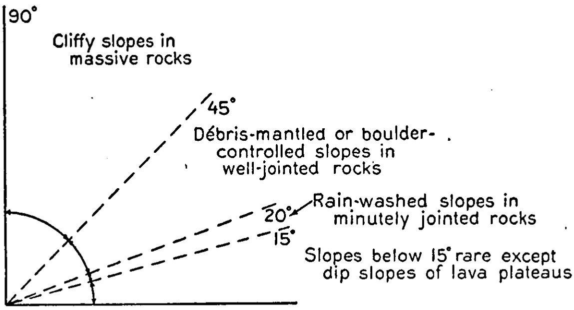
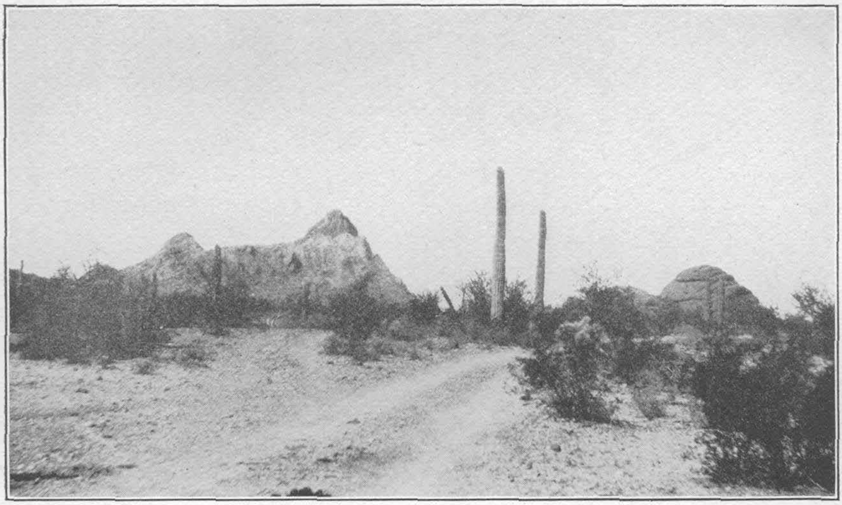


FIGURE 7.—Diagram to show the range of mountain slopes.

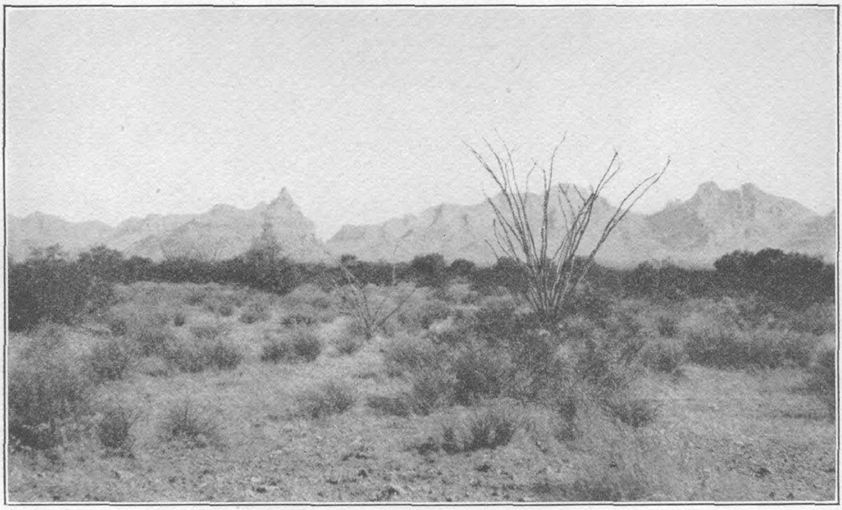
CLIFFY SLOPES.

Mountain slopes inclined between 45° and 90° from the horizontal are developed on granite, granite gneiss, massive lava beds, intrusive fine-grained porphyritic rocks, and arkosic conglomerate. These cliffy slopes are stable under the existing conditions of erosion, and the mountains composed of suitable rocks grow smaller in size but maintain the same angle of slope until they are totally reduced. The rocks are massive, with widely spaced joints, and the steepness of slopes seems to be related to the sparse jointing, for near by may be found the same rocks with more closely spaced joints undergoing erosion on gentler slopes. In sparsely jointed rocks joint blocks are not easily dislodged, and the mountain slope recedes either by undermining at the base or simply by surface disintegration and weathering of the rock wall. When at long intervals blocks are dislodged, they have been so weakened by weathering that in falling to the base they break into fine rubble. Thus no talus forms at the foot of these slopes. Slopes of this type on arkose are shown in Plate X, *A*, on massive lava flows in Plate X, *B*, and on granite in Plate XII, *A*.



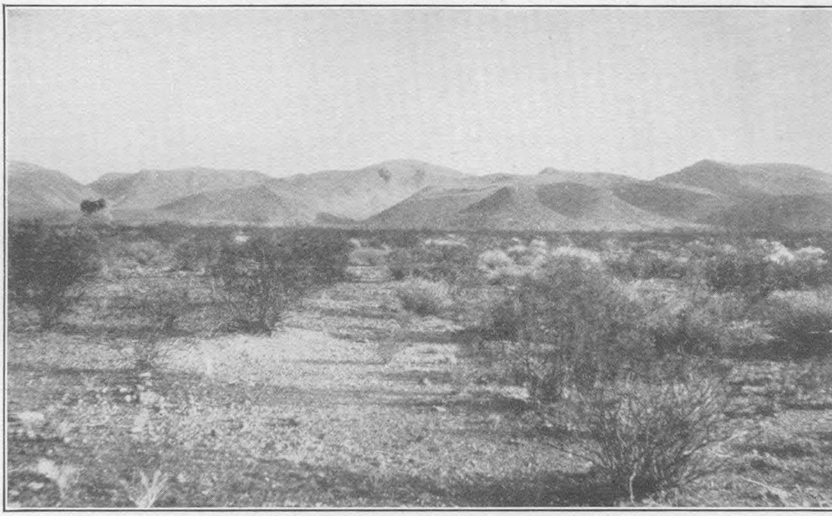
A. AJO PEAKS, ARIZ., FROM THE EAST.

Cliffy slopes of Penasco Peak developed on massive Tertiary conglomerates and dissected pediment in foreground. Exfoliation and niches on bosslike hill at the right.



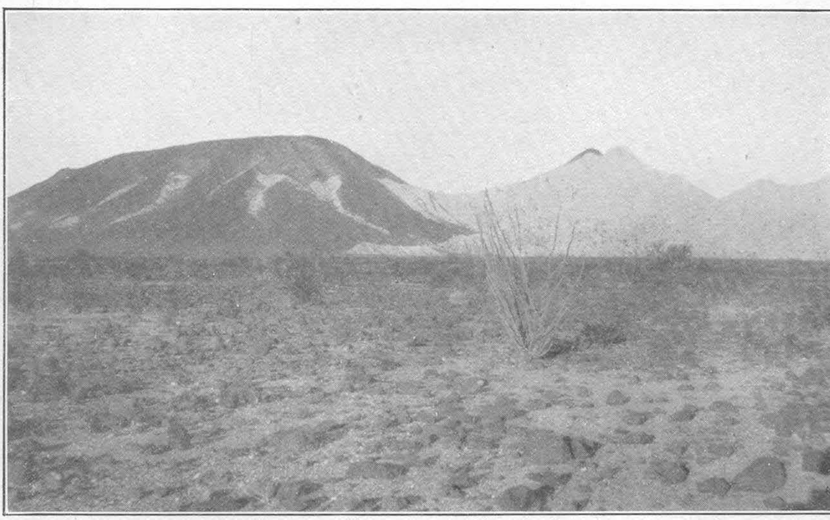
B. CLIFFY SLOPES OF MASSIVE LAVA FLOWS ON THE WEST SIDE OF THE AJO MOUNTAINS, ARIZ.

Montezuma head in the left center.



A. GROWLER MOUNTAINS SOUTH OF BATES WELL, ARIZ., FROM THE WEST.

Unbroken, talus-controlled slopes developed on slightly tilted lavas.



B. LAVA-CAPPED MOUNTAIN IN THE CABEZA PRIETA MOUNTAINS, ARIZ., FROM THE WEST.

Gullied lava talus and, to the right, mountain slope on granite with talus one boulder deep.

BOULDER-CONTROLLED SLOPES.

Mountain slopes inclined between 20° and 45° from the horizontal are characteristic of most granites, granite gneisses, and horizontally bedded lava flows. The angle of the common mountain slope is between 30° and 35°. The steeper slopes are usually interrupted by cliffs, and the gentler ones are interrupted by slopes of the next class.

Mountain slopes of this type composed of bedded lava flows consist of a cliff with talus below, successive cliffs with intervening talus, successive cliffs with smooth intervening slopes developed on tuff, continuous talus, or talus gullied and dissected. Very thick and massive lava flows resist the dislodgement of joint blocks and form cliffs. Whether these cliffs lie at the top or midway of the slope, they simply retard the recession of the mountain slope and increase its average steepness. The processes on the intervening talus slopes are similar to those described below.

Smooth slopes on tuff recede more rapidly than the cliffs above them, and the undermined blocks roll down over them. Only where such slopes are short stretches intervening between two steeper slopes are they free of rock waste. Where they are bare, the processes of erosion on the tuff are those described for rain-washed slopes (p. 46).

Bedded lavas under the attack of weather usually break into joint fragments from 2 to 6 feet in diameter, which, although easily dislodged, are comparatively resistant to disintegration and hence form a talus of rock waste that gradually mantles the whole mountain slope. The grade of the slope then becomes the angle of repose of the average-sized joint fragment (Pl. XI, *A*). Further erosion takes place by removal of the rock waste and formation of a new talus.

On certain mountain slopes part of the talus is removed by the formation of gullies, as shown in Plate XI, *B*. The mountain here illustrated consists of a cap of lava on a base of granite, and because of the difference in color the gullied talus is easy to photograph. Other mountains similar in size and composed wholly of lava have like gullies with like triangular areas of unremoved rock waste. Figure 8 shows the distribution of gullied and ungullied mountains of flat-lying lavas of approximately the same size and height observed in the Papago country. Many others of both kinds exist, and only those observed are included.

No local lowering of base-level is evident at the foot of these mountains, and the formation of the gullies can be ascribed only to the work of unusually heavy local rains. Such rains are well known under the term "cloud-bursts," and if disintegration of the boulders that form the talus and the bedrock on which they lie had proceeded until an unstable condition had been reached a single cloud-burst would be competent to produce the gullies. Weathering and the normal rains combine to dislodge new fragments, which will in time fill the gullies and restore the original unbroken mantle of rock waste.

Confirmation of this explanation is obtained from the talus slopes of the ungullied mountains. The greater part of the rock waste has been in position for a long time. The boulders are cracked, exfoliated, and pitted by the solution and removal of the ferromagnesian minerals. The under surfaces of the boulders are coated with calcium carbonate derived from solution of the minerals. Bushes grow

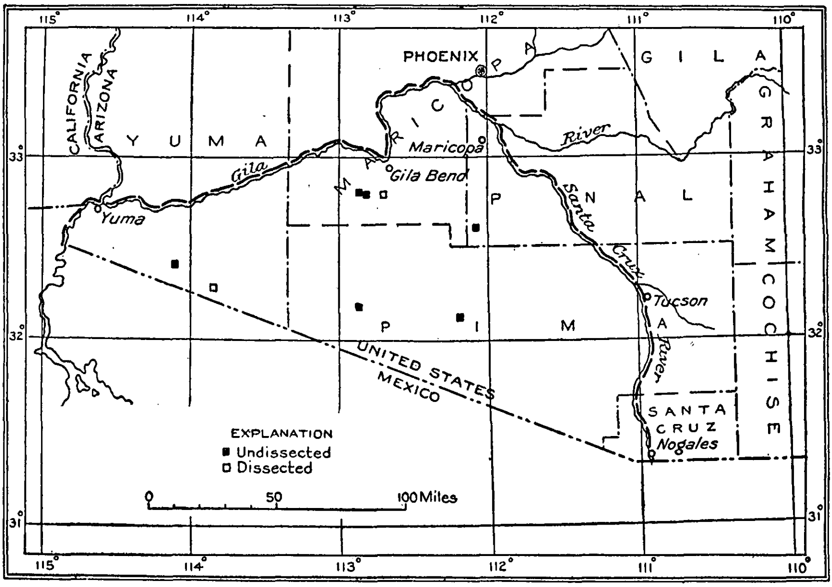


FIGURE 8.—Sketch map of the Papago country, Ariz., showing distribution, so far as observed, of gullied and ungullied mountains of approximately the same size.

between the boulders. Of these the most significant in indicating the stability of the slopes is the palo verde, *Parkinsonia microphylla*, whose age on the slopes of Tumamoc Hill was found to range from 10 to 400 years.[42] In contrast to this ancient rock waste strings and lenses of fresh rock waste occur on all slopes. The blocks are sharp-angled and more closely packed than those of the older rock waste and occupy positions corresponding to the gullies previously described.

The retreat of a talus slope on horizontal lavas takes place by the slow production of the fragments that compose the talus blocks, by their decay, and by the creep of the rock waste from top to bottom of the slope. This slow process is occasionally interrupted by the

[42] Shreve, F., Establishment and behavior of the palo verde: Plant World, vol. 14, p. 293, 1911.

catastrophic removal of large amounts of rock waste by great storms, exposing a fresh rock surface from which rock waste is again gradually produced and the talus is replaced.

Granite slopes at angles between 20° and 45° also have a mantle of rock waste, although it is by no means so nearly complete as the talus on lava slopes, particularly on the steeper slopes. The talus on granite slopes commonly consists of a layer of boulders only, and in many places scattered boulders and patches of boulders between protuberant knobs of the bedrock seem to determine the angle of the slope. The granite boulders range from 10 feet down to 1 foot in diameter, and all sizes may be found on a single slope, but in a general way the size of the boulders is proportional to the grade of the slope. Large boulders mantle steep slopes, and small boulders gentle slopes. As the size of the boulder is determined primarily by the spacing of joints, fine-grained granite and most granite gneisses, which usually have closely spaced joints, yield smaller boulders and consequently produce gentler mountain slopes than coarse-grained granite and gneiss.

Many of the granite boulders have a brown or blackish color from the so-called "desert varnish," which is associated, in granite at least, with the deposition of limonite in the outer 1 or 2 inches of the rock. This outer crust is in many boulders a shell which covers a completely disintegrated interior so soft and crumbling that the minerals may be picked apart with the fingers. Many boulders also are cracked, and some are completely split, many of them in two or three directions. Still others show the work of exfoliation. On many mountain slopes the boulders are so weather beaten and ancient in appearance that it seems that they could not possibly have been produced by any process now in action, but that, laid on the slope in some ancient time, they have ever since been slowly rotting and disintegrating.

The bedrock on which the boulders lie is covered with a loose film of small fragments made up of the mineral grains that once formed the granite. The fragments slip under the foot, and new pieces crumble from the bedrock continually. Disintegration of the bedrock proceeds most rapidly along joints but is effective everywhere. Every rainstorm sets trains of this fine débris moving down the slope. As the fine débris is removed the boulders roll down to find a new lodgment either lower on the slope or at its base. In this movement many of the boulders, already disintegrated within the outside crust, are shattered into fragments. Under normal conditions few of them reach the bottom and no accumulation of boulders takes place there.

As the bedrock disintegrates and rain washes the débris away more rapidly along joint planes protuberances of the bedrock are formed, which consist of the most compact rock between the most widely spaced joints. The protuberances are cut loose by the same process that formed them, and a new crop of boulders comes into existence.

By these slow but continuous processes the mountain front recedes, but the same great storms that affect the slopes of lava mountains fall on granite slopes also. The process of recession is doubtless hastened by these storms, but no direct evidence of their effect has been obtained.

RAIN-WASHED SLOPES.

Mountain slopes at angles less than 20° from the horizontal are rare in the Papago country. They are developed on the least-resistant rocks, which, probably occurring in relatively small amount, have been largely removed by erosion. The mountains are composed almost wholly of the resistant rocks, which thus dominate the mountain slopes and keep them at a relatively high angle, the gentle slopes occurring on hills and as parts of mountains.

Closely jointed gneiss, schist, phyllite, and felsite form gentle slopes. The closely spaced cracks absorb and retain more rain than those developed in rock of other types. These rocks usually contain also a larger percentage of soluble material, either of ferromagnesian minerals in the gneiss and schist or of glass in the felsite, and consequently chemical action takes place more readily when they are exposed to the weather. The processes of mechanical action, because of the smaller size of the joint fragments and smaller grain of the component minerals, tend to produce finer rock débris. This finer débris is readily moved by rain wash on a flatter slope than that on which corresponding material derived from granitic rocks can be moved. The joint fragments, being smaller, are also more easily moved and instead of falling are undermined and carried away by rain wash.

Tuff and shale also develop gentle slopes. The products of the weathering of these rocks are fine and rather easily produced, so that the angle of the slope is determined largely by the grade on which rain wash can transport débris. Certain tuffs, however, are so compact that they weather slowly and hence form steep slopes, the angle being determined wholly by the rapidity with which particles may be detached from the matrix.

CANYON CUTTING.

In the previous sections the recession of slopes has been considered. If rocks were absolutely homogeneous so that no irregularities were formed on slopes in which rain water could be concentrated, then mountains would be eroded wholly by slope recession. But when water is concentrated and flows in a stream it erodes the rock by corrasion at a rate faster than that of slope recession, and to this fact is due much of the diversity of mountain topography and all the larger features of mountain sculpture in the Papago country.

Corrasion is wear by water in a stream and the rock débris which it transports upon the stream bed, and it is assisted by corrosion or solution of the rock so far as this may be accomplished by the passing water. The stream therefore cuts downward in a narrow groove, and in homogeneous material the walls are essentially vertical. Slumping and the processes of slope formation previously described operate to widen the cut so that in time each stream flows in a rather broad valley. As there is a limiting grade below which a given quantity of water can not transport a given quantity of material, corrasion

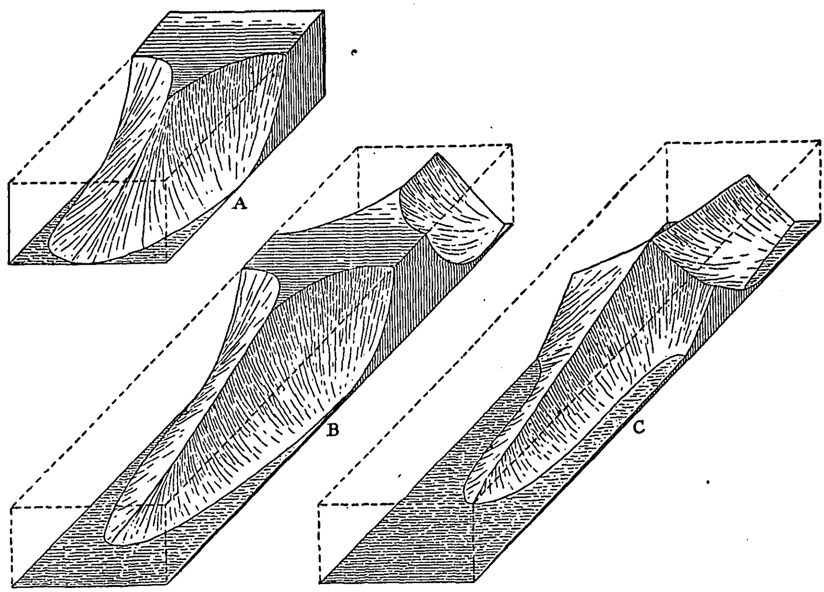


FIGURE 9.—Diagram showing three stages in the erosion of a block of the earth's crust to form the sierra type of mountain.

of the bed can proceed only until this grade is reached, and further lowering is prevented by the deposition of sediment. A stream which has reached this grade in any part is said to be graded.

The way in which canyon cutting produces the sierra type of mountain under the climatic conditions of the Papago country is shown in figure 9. In block A an original rectangular block of rock has been affected by erosion so that the face of the block has receded to the angle of 45°, assumed for the purpose of the diagram to be the slope normal to this type of rock. During the same time canyons whose side walls have the same slope of 45° have been cut into the block. In block B slope recession has carried back the point of the spur or ridge between the canyons, and the side walls of the canyon have also been eroded by the same process. Corrasion has lengthened the canyon. At the mouth of the canyon and at the foot of the ridge a small pediment has been formed. By the recession of the canyon walls the crest of the ridge has been carried below the level of the original block. The ridge, then, has a slope which is a function of the original length of the block, the length of the canyons, and the angle of the mountain slope. In block C the canyons from opposite sides of the block have met, and the head of the canyon now assumes the grade of the mountain slope. From this time on stream erosion is at a minimum and the mountains decrease in size by slope recession and the lateral cutting of the streams on the canyon floors. It is obvious that if blocks similar to block C are placed on either side of it and others beside them, the typical sierra with its crenulated ridge and projecting spurs will be reproduced.

HEADWATER BASINS.

Although the erosive power of mountain streams is great when they are in flood, floods are so infrequent in the Papago country that widening of the valleys takes place slowly. The steep grades necessary to transport débris prevent the formation of meanders, and lateral cutting is at a minimum. The lower section of a mountain canyon, once the stream is brought to grade, is in consequence relatively stable in cross section, and the side walls recede by the slow processes of slope recession.

At the entrance of a tributary, however, there are two spurs, each bounded by one slope of the main canyon and one of the tributary. Here the recession of mountain slopes is doubly active. Near the divide several tributaries usually unite to form the main stream, and the corrugated surface between them affords the optimum conditions for slope recession. Hence, at such junctions headwater basins are formed.

If two or more streams develop such basins on either side of the divide, the divide may be reduced long before the rock mass lying between the lower portions of the streams is reduced. The production of headwater basins is accelerated, especially at the beginning of the process, by the more abundant rainfall which is characteristic of the higher parts of a range.

Development of these headwater basins is a common phenomenon in the Papago country, and part of one is shown in Plate XIII, *A*. Many mountains consist of groups of isolated hills, more or less irregular in size and height, scattered on plains, that rise to low divides which lie in the position of the original mountain crests and constitute merged headwater basins, or mountain pediments. Illustrations of these features are given under the heading "Mountain pediments" (p. 52).

MINOR EROSIONAL FEATURES.

The minor phenomena of erosion throw light on the processes that produce the larger features and the more common land forms. Of these phenomena the small caves or niches characteristic of certain mountain slopes are especially interesting.

Niches in coarse granite are common in the Tule and Tinajas Altas mountains. As shown in Plate XII, *A*, the niches are distributed from top to bottom of the mountain slope and range in size from holes 6 inches in diameter and 2 inches deep to caves 6 to 8 feet across at the mouth and 2 to 4 feet deep. In the cove at Tinajas Altas the niches may be conveniently studied. The granite, which on fresh fracture is white with a pinkish cast, has a mottled brown surface, in places rounded and bosslike between the joints. The brown color is due to the deposition of limonite in a crust usually about 2 inches thick. The niches are without this crust and thus evidently have been formed at a later date. The typical form is shown in figure 10. The roof and back walls have a rough surface, from which scales and fragments of rock can be easily detached. The floor is usually firm and smooth and always slopes abruptly and continuously from the rear of the niche to the outside. On it are loose scales that have dropped from the roof and back walls.

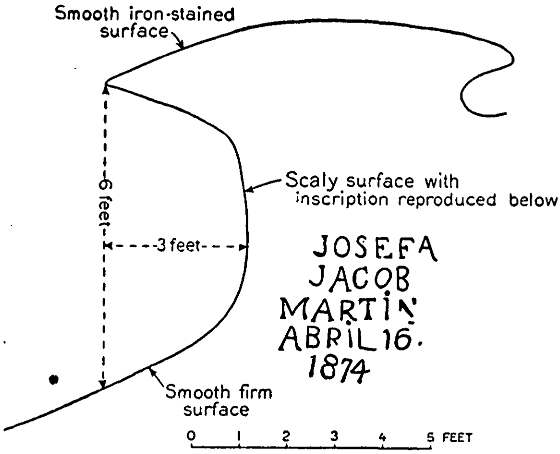


FIGURE 10.—Cross section of niche in granite at Tinajas Altas, Ariz.

The niches appear to be the work of insolation and solution, which, beginning at a place in the surface but poorly protected by the iron-stained crust, work inward, loosening successive flakes and chips. These fall and slip down the smooth floor, doubtless moving more easily when rain beats into the opening. Wind also may assist in removing the débris, but as the chips are ordinarily from a quarter to half an inch in diameter and an eighth of an inch thick, the wind is probably not an effective agent. The retreat of the back wall is not rapid. Some idea of the rate may be gained from the niche illustrated in figure 10. The inscription, "Josefa Jacob[a] Martin Abril 16, 1874," is evidently that of a traveler with the date of her visit. It is painted on the rock with a paint made from the juices of a local bush and iron rust by a process well known to the Mexicans and Indians of the country. When visited October 21, 1917—43 years after it had been written—the inscription was in almost perfect condition except for the last "a" in "Jacoba," which was lost by chipping of the back wall.

Niches very similar in appearance occur on the surfaces of the fantastic rocky hills carved from Tertiary arkosic conglomerate (Pl. X, *A*). These niches were studied in the Papago Saguaro National Monument, 7 miles east of Phoenix, where they are associated with rock shelters. The rock shelters are from 3 to 25 feet across and have an overhang of 3 to 10 feet; the niches are from 3 inches

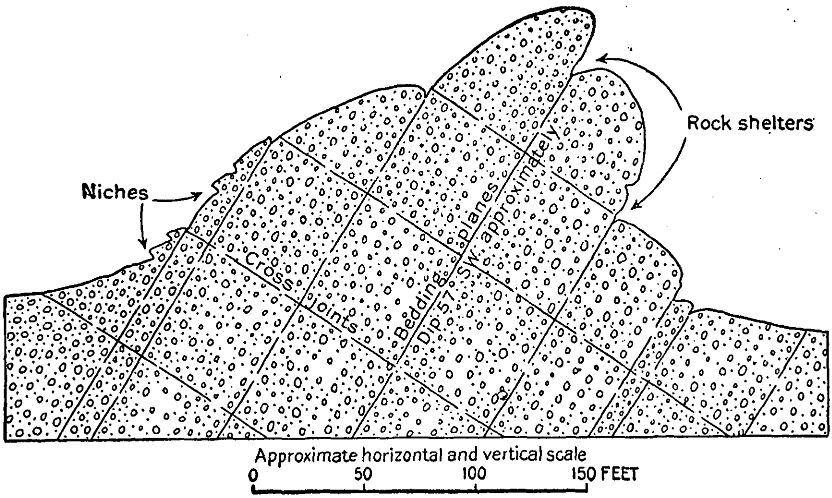


FIGURE 11.—Diagram illustrating weathering of Tertiary arkose conglomerate in the Papago Saguaro National Monument, Ariz.

to 3 feet in diameter and from a few inches to 3 feet deep, the depths being more or less proportional to the size of the opening.

As shown in figure 11, the shelters are due to erosion along the inclined bedding planes and joints. With the removal of certain joint blocks by exfoliation and disintegration, others are left standing with an overhang. Once the overhang is formed, erosion of the back wall begins through solution of the cement and even of the constituent boulders by rain water, which is absorbed by the overlying bare rock and thence seeps down and emerges in the shelter. Thus these rock shelters are formed in the same way as those in northern Arizona described by Gregory.[43]

[43] Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, pp. 133–134, 1917.

The niches occur at intervals in the rock surfaces, and some are so small that they appear to be due to the dislodgment of single boulders from the matrix, and others appear to be due to solution along joint planes. Those of the predominant type are excavated in the rounded rock surfaces and may have no connection with joints. Their form is shown in figure 12. The roof of many of them is covered with red clay or a film of lime carbonate. The lower half inch to 1 inch of rock is separated from the main mass by a crack, and this flake can easily be detached. The back wall is usually rough, boulders of the conglomerate projecting into the niche. The floor slopes outward rather steeply and in many niches is covered with dust and fragments of rock. Joints of the cholla cactus (*Opuntia* sp.) are usually scattered about the floor. for the niches are favorite haunts of the trade rat. The process of formation is clear. Beginning with a small cavity where a boulder has pulled loose from the matrix or where the cement has been dissolved at some particularly porous place, the niche is enlarged inward by the crumbling of the back wall and by the scaling of the roof, both due largely to seepage of rain water through the rock and consequent solution of the rock cement. The débris falls to the floor, along which it slides to the exit, transported principally by rain wash and water that trickles from the back wall.

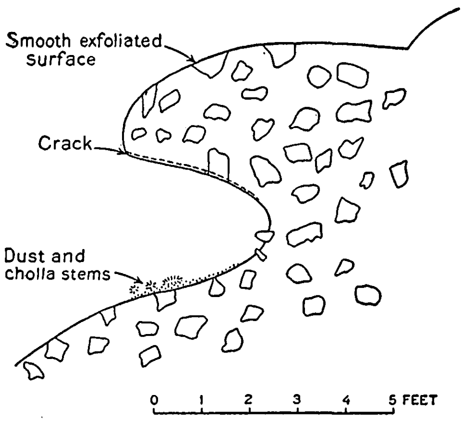


FIGURE 12.—Cross section of a niche in coarse conglomerate, Papago Saguaro National Monument, Ariz.

Isolated pillars and monuments to which the Mexican gives the general name peñascos are commonly formed by the dissection of lava flows; less commonly they are formed of granite. In lava the formation of pillars is controlled by vertical joints in thick nearly horizontal beds. Pillars capping small buttes and mesas or isolated by erosion from a cliff are the common forms and add much to the picturesqueness of the plateau type of mountains. One of the best known of these pillars is Montezuma Head, in the Ajo Mountains, which on distant view resembles a square-shouldered gin bottle (Pl. X, *B*).

Pillars of granite usually consist of some massive portion of the rock from which the surrounding more closely jointed rock has been removed. Once isolated and attacked mainly by changes in temperature, a pillar resists the weather for a long time. Such a pillar on the crest of the Maricopa Mountains can be seen from the base of the Sierra Estrella across the whole width of the Jornada de las Estrellas.

MOUNTAIN PEDIMENTS.

CHARACTER.

In general, the mountains of the Papago country rise from plains which are similar in form to the alluvial plains that commonly front mountains of an arid region, but large parts of the plains

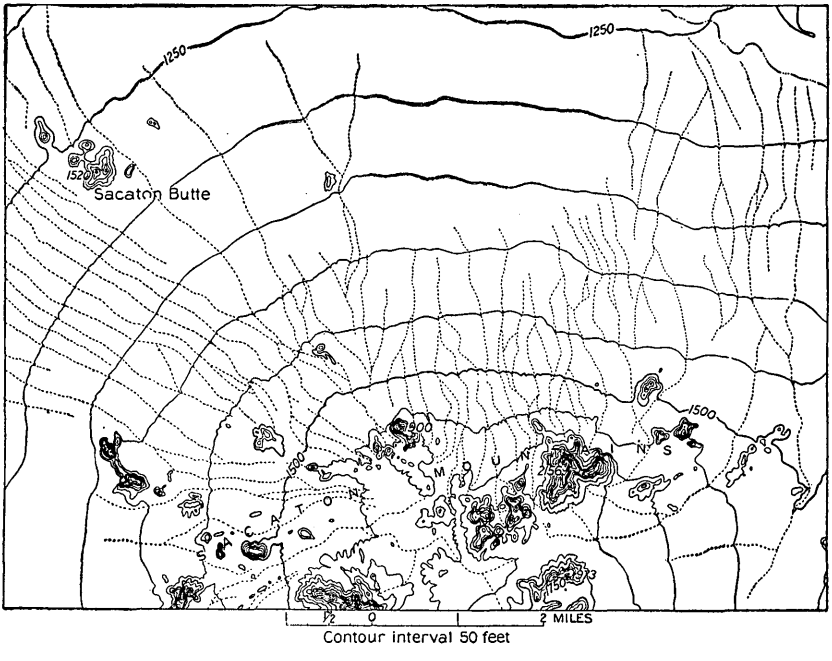


FIGURE 13.—Map of part of the Sacaton Mountains, Ariz.

are without alluvial cover and are composed of solid rock. These plains are called "mountain pediments," a term suggested by McGee's usage,[44] although he applied it to only one of the many similar plains cut on rock in the Papago country that he described. It corresponds to the terms "subaerial platforms" and "sub-alluvial benches" used by Lawson,[45] but certain differences in concept, as well as the awkwardness of his terms, make it advisable to substitute a term which does not imply any particular origin of the topographic form. The normal mountain pediment has smooth slopes, broken only by scattered hills that rise abruptly from the

[44] McGee, W J, Sheet-flood erosion: Geol. Soc. America Bull., vol. 8, pp. 92, 110, 1897.
[45] Lawson, A. C., The epigene profiles of the desert: California Univ. Dept. Geology Bull., vol. 9, p. 34, 1915.

plain and are more or less strung out in lines which are prolongations of the intercanyon ridges of the mountains. Unfortunately no maps that cover large areas of normal pediment are available. The northern slope of the western part of the Sacaton Mountains is shown in figure 13. The plains around the hills and small mountains are cut on rock, but the northern part of the area shown has a heavy burden of alluvium. Schrader[46] states that the "subaerial or nearly subaerial eroded bedrock floor * * * seems to continue to within 3 miles of Casa Blanca," or to the vicinity of Sacaton

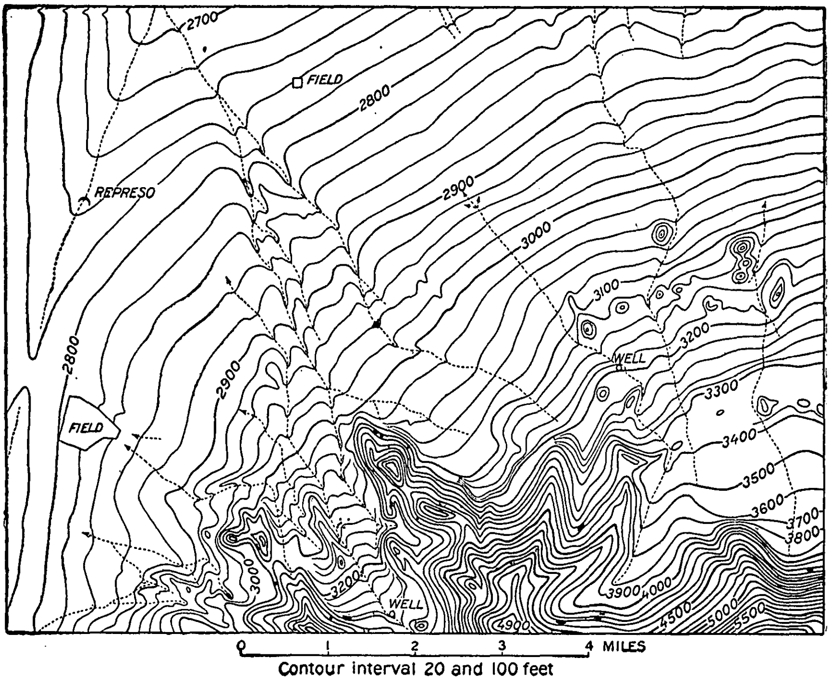


FIGURE 14.—Map of the northern border of the Baboquivari Mountains, Ariz. Redrawn from map by the United States Indian Service.

Butte. (See fig. 13.) Similarly figure 14 shows a pediment dissected by small canyons. This dissection is not so great, however, as to obscure the general form of the pediment.

The angle of slope of pediments ranges from about 50 feet to 200 feet to the mile. It is noticeable, however, that in any one mountain range the slope is steeper opposite the smaller canyons and very much flatter opposite the large canyons. The parts opposite the intercanyon portions of the mountain front are steeper than the parts opposite canyons, and they commonly slope not only outward from the mountains but toward the stream channels, which emerge from the canyon mouths.

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[46] Schrader, F. C., unpublished manuscript.

Exceptions to this general condition occur, for at the mouths of certain canyons the pediments have steep slopes, especially in the direction of the axes of the streams. This exception seems to be due to especially resistant boulders which have been brought down by the stream and dropped at the canyon mouth, causing the stream to spread and lose its carrying power. The boulders, until they weather into fragments small enough to be moved, protect and preserve a slope steeper than is normal to the pediment.

ORIGIN.

The mountain pediment is a plain developed at the foot of the mountains under the processes of erosion normal to the desert. The causes that produce the pediment are obviously different from those which produce the mountain slope. The key to these causes is found in the character of the loose material which covers the respective slopes. The mountain slopes are covered with loose boulders ranging in diameter from 6 inches to 5 or 6 feet. The pediment, on the other hand, is covered with fine fragments one-sixteenth of an inch to 6 inches in diameter.

Davis[47] recognizes that in the closing stages of an erosion cycle in desert regions graded rock floors will intervene between the alluvial slopes and the mountain slopes of an intermontane basin, just as he had previously recognized and shown these plains in a diagram in his discussion of the basin ranges.[48] Under conditions of extreme aridity the development of plains cut on rock does not necessarily indicate old age, but such plains may be produced earlier in the cycle and are dependent for their position on the upper limit of alluvial deposition in the intermontane valleys. Rock plains or pediments develop at or above the edges of the valley fill and are limited in size only by the available area and the factor of time.

As explained on page 42, the angle of slope of the mountain is controlled by the resistance of the rock to the dislodgment of joint blocks and the rate at which these blocks disintegrate. The angle of slope of the pediment, however, is due to corrasion by the streams, and this corrasion is controlled by the ability of water to transport débris, for the pediment is a slope of transportation intervening between the mountain slopes and the alluvial plain in the middle of the valley. Fine rock débris is moved down the mountain slope by rain wash and carried away from the foot of the slope by rivulets and streams that form through the concentration of the rain wash. The supply of this

[47] Davis, W. M., The geographical cycle in an arid climate: Jour. Geology, vol. 13, pp. 381–407, 1905; reprinted in Geographical essays, pp. 296–322, Ginn & Co., 1909.

[48] Davis, W. M., Mountain ranges of the Great Basin: Harvard Coll. Mus. Comp. Zoology Bull., vol. 42, pp. 129–177, 1903; reprinted in Geographical essays, pp. 725–772, Ginn & Co., 1909.

fine material on the mountain slope is, however, so small that it is readily removed, and the angle of the slope is determined by the size of the boulders. In the same way the fine material temporarily accumulating at the foot of the mountain slope by the breaking up of boulders, which have rolled down the slope, is usually carried away by the streams of the pediment as rapidly as it is supplied. The sharpness of angle between the mountain slope and the pediment is one of the most remarkable results of this division of labor between rain wash on the mountain slopes and streams on the pediment. The result, however, merely confirms the dictum of Noë and De Margerie [49]: "The slope of an element of the surface is the more gentle as the force of the current active on that element is the greater."

In many localities the transition between mountain slope and pediment takes place in a belt which ranges in width from 100 to 200 feet. This change in gradient seems to be due to the abrupt concentration of rain wash from the mountain slope into streams on the pediment, though doubtless near the mouths of canyons lateral planation by streams is also an effective process, as suggested in a later paragraph.

In Lawson's excellent description of the forms developed by desert erosion he assumes that the débris from erosion of the mountains is poured into an inclosed basin, and consequently that the middle of the valley constantly rises through filling.[50] He states in substance that the alluvial slopes rise step by step with deposition in the middle of the basin, and their upper edges advance toward and finally engulf the mountains. On the same assumption Paige [51] first stated the results in the following words:

> The rising edge of the gravel sheet acts as an effective control below which erosion can not take place. The result is unavoidable if the time factor and the factor of area are sufficiently large. A process tending toward leveling with respect to the gravel sheet will proceed. But the gravel sheet has been gradually rising; therefore the leveled surface is a sloping plain thinly veneered with gravel.

In other words, erosion can take place only above the level of the alluvium and has its maximum value at the upper edge of the alluvial slope. On this hypothesis a plain is cut in the rock whose position and form are governed by the successive positions of the upper edge of the alluvial slope. With equal or diminishing increases in elevation of the middle of the valley in equal times the plain would have a curvature convex upward. With accelerated increase in elevation of the middle of the valley, which, however, must be slow enough to permit erosion of a plain and not so rapid

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[49] Noë, G. de la, and Margerie, E. de, Les formes du terrain, p. 22, Service Géog. Armée, Paris, 1887.

[50] Lawson, A. C., op. cit., pp. 30–31.

[51] Paige, Sidney, Rock-cut surfaces in the desert ranges: Jour. Geology, vol. 20, p. 449, 1912.

as to bury the original surface, a plain of concave curvature would result. The convex type of plain which Lawson called a suballuvial bench is shown graphically in figure 15.

When, however, streams are able to maintain through drainage and there are no inclosed basins, the level of the middle of a desert valley may remain essentially stationary. A slope is established on the alluvial plain sufficiently steep for the transportation of the available débris by the available water. The edge of the alluvium then becomes relatively stationary, and as the mountain slope recedes a slope cut on rock is formed, which also is a slope of transportation. As the débris decreases in size with movement away from the mountain it can be moved on flatter slopes, and hence a pediment is concave upward.

The formation of pediments in the Papago country has been very generally interrupted by a new cycle of erosion, and the processes may now be observed only in localities of small extent. These

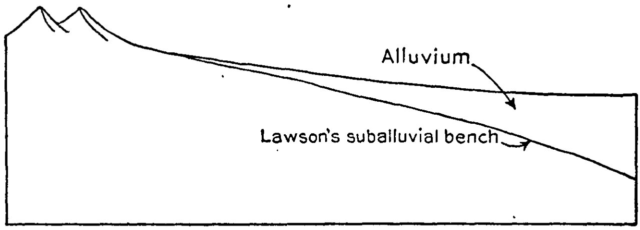


FIGURE 15.—Diagram showing the structural relations resulting from the slow but continuous filling of a structural basin.

processes will be briefly stated. At the base of a mountain front débris is swept outward by ephemeral streams which head in the mountain canyons and by small rills which originate through the concentration of rain wash at the base of the mountain slope. These streams are not permanent or even intermittent; they operate only during or immediately after rain.

From the larger canyons streams move pebbles as much as 6 inches in diameter, but this is the approximate limit in size, except on the east side of the Baboquivari Mountains and around the Tumacacori Mountains. These mountains are the highest and largest in the area and consequently have more rainfall and larger streams, in which boulders from 2 to 3 feet in diameter are not uncommon. In the stream channels a very rigid selection of material takes place; the finer particles move with every flood; the coarser material can be moved only by the larger floods. As the stream emerges from the mountains and its water spreads, the larger particles tend to be dropped and only the smaller ones are carried forward. Because there is an interval of time between floods, often a long interval, the larger pieces are reduced in size by weathering and may then be moved by smaller floods.

At the base of a mountain slope the fine débris washed down by rains is moved forward by little rills toward the larger streams. As the supply of débris is small these rills are not fully loaded and are effective erosive agents, tending to reduce the height of interstream areas, but the grades on which they can work are steeper than those of the larger streams. Thus the pediment has a steeper gradient near the mountains between the canyon mouths and these portions also slope to the streams on either side.

The pediment is greatly increased in size by lateral migration of the streams at and below the mouths of the canyons. The irregularities of the pediment are removed, the higher places being eroded and the lower filled with débris and protected. The lower parts of the canyons are also widened by undermining the slopes of the intervening spurs.[52] When the spurs become narrow they are cut through by slope recession on both sides, and hills are left standing as outliers on the pediment. These solitary hills are worn away with extreme slowness. Their erosion depends entirely on the gradual disaggregation of the rock which composes them and on the movement of the débris over the pediment during rains. The hills retain the same steep slopes as the original mountain but grow gradually smaller until the last remnants are masses of boulders or single rocks projecting above the general level.

The development of the pediment is therefore due to erosion, which may be summed up under three heads—(1) lateral planation by the streams issuing from the canyons, (2) rill cutting at the foot of mountain slopes, (3) weathering of outliers and unreduced remnants, with transportation of the débris by rills. The processes can not operate below a level determined by the grade necessary to transport débris away from the mountains. All depressions below this level will be filled up just as those above it are eroded. Thus the pediment is a slope of transportation and is usually covered with a veneer, from 18 inches to 5 feet thick, of débris in transit.

As transportation of relatively fine material by water is the essential factor in the formation of the pediment, in contradistinction to the erosion of mountain slopes, which is largely controlled by the movement of large boulders, it is obvious that the pediment grows most rapidly along the major streams. In every indentation in the mountain front and in places where streams emerge from the canyons onto the plains the rate of formation of the pediment is rapid, and consequently extensions of the pediment into the mountains are com-

[52] Paige, Sidney, Rock-cut surfaces of the desert ranges: Jour. Geology, vol. 20, p. 450, 1912.

mon. These extensions consist of branching valleys, many of which are 2 miles or more in width and reach far into the interior of the mountain mass. The erosion of the mountains at the headwaters of many streams is much faster than in the lower portions of the same streams, for there is obviously more water pouring down the mountain slopes of the larger mountain masses, and feeble streams are incapable of much planation. Consequently the headwater slopes may recede more rapidly than the side walls of valleys. The extension of the pediment may thus divide the original mountain into groups of detached hills separated by relatively broad surfaces cut on rock, as in the Sacaton Mountains (fig. 13).

CONCEALED PEDIMENTS.

If the débris eroded from a desert mountain range and poured into the adjacent valleys is carried away by some through-flowing

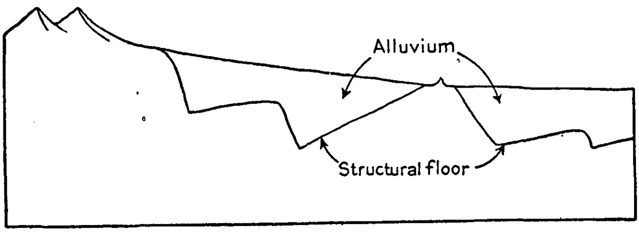


FIGURE 16.—Diagram showing the structural relations resulting from rapid and continuous filling of a structural basin.

stream and the base-level of erosion remains constant for an indefinitely long period, the pediment becomes simply the floor over which transportation is carried on, and as it is in a balanced condition between degradation and aggradation it can not be further lowered. On the other hand, if the adjacent valleys have no outlets or insufficient outlets sediment accumulates in them and the local base-level of the streams flowing from the mountains is raised. Deposition begins in the lower part of the stream courses, and the sediment gradually increases in thickness and extends toward the mountains. The edge and finally a large part of the mountain pediment may thus become concealed beneath a covering of alluvium.[53] A mountain pediment buried in alluvium may be called a concealed pediment.

If alluviation in the valleys proceeds slowly the formation of pediments will continue at and above the upper edge of the alluvium, but as this edge advances it will bury a surface convex upward, as postulated by Lawson. (See fig. 15.) On the other hand, accumulation of alluvium may be so rapid that the formation of a mountain pediment is not possible until a condition of stability is reached, and

[53] Paige, Sidney, op. cit., p. 449.

hence the alluvium covers and conceals a floor largely of structural origin, as shown in figure 16. A pediment may then form above the level of the alluvium, as illustrated in the figure.

A more complicated sequence of events is possible by which there is a slow but continuous filling of a structural basin with the formation of a suballuvial bench, a pause in alluviation during which an extensive pediment is formed, and then rapid filling that buries and conceals the pediment. This sequence is shown in figure 17 and is illustrated in part by an example described in one of the following paragraphs.

Identification of a concealed pediment is difficult, for the surface has the form of a normal alluvial slope and there is no surface indication of the buried rock floor. Large outliers such as characterize a pediment may not be wholly buried, but they can not easily be distinguished from projections above the general level of a structural floor. Positive identification of a concealed pediment must

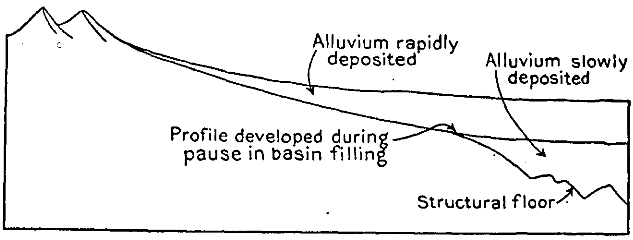


FIGURE 17.—Diagram showing the structural relations resulting from the discontinuous filling of a structural basin.

rest on excavations and wells which show alluvium resting on rock and also the form and character of this rock floor. The thickness of the alluvium must be greater than the ordinary depth of scour by streams, for pediments while being formed may have a shifting mantle of alluvium from 18 inches to 5 feet thick.

The presence of a concealed pediment may be inferred on a general physiographic argument, as illustrated by the following example. Westward-flowing streams in the Sand Tank Mountains, after passing across a large mountain pediment in which they are intrenched in little canyons below the general surface, flow out on grade into the Gila Bend plains (fig. 18). This alluvial slope is dominated by débris moving from the Sauceda Mountains northward to Gila River. The lava plateaus of the Sand Tank Mountains, which rise above the pediment on the east, are bounded on the west by talus slopes from 150 to 500 feet in height, whose lower portions are buried in alluvium. These slopes are the result of a considerable recession of the plateaus, for a continuance of the dip of the lava beds indicates that they once extended farther west, as shown in the cross section, figure 4 (p. 34). The large pediment east of the plateaus (Pl. XIII, *A*) required for its erosion a period of time more than sufficient to provide for recession of these slopes and the formation of a corresponding pediment on the west side of the plateaus. Since then the pediment within the mountains has been dissected, but the same streams choked by a flood of alluvium derived from the Sauceda Mountains have buried the pediment on the western border.

COALESCING PEDIMENTS.

When a mountain range has been subjected to erosion for a long period of time, mountain pediments formed along individual streams

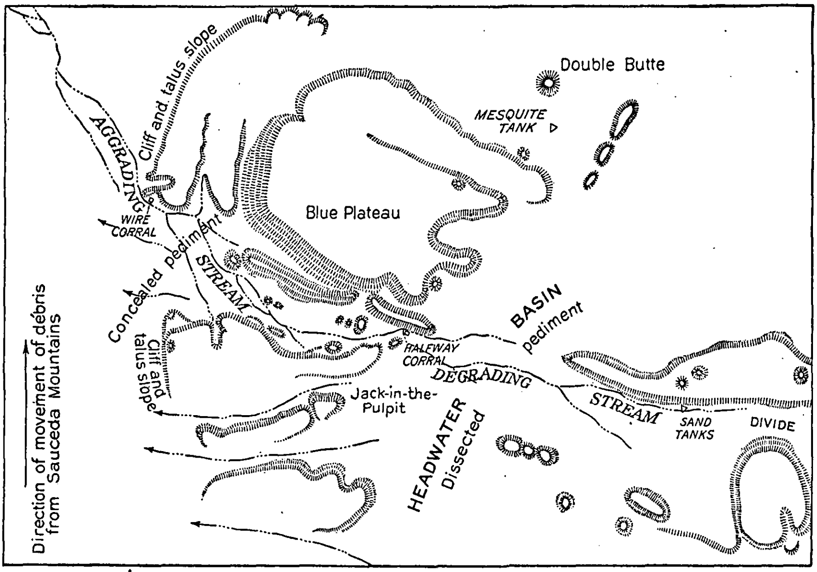
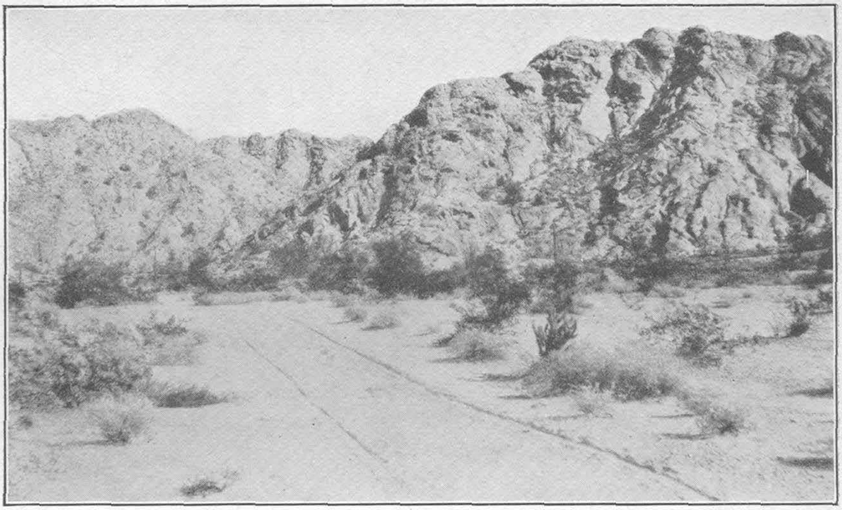


FIGURE 18.—Sketch map of the northwestern part of the Sand Tank Mountains, Ariz., showing location of dissected and concealed pediments.

will tend to unite, and eventually the range will be surrounded by a continuous pediment formed by the coalescing of many individuals. Coalescing pediments begin to be formed in the old-age stage of erosion of desert mountains, and when the projecting hills have been removed the grades will be almost stable.

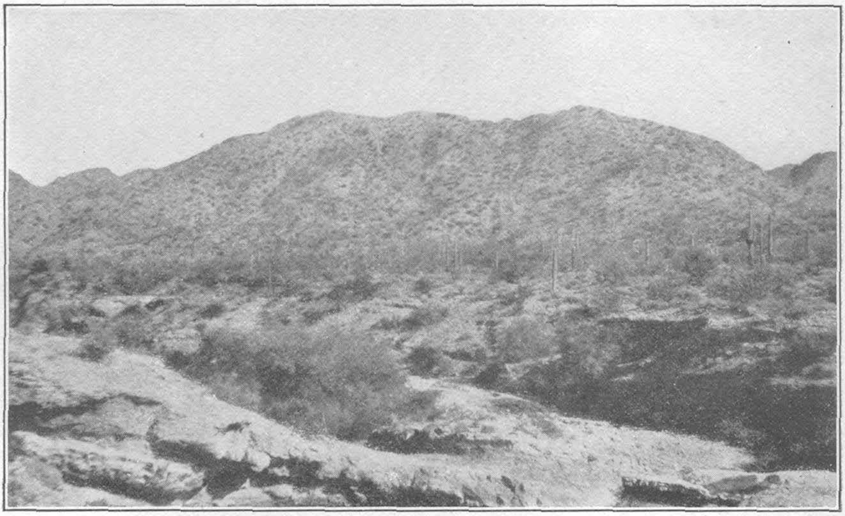
DISSECTED PEDIMENTS.

If the base-level of erosion of streams flowing from the mountains is lowered, the streams carry their load of débris with ease on the increased gradient and begin to dissect the mountain pediment. Narrow canyons are cut by the streams; the canyons begin to form near the center of the basin within or on the margin of the alluvial plains and increase in length by headward erosion. As the little canyons



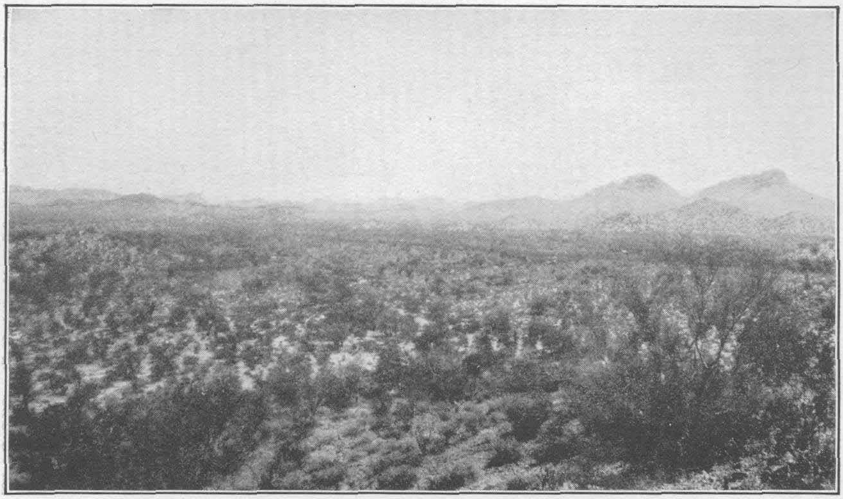
A. PASS WEST OF TULE TANK, ARIZ.

Niches in a granite mountain slope of the cliffy type due to massive jointing.



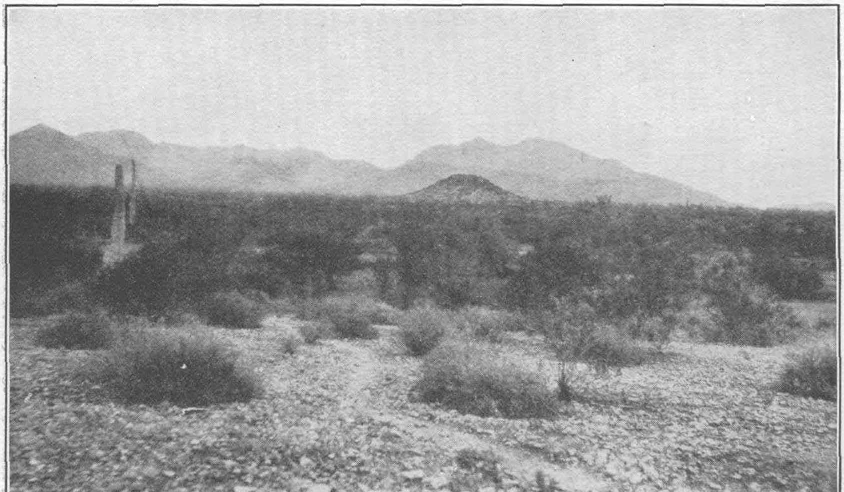
B. MOUNTAIN SLOPE AND DISSECTED PEDIMENT.

View north across Sand Tanks, which are in the small canyon in the foreground.



A. HEADWATER BASIN AND DISSECTED PEDIMENT IN THE SAND TANK MOUNTAINS, ARIZ.

Tilted lavas of Jack-in-the-Pulpit, on the extreme right, rest on the crystalline rocks in the foreground.



B. EAST SLOPE OF MARICOPA MOUNTAINS, ARIZ.

Undissected mountain pediment, with an outlier. In the outlier lava and gravel rest on an old erosion surface (pediment) from which the present pediment has been developed by a relatively small amount of erosion.

increase in length and complexity the pediment is carved into a maze of small hills with intervening sharply cut valleys, and the original surface is preserved only in the tops of hills or interstream areas.

Dissection of the pediment may be brought about by uplift of the mountain mass, as in the Burro Mountains, N. Mex,[54] or the trunk stream may intrench itself and thus lower the base-level. At the north end of the Gila Mountains dissection of the narrow pediment is due to the lowering of Gila River in late Pleistocene time. Similar lowering of Santa Cruz River near its junction with Gila River has caused the dissection of alluvial fans and a very narrow pediment at the north end of the Estrella Mountains.

However, dissection of pediments due solely to lowering of a trunk stream is the exception in the Papago country; yet the pediments are commonly dissected, as shown in Plates X, *A*; XII, *B*; and XIII, *A*. Near or within the mountain borders each stream passes over falls or through rapids into a steep-walled canyon. The walls are rock, in many places capped with a few feet of gravel, and average about 10 feet high (Pl. XII, *B*). Near the mountain they may be from 20 to 150 feet high, but downstream they become lower, and near the outer border of the pediment they gradually fade out in broad plains of alluviation, as shown in figure 19.

This type of dissection of the pediment has taken place generally and irrespective of the conditions of erosion and sedimentation in the adjacent valleys. In some valleys, such as the upper part of Altar Valley, where the axial stream runs in a trench, the canyons of the pediment connect with similar canyons in the alluvial plains and with the axial trench. Dissection of the pediment in this locality may not, however, be ascribed wholly to lowering of local base-level, but the dissection of the pediment and the dissection of the valley by its axial stream are doubtless due to the same cause. In the northern part of Altar Valley there is no middle trench, yet the pediment on the northern border of the Coyote Mountains and also in the Tucson Mountains is dissected. Thus the trench of the axial stream fades out downstream, as do also the little canyons of the pediment. (See p. 73.)

The lower margin of a mountain pediment is generally mantled with the alluvium, which can be seen resting on the rock, both being dissected by the streams. This alluvium is therefore older than the undissected alluvial plains characteristic of the northern part of the Altar Valley and the interior valleys of the Papago country. What is the relation of this older alluvium to the extension of the pediment under the valley and to the original rock floor? The relations which are thought to be general in the Papago country are shown in figure

[54] Paige, Sidney, op. cit., pp. 444 et seq.

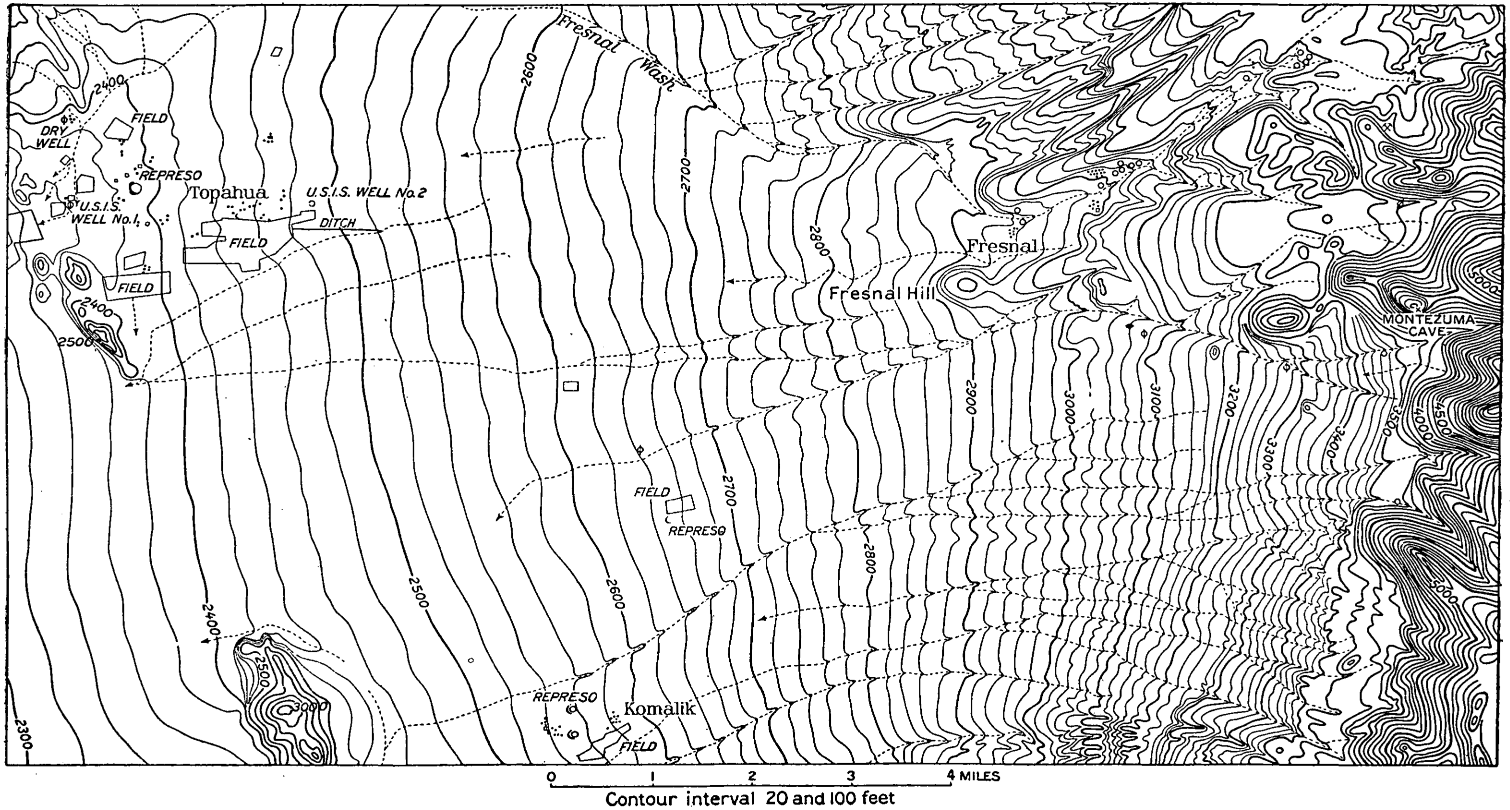


FIGURE 19.—Map of the vicinity of Fresnal and Topahua, Ariz., showing dissected pediment. Redrawn from map by the United States Indian Service.

20. It is believed that during the deposition of the older alluvium there was a gradual rise by aggradation of the middle portions of the valleys, accompanied by the erosion of a convex suballuvial bench. The alluvium then remained essentially stationary, occupying a slope of transportation of the available débris toward the local base-level. The erosion of the pediment took place during this time. The dissection of the pediment by small canyons took place after the completion of the pediment, and in that process the edges of the older alluvium were eroded, but the great mass in the middle portions of the valleys was either slightly buried or perhaps simply reworked by streams. The strict correlation of this older alluvium with that found in the valleys of Gila and Santa Cruz rivers has not been made but is discussed on page 30.

The two cross sections in figure 21 present the best data available regarding the rock floor of the valleys. Section A–B crosses the area represented in figure 14 to the Santa Rosa well, which is 920

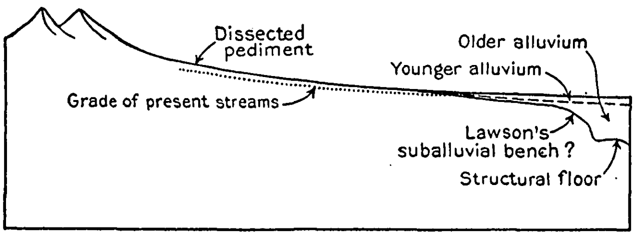


FIGURE 20.—Diagram showing the structural relations assumed for a typical valley in the Papago country, Ariz.

feet deep and does not reach the rock floor. To provide the requisite depth of alluvium at the well the rock floor under the alluvium from the edge of the pediment must be convex upward, and an error of as much as 2 miles in the location of the edge of the pediment will not vitiate this conclusion. Section C–D runs from the crest of the mountains westward across the area shown in figure 19 through the United States Indian Service wells. Well No. 2 is 602 feet deep and does not reach rock, but well No. 1 reaches rock at 100 feet. An even greater convexity of the rock floor must be assumed here, and the depression in which well No. 2 is sunk can not drain through the pass in the Artesa Mountains like the present streams.

The rock floors in both sections A–B and C–D have been drawn smoothly convex as if they were suballuvial benches, but it seems probable that their form is, in part at least, structural.

CAUSE OF DISSECTED PEDIMENTS IN THE PAPAGO COUNTRY.

Dissected pediments are widely scattered, lie at various elevations, and border valleys of unlike characteristics. The little canyons

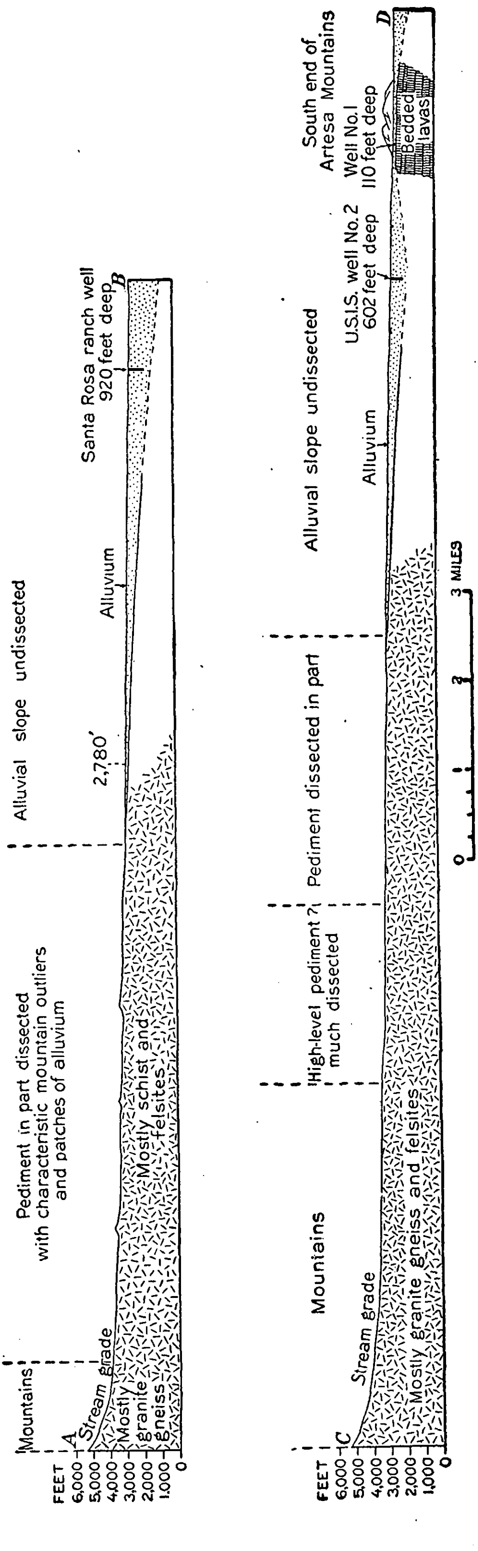


FIGURE 21.—Cross sections on the north and west sides of the Baboquivari Mountains, Ariz.

which dissect them must be due to some cause that affects the characteristics of the streams within the pediments. For a general condition a general cause must be sought, and the following analysis leads to a partial conclusion.

After the establishment of a pediment stream grades are adjusted to the supply of rock débris and the amount of water available in average floods. As the mountain front recedes there is a tendency for the slope of the pediment to become less steep as streams work farther into the mountains at the upper end; at the same time the mantle of alluvium at the lower end tends to increase in extent and still further cover the lower end of the pediment. In the interstream areas weathering and later planation tend to reduce the surface to the level of the stream beds. Conditions, however, are relatively stable.

Canyon cutting by the streams can take place only by an increase in the amount of water in proportion to the sediment carried, either by an increase in the supply of water or by a decrease in the supply of sediment. Because the streams are wholly ephemeral, the quantity of water in them is dependent directly on the amount and rate of rainfall. On the other hand, the supply of sediment depends upon the rapidity of mechanical and chemical erosion of the rocks on the mountain slopes. The principal factor in weathering is expansion and contraction through the influence of changes in temperature. It seems improbable that any general change in temperature could be sufficiently great to make an essential difference in the daily or seasonal changes in temperature in the desert. If these changes in temperature crossed the frost line, it would, of course, make a great deal of difference whether it was colder in any period of years than it had been in the preceding period of the same length. Although freezing temperatures are common throughout the winter, it is doubtful if frost action is an effective factor in the weathering of rocks in the desert ranges. In most of the mountains the rocks do not contain sufficient moisture to make freezing temperatures of any moment in their disintegration. None of the smaller peaks appear to be affected by frost action, but in a few of the higher summits there is some evidence that frost action may aid erosion.

It seems probable, then, that the dissection of the mountain pediments at the present time is due to increased rainfall, or to a greater concentration of rainfall with consequent increased stream action. It is also probable, however, that in this region of extreme aridity minor fluctuations in climate are not recorded with great sensitiveness. The conclusion that the present state of dissection of the mountain pediment is due to increased or more concentrated rainfall does not indicate that the present is a wet period. It implies only that the last change in climate which was effective on the mountain pediments was from a somewhat dryer to a somewhat wetter period.

VALLEYS.

STRUCTURAL ORIGIN OF VALLEYS.

Between the mountains of the Papago country lie great plains or valleys. They resemble the valleys of humid regions only in that they are bounded by higher land and contain the main lines of drainage. They are actually broad plains floored with alluvial material, which rise gently to the mountains on either side. Commonly they descend in the direction of an axial stream, though some of them drain through more than one outlet. They constitute about 80 per cent of the area of the region.

In previous pages it has been shown that of the 64 mountains whose structure is partly known, 25 have been uplifted and faulted, and 21 of these have been uplifted in the same period and doubtless by the same process. The valleys seem to be the blocks of the earth's crust which were down-faulted at the same time that the mountain blocks were uplifted. The evidence pointing to this structural relationship is of many kinds.

The valleys are prolonged in the general direction of the mountains and in the direction of what are presumed to be the major fault lines. In many places the lavas which make the mountains or small areas of lava which are remnants of larger masses that once capped the mountains dip toward the valley. Dips of this character were observed at one or more localities in 13 valleys. In many of the valleys isolated buttes of lava stand far out from the mountains, though the mountains may have been stripped of the lava which once covered them. A well in the Valley of the Ajo struck lava at a depth of 173 feet, and a well in the valley between the Crater and Sauceda mountains found lava at 615 feet. In both places deformation, presumably accompanied by faulting, must be postulated to account for the presence of lava.

That the structural valleys may have been profoundly modified by erosion before the initiation of valley filling can not be denied. It is, however, not supported by evidence in this region.

PROCESSES OF CHANGE OPERATING IN THE VALLEYS.

The processes of change now in operation in the valleys are largely those of transportation and deposition of sediment. Erosion, which is the dominant process in the mountains and on the pediments, is inoperative in the valleys except on their borders. Thus on the edges of most pediments the alluvium is dissected by the same streams which form the little rock canyons of the pediments, and at the mouths of some of the mountain canyons, where there is no pediment, the streams are incised in the alluvium from 5 to 20 feet. The areas of dissection, however, are small. The slopes from the mountains are molded to grades determined by the amount of water in the ephemeral streams and by the supply of sediment. The wind plays a subordinate part, shifting relatively small quantities of sand from place to place.

FEATURES OF THE VALLEY FLOORS.

DRAINAGE.

In spite of the excessive aridity of the Papago country, the valleys, except the southern part of Tule Desert, drain to the sea. Part of them are tributary to the Santa Cruz-Gila system and others to Sonoita River, which reaches the Gulf of California south of the Pinacate Mountains.[55] A few of the valleys are drained by more

[55] Lumholtz, Carl, op. cit., map.

than one stream, but the typical valley is lozenge-shaped with a main stream in the axis of the lozenge, toward which the ephemeral streams from the surrounding mountains flow and the alluvial fans built by these streams slope.

AXIAL STREAMS.

The residue of the floods from the mountains that is not absorbed or evaporated on the alluvial slopes is carried off by the main or axial streams of the valleys. It is probable that there are years when the residue is insufficient to cause the water to flow out of the valley into some other valley, but when there is sufficient water it flows from valley to valley and finally into the sea. The character of these streams can best be brought out by the description of examples.

One of the longest drainage lines, though in numerous places poorly defined, runs from the Baboquivari Mountains southwestward to Sonoita River. The water from Fresnal Canyon, on the west flank of the Baboquivari Mountains (see map, Pl. IX), goes slightly northwestward through the dissected pediment and then spreads over the plain, the larger part, however, going through the gap at the south end of the Artesa Mountains and irrigating the fields of Topahua. In this part of the course there is no definite channel, the water spreading over broad flats. West of Topahua several channels branch out. The water from all of them, if sufficient, reaches Valshni Wash, which runs northwestward through Kavolik toward Tonukvo. The surface in the vicinity of Kavolik is very flat and some water probably joins Big Wash and goes directly west to join the main drain of The Great Plain north of Serventi Well. Valshni Wash almost fades out as a definite channel before reaching Tonukvo, but the larger floods undoubtedly go through to this place, whence there is a small channel and a series of smooth flats through Copeka to Quijotoa Valley, north of the Copeka Mountains. This channel becomes very indefinite but joins the equally indefinite main drain of Quijotoa Valley southwest of Hardimui. Thence indefinite channels go southward through Comovo into Comovo Valley, at the south end of which there is a well-defined channel that carries all the water which reaches this part of Quijotoa Valley past the southern point of the Mesquite Mountains. Here the water spreads and very inconspicuous channels carry it and that which drains from the west slope of the Mesquite Mountains across The Great Plain past Camote into Sonoita River. The drainage thus traced has a length from the crest of the Baboquivari Mountains to Sonoita River of about 70 miles. The times when water traverses the whole distance must be comparatively rare. Small floods probably flow down the definite channels and then spread out over the broad flats and sink into the ground or evaporate. The continuous drainage line is probably maintained only by successive floods coming down tributaries.

One of the longest drainage lines begins with a stream which heads in granite hills east of Barajita Valley and flows about 3 miles northwestward to a narrow gap south of Walls Well. In this part of its course there is a small sandy channel which gives way in places to smooth areas of clay. From the gap and thence through Walls Well and westward for a mile or more there is a well-defined arroyo about 50 feet wide with banks 2 to 4 feet high. This channel disappears in the alluvial slopes of the Valley of the Ajo and is replaced by numerous smaller channels which lead westward toward Growler Pass. Just east of the pass is an extensive flat with clayey soils and a forest of mesquite trees, and here the small channels fade out. Two fairly definite channels flow into this flat from the southeast and northeast. By rather vague and indefinite channels in the flat the waters unite into a single channel with a gravelly bed which is about 50 feet wide and has banks from 3 to 4 feet high. This arroyo persists through Growler Pass and extends to a point about 3 miles southwest of Bates Well, where it fades out into minor channels. These channels in turn join the main wash of Growler Valley, which pursues a northwesterly course for about 30 miles to the Mesquital, an adobe flat that is similar to the one east of Growler Pass and that lies southeast of the southern point of the Aguila Mountains. From the Mesquital a channel leads to the axial stream of San Cristobal Valley. This axial stream has a well-defined channel about 50 feet wide trending northwestward, but near Garcia Well it fades out into an adobe flat which gradually increases in width until 9 miles farther on, at the Southern Pacific Railroad, it is almost 2 miles wide. Around the borders of the flat are low bluffs which are 2 to 5 feet high near Garcia Well and increase to 20 feet in height near the railroad. In this flat the channels are very small, but at the railroad a channel about 20 feet wide and 3 to 4 feet deep begins, which increases in width and depth until it reaches the flood plain of Gila River.

TRIBUTARY STREAMS.

The tributary streams that discharge into the axial streams are all of the ephemeral type and are active only during or immediately after rains. Near the mountains they commonly run in well-defined channels; farther down the slope they divide into several channels or spread out into broad sheets.

McGee has recorded in great detail a sheet flood which he observed in 1894 on one of the tributaries of Santa Cruz River. This tributary rises in the Santa Rita Mountains, crosses the dissected pediment and the dissected alluvial slope, and joins the flood plain of the Santa Cruz on a broad, smoothly sloping plain with a grade of 150 feet to the mile. McGee's description,[56] somewhat condensed, follows:

During the 1894 expedition a moderate local rain occurred. The rainfall was perhaps one-fifth of an inch, sufficient to moisten the dry ground, and was probably greater in the adjacent foothills of Santa Rita Range. Within half an hour a roar was heard in the foothills, rapidly increasing in volume; the teamster set out along the road up the [Santa Cruz] valley at best speed; but before he had gone 100 yards the flood was about him. The water was thick with mud, slimy with foam, loaded with twigs, dead leaflets, and other flotsam; it was seen up and down the road in either direction, fully half a mile in all, covering the entire surface save a few islands protected by exceptionally large mesquite clumps. The torrent advanced at race-horse speed at first, but, slowing rapidly, died out in irregular lobes not more than a quarter of a mile below [west of] the road; yet, though so broad and tumultuous, it was nowhere more than about 18 inches, and generally only 8 to 12 inches, in depth. The front of the flood was commonly a low, lobate wall of water 6 to 12 inches high, and it was evident that most of the water first touching the earth as the wave advanced was immediately absorbed and as quickly replaced by the oncoming torrent rushing over previously wetted ground. Such were the conspicuous features of the sheet flood—a thick film of muddy slime rolling viscously over a gently sloping plain; and this film was a transformed stream still roaring through a rugged barranca [canyon] only a few miles away. For perhaps five minutes the sheet flood maintained its vigor and even seemed to augment in volume; the next five minutes it held its own in the interior, though the advance of the frontal wave slackened and at length ceased, and in half an hour from the advent of the flood the ground was again whitening in the sun, save in a few depressions where muddy puddles still lingered.

The after effects of the flood were the accumulation of flotsam against the upper sides of clumps of shrubbery, ant hills, and ground-squirrel mounds; from these the limits of the flood could be traced, showing that it nearly blended with other similar floods from neighboring barrancas and arroyas. A less striking effect was the accumulation of a nearly continuous film of sediment, chiefly fine sand or silt. This film was usually an inch or less in thickness, though sometimes it lined depressions to depths of several inches.

Floods of the type described seem to be normal to the region. On the upper parts of the alluvial slope they flow in linked and shifting channels, but farther down, where they have dropped all the coarse sediment and are carrying only sand and mud, they spread out in broad sheets. Concentration of these sheets by permanent or temporary obstacles may cause the formation of a channel, but many of these channels are discontinuous, and there are broad flats without channels.

ADOBE FLATS.

The broad flats that are formed by deposition from sheet floods are floored with sandy clay or, in local parlance, adobe. Hence they are called adobe flats.

[56] McGee, W J, Sheet-flood erosion: Geol. Soc. America Bull., vol. 8, pp. 100–101, 1897.

The channels in the flats are of two types—shallow sandy channels ordinarily 2 to 5 feet wide and 3 inches to a foot deep, and deep channels from 5 to 6 feet deep and 15 to 30 feet wide. Parts of these larger channels may have a clay bottom and hold water for a time after rains or floods. Other shallow basins or pans, apparently produced largely by the trampling of animals, also hold water, and these two types of pools are called charcos.[57]

Orchard-like forests of mesquite are common on adobe flats. Usually the trees grow along the channels, and not uncommonly these lines of trees are paralleled by similar lines of dead or dying trees that mark the position of channels which have now disappeared. The adobe flats of Vekol Valley, however, are bare of trees and are covered by hummocks of "galleta" grass. Scraggly bushes of mesquite and unusually large creosote bushes separate the grassy adobe flat from the alluvial slope covered by vegetation of the normal type, dominated by the creosote bush.

Adobe flats are of all sizes. Many small ones 30 to 40 feet wide and a few hundred feet long occur along streams otherwise marked by channels. Others cover square miles of country and when flooded are gently moving sheets of water. The surface when dry is normally hard and smooth and somewhat streaked in appearance owing to the presence of fine crenulations in the direction of flow. There are also bits of rubbish collected on the upstream side of every obstruction.

PLAYAS.

The only temporary lake in the region lies on the international boundary and receives the drainage of the southern part of Tule Desert. The locality is called Las Playas, and the bed of the temporary lake is a good example of a playa, a flat area occasionally flooded by water which stands and evaporates. The surface is crossed by mud cracks which break the dark clay soil into large blocks. Many of the cracks are 3 to 4 inches wide at the surface and extend downward at least 3 feet. The edge of the barren flat is marked by scrubby mesquite bushes clustered about the charcos and channels that occur at the places of entrance of tributary streams.

WIND DEPOSITS.

In the area west of Ajo, on the whole the dryest part of the region, wind-blown sand is fairly common. The Yuma Desert is almost completely mantled with sand from 1 to 10 feet deep. The presence of grass and bushes and the general shapelessness of the dunes indicate that the movement of sand is not rapid. The eastern margin of the Yuma Desert and the west side of the Gila Mountains are

[57] Bryan, Kirk, Origin of rock tanks and charcos: Am. Jour. Sci., 4th ser., vol. 50, pp. 203–206, 1920.

drained by a stream flowing northward to Gila River, and along this stream erosion is sufficiently active to prevent the deposition of sand.

In the flood plain of Gila River there are many groups of low dunes, composed of sand derived from the broad sandy river channels. These dunes are commonly fixed in position by clumps of mesquite.

Along the eastern margin of the Lechuguilla Desert, Tule Desert, and Mohawk Valley are belts of sand dunes, which appear to be the residue of sand accumulated by the winds after sweeping the entire width of the valleys. The belt of dunes is particularly conspicuous at the southern end of the Pinta Mountains. In this locality the dunes are invading the mouths of the mountain canyons and impeding stream erosion. A belt of wind-blown sand from a quarter of a mile to a mile wide surrounds the Pinacate plain. Growler Valley and the Valley of the Ajo are almost free of wind-blown sand, but patches of drifted sand occur on the Sentinel plain and around its margin.

In the Quijotoa Valley, The Great Plain, and the plain near Copeka there are areas of wind-blown sand. The sand is usually only from a few inches to 4 feet thick and lies on the clayey surface of extensive adobe flats. The irregular distribution of the sand impedes the drainage and helps to break up and spread the floods. In making the artificial ponds of Tonukvo, Copeka, Comovo, and Camote the Papago Indians have taken advantage of the partial damming of channels in the adobe flats by wind-blown sand.

Interference with stream channels is perhaps the most notable effect of wind work in this region. In many localities channels in which water ran six months or a year before are blocked by low dams of wind-blown sand from 6 inches to a foot high. The next flood will probably take a new course, which will in turn be blocked. Thus the wind assists in the further diversion of streams which are already likely to be diverted under the laws of stream action.

TERRACES.

Many of the streams of the Papago country now flow below the level of deposits which they have laid down in past time. They flow in trenches bordered by bluffs leading to a broad terrace which, conforming to the grade of the alluvial slope, extends to the mountains. Some streams have deposited material at more than one level and thus are bordered by several terraces.

TERRACES OF GILA RIVER.

The valley of Gila River contains many terraces which parallel the river. The highest terrace is represented only in a few localities by small benches or by the tops of isolated hills and is composed of the material already described as older alluvium (p. 29). The lower terrace is well developed along the whole length of the river and is bounded on the lower side by bluffs about 75 feet high. It is composed of alluvium deposited in part by the river itself and in part by side wash from the ephemeral tributaries of the river. This material is referred to as the younger alluvium (p. 30). Below the terrace is the flood plain of the river, with its Recent deposits. These relations were recognized by Lee,[58] who correlated the alluvium of the higher terrace with similar material on Colorado River, which he called the Temple Bar conglomerate,[59] and the lower terrace would thus be the equivalent of the Chemehuevis gravel of the same river. The older alluvium, which corresponds perhaps to only a part of the Temple Bar conglomerate, lies at various elevations and is tilted in a number of localities, as at the north end of the Gila Mountains, 5 miles north of Blaisdell, south of Wellton, and in Tonto Basin.[60] Near Mesa a well 1,305 feet deep penetrates only alluvium and shows that the valley fill extends more than 100 feet below sea level.[62] As Gila River could not excavate a valley below sea level, earth movements must have followed the deposition of the older alluvium. Doubtless to these movements and the subsequent extensive erosion may be attributed the small areas now covered by the older alluvium and the inequality in height of the several outcrops. Field work in San Pedro Valley in 1920 and 1921 indicates that a large part of the deeper valley fill is of Tertiary age and older than the older alluvium.

The younger alluvium, of Chemehuevis age, forms a well-defined terrace and indicates that in Pleistocene time the river filled its valley to a level about 75 feet above its present elevation. The data for the age of the younger alluvium are presented on page 30.

Since that time the river has cut a valley through the deposits of Chemehuevis age and is again depositing material on its flood plain. Early reports indicate that up to about 1880 the Gila flowed in a relatively deep channel through its flood plain, overflowing it only in times of flood. There was also a considerable low-water flow. At present the channel is a sandy waste with many tortuous subsidiary channels, constantly shifting in position, and there is no low-water

[58] Lee, W. T., Underground waters of Salt River valley, Ariz.: U. S. Geol. Survey Water-Supply Paper 136, p. 112, 1905.

[59] Lee, W. T., Geologic reconnaissance of a part of western Arizona: U. S. Geol. Survey Bull. 352, p. 18, 1908.

[60] Lee, W. T., Underground waters of Salt River valley, Ariz.: U. S. Geol. Survey Water-Supply Paper 136, p. 112, 1905.

[62] Lee, W. T., op. cit., p. 115. Additional evidence from well records is given by Ross, C. P., The lower Gila region, Ariz.: U. S. Geol. Survey Water-Supply Paper — (in preparation).

flow except in favored places. There seems to be a greater proportionate load of sediment, which under present conditions is silting up the channel.

TERRACES OF ALTAR AND SANTA CRUZ VALLEYS.

Santa Cruz Valley and its tributary, Altar Valley, which lies parallel to and west of it, are marked by several common features. Altar Valley lies between the Baboquivari and Coyote mountains on the west and the Tumacacori, Cerro Colorado, Sierrita, and Tucson mountains on the east and drains north to Abra Valley and thence to the Santa Cruz. It is about 40 miles long and ranges in width from 8 to 15 miles. The head of the valley from Buenos Aires south, and for 3 to 4 miles out from the mountains on the west side as far north as Las Moras and on the east side as far north as the San Luis ranch, is a plain cut on rock—a mountain pediment. About 4 miles south of Buenos Aires is the divide which separates the drainage going south past Sasabe into Mexico. It is smooth and flat. The head of the valley consists of confluent pediments formed by streams from the adjacent mountains, some of which flow north and others south.

Pediments border the east side of the valley and are probably extensive. On the west, however, from Las Moras to the Coyote Mountains, the pediment is narrow and the plains are covered by very coarse alluvium. Along the Coyote Mountains the exposed pediment is from half a mile to 3 miles wide.

The headwater streams in the pediment areas are incised in narrow valleys from 10 to 50 feet deep. These trenches lead from all the mountain canyons to an axial stream which, originating in the union of Arivaca Creek and the stream which follows San Luis Canyon, runs north almost to the Anvil ranch. Each trench is a flat-bottomed valley from a quarter of a mile to 1½ miles wide. The loamy bottom is marked by a well-defined arroyo with banks from 2 to 6 feet in height. The bluffs of the trench have their maximum height of about 75 feet near Buenos Aires, decreasing in height upstream and downstream. Near the Anvil ranch the bluffs are about 20 feet high, and thence northward they fade out rapidly, so that at the Robles ranch there is no sharp separation between the plain of alluviation of the main stream and those of its tributaries.

The trench of the main or axial stream shows no definite terrace, but a terrace is common on the tributaries, though owing to the "accidents" of erosion it is absent in many places. West of Pozo Nuevo the tributary valleys are from a quarter to half a mile wide. Each valley has a flood plain in which the stream is intrenched about

10 feet, like the axial stream. Above the flood plain is a terrace about 15 feet high, and then a narrow flat, followed by a gentle slope to the level of the plains, 35 to 40 feet higher.

Near Arivaca the flood plain of Arivaca Creek is bounded by low bluffs about 20 feet high which constitute the face of a narrow discontinuous terrace. About 40 or 50 feet above the terrace lies a rolling plain cut on rock, which is part of a well-developed mountain pediment. Arivaca Creek near the town now runs in a trench about 200 yards wide and 15 feet deep. This trench has been formed within recent time, for when white men first came into the country the flood plain was a marshy flat. Lieut. Michler[64] visited Arivaca in July, 1855, and his narrative states that "numerous springs lie concealed among the tule," a phraseology which implies that there was a swamp with rushes or "tule" at this locality.

Santa Cruz River rises in Arizona at the southern base of the Canelo Hills and flows southward through a broad depression called

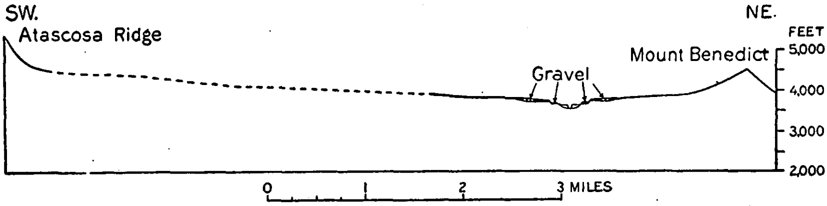


FIGURE 22.—Cross section of part of Santa Cruz Valley (Nogales Wash), Ariz., from Mount Benedict to the Tumacacori Mountains.

the San Rafael Valley, between the Patagonia and Huachuca mountains. Crossing the international boundary, the river describes a loop of 30 miles and reenters the United States 6 miles east of Nogales. At the international boundary the stream has an elevation of about 3,700 feet and thence northeastward to Calabasas its grade is 40 feet to the mile. Near Calabasas the Santa Cruz is joined by Nogales Wash, sometimes called Potrero Creek, which flows northward from Nogales, and by Sonoita Creek, which heads on the east side of the Santa Rita and Patagonia mountains. This part of the Santa Cruz Valley is a broad lowland about 17 miles wide from the base of the Patagonia Mountains to Atascosa Ridge, in the Tumacacori Mountains. The lowland is composed of long ridges and flat-topped spurs extending from the bordering mountains toward Santa Cruz River and its tributaries. Similar ridges slope from the divide between Nogales Wash and the river. The culminating point of this divide is Mount Benedict, a bold, somewhat conical mountain. Between the ridges are sharp-walled, terraced canyons, which

[64] Emory, W. H., Report on the United States and Mexican Boundary Survey, vol. 1, p. 119, 1857.

lead to the flat inner valleys along Santa Cruz River and its two main tributaries. The flat floor of Nogales Wash is from an eighth to half a mile wide, a moist and fertile meadowland which narrows in places but grows wider downstream until it merges into the similar floors of the inner valleys of Santa Cruz River and Sonoita Creek. In these flat meadows the streams have cut narrow, steep-sided gullies from 10 to 30 feet deep.

The bluffs bordering these flood plains show a double terrace, the upper one coincident with the sloping ridges and the lower about 50 feet above the flood plains. These relations are shown in figure 22.

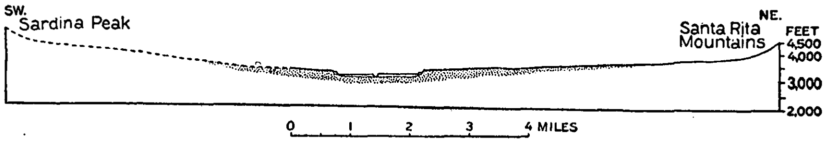


FIGURE 23.—Cross section of Santa Cruz Valley from Sardina Peak to the Santa Rita Mountains near Tubac, Ariz.

The upper terrace is in places covered with thin alluvium. The lower terrace is everywhere capped with 10 to 20 feet of gravel.

From Calabasas to the mouth of Sopori Creek, Santa Cruz Valley is from 8 to 12 miles wide. Long-dissected slopes lead down to an inner valley bounded by bluffs. Near the mountains the side streams flow in deep gorges through narrow pediments, and lower down they occupy flat-bottomed valleys bounded by bluffs of alluvium. The floors of the tributaries join and merge with the flood plain of Santa Cruz River. This flood plain is 1 to 2 miles wide, and through it

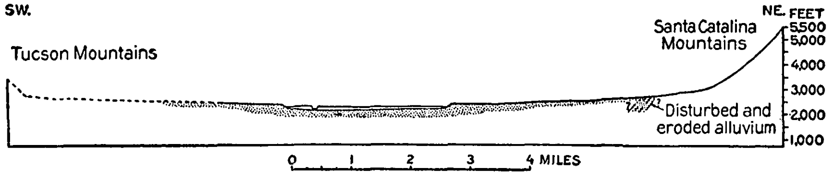


FIGURE 24.—Cross section of Santa Cruz Valley at Jaynes, Ariz.

the stream flows in a steep-walled channel from 10 to 20 feet deep. The cross section in figure 23 shows the character of the slopes and the form of the inner valley near Tubac, a location typical of this portion of the valley. The cross section brings out the double terracing of the valley, but these terraces, though of approximately the same height as those farther upstream, are unlike them in being composed wholly of alluvium.

Forty miles to the north, near Tucson, the inner valley, with its flood plain and the narrow trench in which the river runs, is bounded by ragged bluffs about 25 feet high, as shown in figure 24. From the tops of these bluffs the alluvial slopes sweep upward to the mountains.

There is no second terrace, but vague irregularities in these slopes look like the remnants of an older valley filling, and were so interpreted by Huntington.[65]

From Tucson northward the bluffs bounding the inner valley of the river decrease in height and near the north end of the Tucson Mountains disappear. Similarly, the trench in the flood plain becomes shallower, and Santa Cruz River in flood spreads widely over great adobe flats in which the main channel is so obscure that its mapping is arbitrary. Figure 25 is a cross section through Toltec, where the river has two main channels, which are, however, very shallow and seldom hold all the flood waters. The great flats of Santa Cruz River merge with those of its tributaries. The stream that drains Altar and Abra valleys has, like the others, lost the terracing characteristic of its headwaters. The flats of Santa Cruz River lie at or only slightly above the level of the bluffs along Gila River, which are about 50 feet high in the stretch from Florence to Gila Crossing. The flats were evidently developed when Gila River flowed at the level of these bluffs. The lowering of Gila River has

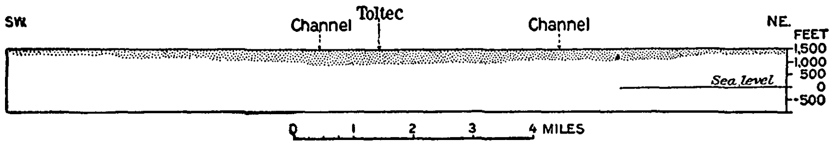


FIGURE 25.—Cross section of Santa Cruz Valley near Toltec, Ariz.

affected its tributary in its lower portion only, where for a distance of 5 or 6 miles upstream from the junction near Gila Crossing Santa Cruz River lies in a shallow valley 10 to 50 feet below the surrounding plain.

The physiographic features of Santa Cruz River, just recounted, are similar to those of Altar Valley. From Calabasas southward the Santa Cruz Valley and its tributary valleys consist of dissected pediments sloping from the bordering mountains to a terraced inner valley. The topography is similar to that near Arivaca and in the southern part of Altar Valley. The events recorded by this topography seem to be (1) long-continued erosion following the original uplift of the mountains and forming extensive mountain pediments; (2) deposition of alluvium on the lower portions of the pediments in a period of deposition either following the first period of erosion or concurrent with it; (3) erosion of an inner trench at the level of the terrace, shallower but wider than the present trench; (4) deposition on the floor of this trench in a second period of deposition either following the second period of erosion or concurrent

[65] Huntington, Ellsworth, The climatic factor: Carnegie Inst. Washington Pub. 192, p. 24, 1914.

with it; (5) erosion of the inner valley to a depth slightly below the flood plain; (6) deposition of the silt and sand of the flood plain in a third period of deposition either following the third period of erosion or concurrent with it; (7) erosion of the trench or channel in the flood plain. The last event has taken place within historic time and is discussed more fully in a later paragraph.

The cross section at Tubac resembles the part of Altar Valley near Secundino Well, where the bluffs of the inner valley are of alluvium. The terrace, however, is not well developed in Altar Valley except in certain tributary streams. (See p. 73.) The events recorded are similar in sequence to those recorded farther south and fall into seven stages, but deposition has been far more important than erosion, especially in the earlier stages.

The cross section near Tucson (fig. 24) probably indicates the same sequence of events, but the reddish faulted and eroded alluvium near the mountains can not be correlated with the alluvium capping the dissected pediments near Calabasas or the great body of alluvium of the dissected alluvial slopes near Tubac, as it is doubtless of Tertiary age. The alluvium of the sloping plains and terraces can not be separated into an older and a younger division without further field work.

The cross section near Toltec (fig. 25) shows deposition only, and the Santa Cruz Valley in this part of its course resembles Altar Valley at the Robles ranch. Not even the recent channel trench persists into the Santa Cruz flats, and the history of this part of the Santa Cruz Valley, so far as it is recorded in the surface features, is one of uninterrupted deposition.

The recency of the cutting of the channel trench of Santa Cruz River in the stretch between Calabasas and Tucson was first pointed out by Spaulding [66] and has been studied in detail by Huntington.[67] According to the testimony of local residents, the flood plain was once covered with sacaton grass, the channel of the river was insignificant, water during floods spread over most of the grassy flood plain, and tules (bulrushes) grew in the boggy places. Late in the eighties ditches and cattle trails were enlarged by floods and the present channel, which is from 100 to 300 feet wide and from 12 to 15 feet deep at Tucson, was made. The great floods of 1905 completed the channel, and Huntington thinks that since that time there has been a tendency for the channel to silt up.[68] Near Point of Rocks, north of Tucson, Huntington found palo verde trees (prob-

[66] Spaulding, V. M., Distribution and movements of desert plants: Carnegie Inst. Washington Pub. 113, p. 9, 1909.

[67] Huntington, Ellsworth, op. cit., pp. 33–34.

[68] Idem, pp. 24, 33.

ably *Cercidium torreyanum*) whose lower trunks were buried in alluvium and reexcavated by the cutting of the channel. On cutting down one of these trees and examining its rings of annual growth he found that it began to grow between the years 1670 and 1680 on a plain about 5 feet below the level of the flood plain of 1880. Gradual deposition of silt buried the base of the tree during the next 200 years.[69]

Father Kino's account of the valley near Tucson is of course colored by his enthusiasm and missionary zeal, but his statements imply conditions very unlike those of the present. In 1692 he found 800 persons at San Xavier del Bac, 12 miles south of Tucson.[70] In January, 1697, there were at the same place "beginnings of good sowings and harvests of wheat," and in November of the same year he counted in the ranchería and environs 6,000 persons and "found even bread, fresh and very good."[71] In October, 1699, he counted 1,000 persons in the ranchería of San Xavier del Bac and states: "The fields and lands for sowing were so extensive and supplied with so many irrigation ditches running along the ground that the father visitor [Antonio Leal] said they were sufficient for another city like Mexico."[72] Of San Cosme del Tucson, probably located just west of the present city of Tucson, he says that it had "splendid fields." Similarly he states that he counted 200 men representing 200 families at San Agustin del Oyaut (Oiaur), probably between Jaynes and Rillito. At Santa Catarina del Cuytoabagum he found 300 men representing 300 families.[73] This ranchería was probably near the present Picacho. In April, 1700, after erecting the foundation of a church and beginning a mission at San Xavier del Bac, Kino states that the mission "will be able to have throughout the year all the water it may need, running to any place or workroom one may please, and one of the greatest and best fields in all Nueva Biscaya."[74]

The purport of these statements is that at the beginning of the eighteenth century, about 20 years after the palo verde which Huntington examined had sprouted, the flood plain of Santa Cruz River was without a deep channel and had a permanent stream, else the Indians with their primitive wooden tools would not have been able to divert the water into ditches, nor would the water have lasted all the year. It should be remembered also that the cutting of the channel trench has facilitated the flow of ground water at the present time. There must, then, have been much more water available in 1700 to cause the river to flow the year round. The extensive settle-

[69] Huntington, Ellsworth, op. cit., pp. 33, 34.

[70] Bolton, H. E., Kino's historical memoir of Pimería Alta, vol. 1, p. 122, Cleveland, 1919.

[71] Idem, p. 173.

[72] Idem, p. 205.

[73] Idem, p. 206.

[74] Idem, p. 236.

ments down the river from Tucson are also significant, for, unless the floods were stronger and more frequent than now, 200 families could not live by primitive agriculture between Jaynes and Rillito, nor could 300 families live near Picacho. The narrative of Kino thus adds force to the arguments of Huntington that there was once a wetter climate in southern Arizona. One of these periods of slightly wetter climate appears to have been during the time of the missionaries. The first effect on topography of a change to drier conditions came between 1880 and 1890, when changes in the channels of streams took place in widely scattered localities in the Southwest. In northern Arizona Gregory [75] has been able to fix the dates when a number of streams began to cut trenches. These dates range from 1880 to 1894, but the most extensive work was done late in the eighties. Lumholtz [76] states, on the authority of Señor Isauro Quíroz, a resident of Sonoita, that the recent changes in Sonoita River took place on the night of August 6, 1891. Before that time the head of permanent water in the river was in a narrow channel, above which were extensive swamps (ciénagas) for about 3 miles. The present channel, which in 1912 was 250 feet wide and from 18 to 20 feet deep, formed suddenly after a heavy rain. The swamps were drained, and a forest of mesquite sprang up. Many metates, manos, and seashell ornaments were found by local people after the cutting of this channel, which, according to the location pointed out by Señor Quíroz, must have been buried at least 20 feet below the surface of the flood plain. Lumholtz found one metate embedded in the embankment about 12 feet below the surface. There is, then, good evidence that there were considerable meadows and ciénagas at Sonoita, where Indians lived for a very long time, during which there was a filling of silt to a depth of 20 feet. This accords with the following statements made by Father Kino [77] in October, 1700:

> This post and ranchería of San Marcelo [del Sonoydag] is the best there is on this coast. It has fertile land, with irrigation ditches for good crops, water which runs all the year, good pasture for cattle, and everything necessary for a good settlement, for it has very near here more than a thousand souls, and many more in its environs.

The significant part of this statement is the number of people "very near here," for at present the whole valley of the Sonoita will not support more than a fifth as many. Lumholtz says that in 1912 there were in this valley 100 Mexicans and 70 to 80 Indians.[78] Even with the benefits of domestic animals, wheat, fruit trees, and other

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[75] Gregory, H. E., Geology of the Navajo country, Ariz.: U. S. Geol. Survey Prof. Paper 93, pp. 130–131, 1917.

[76] Lumholtz, Carl, New trails in Mexico, pp. 178–180, 1912.

[77] Bolton, H. E., op. cit., p. 255.

[78] Lumholtz, Carl, op. cit., pp. 176, 387.

facilities which were unknown before Kino's time, it is doubtful if more than 300 people have lived in the Sonoita Valley in recent years.

Similar changes in conditions have been widespread in the Southwest. Old-timers tell of "cutting hay with a hoe" and riding in grass "stirrup high" during the seventies on the "mesa" east of Albuquerque, in central New Mexico. These tales are in marked contrast to conditions since 1900, with which the writer is familiar. The valley of the Rio Puerco (of the East) west of Albuquerque has had a history like that of the Santa Cruz. Once the stream had a channel only 2 or 3 feet deep and during great floods spread over its flood plain, which ranges in width from a quarter of a mile to a mile. The Spaniards drove the Navajos out of the valley and founded the towns of San Ignacio, San Fernando y Blas, and San Francisco on the tract of land now known as the Bernabe M. Montaña grant. Water was diverted by low brush dams from the river to acequias for irrigation. Large floods gave a natural irrigation to the crops. According to local residents, the cutting of the present channel trench, which is from 25 to 30 feet deep and from 200 to 300 feet wide, began in the eighties. The cut progressed upstream by headward erosion and thus successively cut off the ditches from access to the stream. The violent floods flowed in the deep channel, no longer covering the flood plain, and they also prevented the building of adequate diversion dams, so that the towns were gradually abandoned. San Ignacio persisted longer than the others. The inhabitants could not carry on agriculture, except for a little precarious flood-water farming, but were supported by trade, stock raising, and freight hauling.

These scattered records indicate that before 1880 the streams of the arid Southwest and of Arizona in particular were largely engaged in depositing sediment, and many flood plains were grassy or swampy. Erosion began during the eighties and has continued to the present time. Somewhat different features are presented by Gila River (p. 71), on which the change in regimen coincides in time with the changes on Santa Cruz River but differs in character.

TERRACES IN THE INTERIOR VALLEYS.

Pumpelly [79] was the first to observe that the valleys west of the Baboquivari Mountains are undissected compared to those east of these mountains. The dissection of the pediments and the upper parts of the alluvial slopes has already been mentioned (pp. 62, 66). Vekol Valley, however, presents some anomalous features. The main stream, after passing through extensive flats covered with

[79] Pumpelly, Raphael, Mineralogical sketch of the silver mines of Arizona: California Acad. Sci. Proc., vol. 2, pp. 127–139, 1863.

"galleta" grass where deposition is going on, enters, near the Brush Corral, a shallow trench. The trench is from 5 to 10 feet below the adjacent slopes and is from 100 to 300 feet wide. The floor of the trench is formed of a deep loamy or sandy clay soil and supports a thicket of large mesquite trees. The stream is still further intrenched in a channel trench from 5 to 10 feet deep and apparently no longer covers the plain in time of flood. This arrangement of slightly dissected alluvial slopes, low bluffs flanking a flood plain, and a channel trench continues northward for about 10 miles and then fades out, so that at Mobile, on the Southern Pacific Railroad, 18 miles farther north, the stream has several channels, none of which are well marked. In miniature, then, there is reproduced on this stream the physiography of the Santa Cruz at Tucson, and in similar fashion the terraces fade out downstream.

Somewhat similar but vaguer terraces were observed on the stream that drains the southern part of Barajita Valley. A gravel-covered hill about 10 feet high, which gives the name to Charco de la Lomita, and similar hills near Totobit Tanks and at other localities may be vestiges of terraces of a like kind now destroyed or largely buried in the present cycle of sedimentation in the interior valleys.

GEOLOGIC AND PHYSIOGRAPHIC HISTORY.

PRE-TERTIARY EPISODES.

The geologic history of the Papago country begins in the obscurity of early pre-Cambrian time. As in other parts of Arizona, sedimentation, now represented by schists, was followed by igneous intrusion of granitic rocks, accompanied by intense dynamic metamorphism. Then followed a long period of erosion, which, so far as the evidence goes, continued to the beginning of Cambrian time. The later pre-Cambrian, known from the Grand Canyon [80] region, has not yet been differentiated in the Papago country and may be absent.

Paleozoic time seems to have been an era of quiet in respect to earth movements, with spreading seas which lapped over the region from the southeast. The expansion of the sea from the southeast is recorded by the occurrence of Cambrian, Devonian, and Carboniferous rocks in the Santa Rita Mountains and of Cambrian and Carboniferous rocks in the Tucson Mountains, but in general west of Santa Cruz River only Pennsylvanian rocks have been found. The absence of Paleozoic rocks from the region west of Ajo and from the lower Gila region seems to imply either that these regions remained above the

[80] Noble, L. F., The Shinumo quadrangle, Grand Canyon district, Ariz.: U. S. Geol. Survey Bull. 549, pp. 37–60, 1914.

Paleozoic seas or that they were particularly affected during the succeeding revolution, when folding took place in the ranges east of Santa Cruz River.

Early Mesozoic time was in other parts of Arizona marked by the deposition of continental deposits, many of them indicating arid conditions. No sedimentary record is available in the Papago country except in the Tucson Mountains, but the Paleozoic rocks were dislocated and large parts of them removed before the Mesozoic igneous intrusions took place. The igneous activity of Mesozoic time included extrusion of lava and intrusion of large batholithic masses. Hardly had this activity ceased when deposition by streams began. The area of deposition, however, covered only the southeastern part of the region toward the early Cretaceous sea. In this area folding and overthrusting took place in post-Cretaceous time. The Papago country may also have been involved in these movements, but continuous erosion down to Tertiary time has largely obliterated the evidence.

TERTIARY LANDSCAPE.

The Tertiary history of the region is striking in character and represented by a profusion of rocks. The details of this history can not be given, however, for lack of evidence. Three glimpses of the region during this period are revealed.

At the beginning of Tertiary time uplift and erosion began and the major features of the present time were rudely blocked out. It is not likely that this uplift was simultaneous over the whole area, but the present high land seems to have been elevated, and deposition by streams took place in local basins.

Of the deposits of Tertiary time, the beds in Adobe Canyon, in the Santa Rita Mountains, are definitely known to be Eocene. The other Tertiary sedimentary rocks can not be definitely dated, but they testify to the climatic and physiographic conditions of the time. All the beds are arkosic—that is, they are composed in part of undecomposed grains of feldspar. Rudely bedded, unsorted, in places with large boulders, they must have been laid down by torrential, probably ephemeral streams under climatic conditions very similar to those of the present day. They commonly rest on the eroded surface of the underlying rocks, and the basal beds are made up largely of material derived from local sources. The beds consist of the coarse detritus derived from the erosion of desert mountains, laid down on the flanks of these mountains. The succeeding lava flows extended, in places, over the Tertiary conglomerates and usually far beyond them, covering the mountains in whole or in part. As uplifted and exposed by erosion, the surface on which the conglomerates and volcanic rocks rest is in many places smooth, but protuberances stand from a few feet to as much as 1,500 feet above the general level. The elevations were low residual mountains of the sierra type, surrounded by pediments leading down to the basins in which the conglomerates had accumulated. The end of the Tertiary volcanic period found this topography masked by lavas accumulated to maximum thicknesses of 2,000 feet.

Much more work will be necessary to determine the areas that were once covered by lava. In the central part of the region the lavas were almost continuous, and the district including the Sand Tank, Sauceda, Ajo, and Growler mountains seems to have been one of the great lava fields of Tertiary time. In other localities, such as the Maricopa and Salt River mountains (p. 27), the lavas were thin, and probably there were some areas without lava.

Between the areas of accumulation of lavas were doubtless basins in which streams deposited the gravel now found interbedded with the lavas. Farther north, in the lower Gila region, there were brackish waters in which limestone was deposited.[82]

The third glimpse of Tertiary time shows the region after the period of faulting, in which great strips and blocks of the earth's crust had been uplifted and tilted to form the present mountains and similar blocks and strips had been relatively depressed to form the valleys. These movements probably took place in or at the end of Pliocene time.

PLEISTOCENE AND RECENT TIME.

The later history of the region is largely one of erosion of the mountains and sedimentation in the valleys. Both of these processes have been interrupted, and the Pleistocene comprised two cycles of erosion and sedimentation and part of a third, which was continued into Recent time.

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[82] Ross, C. P., op. cit.

The following table summarizes the events as recorded in the Gila Valley:

Events in geologic history of Gila Valley.

Period.	Epoch.	Deposition.	Erosion.
Quaternary.	Recent.	10. Silting of channels, continuing at present.	
		9.	Erosion of channels, which continued until 30 years ago.
		8. Deposition of the flood-plain materials.	
	Pleistocene.	7.	Erosion of the inner trench of Gila River.
		6. Deposition of younger alluvium (of Chemehuevis age?) to levels 75 feet above present Gila River. Outpourings of basalt.	
		5.	Minor dislocations and upheavals. Erosion of Gila River below present grade.
		4. Deposition of the older alluvium (of Temple Bar age?) to depths of 1,000 to 1,500 feet.	
——(?)——	——(?)——		
Tertiary.	Pliocene (?).	3.	Uplift and block-faulting of mountains. Followed by erosion of the mountains and beginning of the present pediments.
	Miocene (?).	2. Period of volcanism, great extensions of lava; stream-laid conglomerates; those at the base representing later part of period 1.	
	Eocene (?).	1.	General erosion of the region resulting in extensive coalescing pediments, surmounted by small mountains, and the deposition of alluvium in the valleys.

As the several parts of the Papago country present anomalous features, correlation of the events of post-Miocene time is somewhat hazardous. In addition to earth movements the known fluctuations of climate must have had their effect on erosion and sedimentation. In the table given below the history of the Gila Valley, already summarized, is compared with that of the Santa Cruz, Altar, and interior valleys of the Papago region and with that of Colorado River.

If the fluctuations of erosion and sedimentation are to be explained wholly by earth movements, then these movements must have been very complex. At the same time they must have been singularly harmonious; otherwise the Santa Cruz and Altar valleys would not have experienced conditions so similar in three separate sections of their courses. On the other hand, if changes in climate cause the fluctuations of erosion and sedimentation, then certain changes in climate which affected the region east of the Baboquivari Mountains did not affect the valleys west of the mountains.

Geologic history of certain localities in the Papago country, Ariz., and elsewhere in relation to known earth movements and postulated climatic changes.

Locality.	Pliocene uplift and humidity(?).	Early Pleistocene with basalt flows at the close, and aridity(?).	Minor earth movements and humidity(?).	Pleistocene with basalt flows toward the close and aridity(?).	Humidity(?).	Aridity(?).	Continued aridity; minor fluctuations, trend not known.
Gila Valley	Erosion; stage 3 [a]	Deposition; stage 4.	Dislocation and erosion; stage 5.	Deposition and basalt flows; stage 6.	Erosion; stage 7.	Deposition of the flood plain; stages 8 and 9.	Deposition; stage 10.
Santa Cruz Valley and Nogales Wash above Calabasas.	Erosion of mountain pediments.	Slight fill of alluvium.	Erosion of first inner valley.	Deposition of gravel in inner valley.	Erosion to present levels of streams.	Deposition of flood-plain materials.	Recent trench in flood plain.
Santa Cruz Valley at Tubac.	Erosion of great valley and pediments near mountains.	Deposition of alluvium.	Erosion of alluvium.	Deposition of alluvium of terrace.	Erosion of alluvium.	....do.	Recent trench.
Santa Cruz Valley at Tucson.	Erosion of great valley.	Deposition of alluvium.	(?); probably faulting and erosion.	Deposition of alluvium.	Erosion of inner valley.	....do.	Do.
Santa Cruz Valley near Toltec.	....do.	Deposition.	(?).	Deposition.	(?).	Deposition.	Deposition.
Altar Valley near head.	Erosion of pediments	(?); slight deposition in places near Arivaca.	Erosion of inner valley.	Deposition of terrace on a few streams only.	Erosion.	Deposition of flood plain on certain streams as Arivaca Creek.	Recent trench of Arivaca Creek.
Altar Valley near Palo Alto.	Erosion of great valley and pediments near mountains.	Deposition.	(?).	Deposition.	....do.	Deposition of flood plain.	Recent trench.
Altar Valley near Robles ranch.	....do.	....do.	(?).	....do.	Erosion of pediments only.	Deposition in center of valley, erosion of pediments.	Deposition in center of valley; erosion of pediments.
Typical valley west of Baboquivari Mountains.	Erosion of pediments with deposition in center of valley.	Slight deposition on mountain pediments.	(?).	Slight deposition on mountain pediments(?).	Erosion of pediments. Continued deposition in center of valley.	Deposition in center of valley and near mountains in some localities; erosion of pediments.	Deposition in center of valley; erosion of pediments and dissection of the minor deposits near the mountains in some localities.
Colorado River [b]	Erosion of Grand Canyon and flow of Colorado in detrital Sacramento Valley.	Aggregation and volcanic activity; Temple Bar conglomerate 2,000 feet.	Rejuvenation of streams. Colorado River cuts 2,000 feet or more west of Black Mountains.	Deposition of Chemehuevis gravel.	Rejuvenation of streams. Colorado reexcavates old valley and cuts several short rock gorges.	Formation of flood plains.	

[a] Numbers refer to table on p. 84.

[b] Lee, W. T., U. S. Geol. Survey Bull. 352, p. 67, 1908.

GLOSSARY.[83]

Adobe flat. A generally narrow plain, having a slope of 5 to 20 feet to the mile, built of fine sandy clay or adobe brought down by an ephemeral stream, having a smooth surface that is usually unmarked by stream channels, but where so marked the channels are insignificant.

Alluvial fan. A sloping, fan-shaped mass of loose rock material deposited by a stream at the place where it emerges from an upland into a broad valley or a plain. The highest point is at the apex of the fan, which is generally composed of boulders and cobbles that are dropped as soon as the stream emerges from its confining canyon walls. The slope of the surface near the apex may be as much as 300 feet to the mile, but it decreases toward the outer limit to as little as 10 feet to the mile. The smoothness and regularity of the surface is due to the fact that the stream soon blocks its own course with the material which it drops and so is forced to shift its channel from place to place, occupying, in time, all parts of the fan and building it up and extending it in a regular manner. If the mass of material has steep slopes it is generally called an alluvial cone, but if the slopes are relatively flat it is called an alluvial fan.

Alluvial plain. A plain resulting from the deposition of alluvium by water. in the southwestern United States most alluvial plains are formed by streams having a considerable grade, and hence they are generally referred to as alluvial slopes.

Alluvial slope. A surface composed of alluvium which slopes down and away from the sides of mountains and which merges with the plain or broad valley floor upon which it rests. The slope near the mountains may be as much as 300 feet to the mile. The plain is built by deposition from streams, commonly ephemeral or intermittent, through the union or coalescence of their alluvial fans, and is often called a fan apron, débris apron, or piedmont plain or slope.

Alluvium. The material deposited permanently or in transit by streams, including gravel, sand, silt, and clay and their mixtures and variations. Unless otherwise stated, alluvium is unconsolidated.

Arkose. A sand or sandstone composed of mineral fragments derived from decayed granite. A large part of the component grains are quartz and feldspar. Arkosic conglomerate is a conglomerate in which the finer material or matrix containing the boulders or pebbles is an arkose.

Arroyo. The channel of an ephemeral or intermittent stream, usually with vertical banks of unconsolidated material 2 feet or more high. The term is frequently applied to the stream which occupies such a channel.

Axial stream. The main stream of an intermontane valley, which flows along the lowest part of the valley and parallel to its longer dimension, in contradistinction to the numerous streams which flow from the mountains on either side and build up the alluvial slopes. The term is also applied to a stream which follows the axis of an anticlinal or synclinal fold.

Barranca. A deep break or hole made by heavy rain; a ravine; a precipice; also used in some parts of Spanish America as the equivalent of canyon; as used in New Mexico it is practically equivalent to cliff.

[83] This glossary of terms is prepared for the use of the lay reader and is not intended for geologists or physiographers. The scientific reader will realize that full and accurate explanations of most scientific terms in familiar language is impossible, and only a rough approximation to the full meaning can usually be given.

Base-level. The theoretical limit toward which erosion constantly tends to reduce the land. Sea level is the general base-level, but in the reduction of the land there may be many temporary base-levels below which, for the time being, the streams can not reduce the land. These temporary base-levels may be controlled by the level of a lake or a river into which the streams flow, or by a particularly resistant stratum of rock that the streams have difficulty in removing.

Boulder. A more or less rounded block of rock, commonly larger than a cobblestone. Usually boulders are rounded by being carried or rolled along by water or ice, but certain boulders have been rounded by weathering in place and are known as boulders of weathering, disintegration, or exfoliation.

Canyon. A steep-walled valley or gorge in a plateau or mountainous area. The high and precipitous slopes impress the observer more than the flat land which may occur along the stream, and on this impression depends the distinction between canyons and other valleys.

Charco. A watering place in an alluvial plain in the desert. It consists of a pool of water supplied by floods, or the basin in which such a pool is held.

Ciénaga. A swamp or swampy place. A Spanish word, in common use in the Southwest.

Corrasion. Corrasion is a term first used by Powell to designate the erosion effected by running water. Running water erodes its bed chiefly by the mechanical wear or abrasion of the rock waste which it carries against the bottom and sides of its bed, by removal of joint blocks, and by solution. Hence corrasion must be defined as consisting of these various processes.

Corrosion. Corrosion literally means gnawing away, but in this country it is generally restricted to the gnawing effected by chemical agencies—in other words, it means the solution of rocks and other material, especially in contradistinction to corrasion.

Cove. A small bay or open harbor; it is also popularly applied to small areas of plain or valley that extend into mountains or plateaus. In New Mexico and Arizona the reentrants in the borders of mesas and plateaus are also called rincons (from the Spanish rincón, an inner corner).

Creep (of soil or rock waste). The slow movement of soil and rock waste down the slope from which these materials have been derived by weathering. Creep is due primarily to gravity but is facilitated by the presence of water, alternate wetting and drying, freezing and thawing, growth and decay of roots, and the work of burrowing animals.

Débris (rock). The material resulting from the decay and disintegration of rocks. It may occur in the place where it was produced, or it may be transported by streams of water or ice and deposited in other localities. Same as rock waste.

Decay (of rock). General disaggregation of rocks; it includes the effects of both chemical and mechanical agents of weathering, with, however, a stress on the chemical effects.

Desert varnish. A surface stain or crust of manganese or iron oxide, of brown or black color and usually with a glistening luster, which characterizes many exposed rock surfaces in the desert. It coats not only ledges of rock in place but also boulders and pebbles that are scattered over the surface of the ground.

Dip slope. A slope of the land surface which conforms approximately to the dip of the underlying rocks.

Disintegration. The process by which through the differential expansion of the minerals in a rock due to changes in temperature or through the partial solution or change due to the absorption of water the rock is disrupted into its component mineral fragments.

Dissected. Cut by erosion into hills and valleys or into flat interstream areas and valleys, as dissected plateau or pediment.

Dissection. The work of erosion in destroying the continuity of a relatively even surface by the cutting of ravines or valleys.

Ephemeral stream. A stream or portion of a stream which flows only in direct response to precipitation. It receives little or no water from springs and no long-continued supply from melting snow or other sources. Its channel is at all times above the water table. The term may be arbitrarily restricted to streams or portions of streams which do not flow continuously during periods of one month.

Erosion. A term which includes all processes by which earthy matter or rock is loosened and removed from place to place. In this country it is regarded as including weathering, corrasion, and transportation.

Exfoliation. The process by which under changes of temperature or other causes successive sheets of rock are split off the parent mass.

Fanglomerate. A fanglomerate is composed of heterogeneous materials which were originally deposited in an alluvial fan but which since deposition have been cemented into solid rock.

Flood plain. A strip of relatively smooth land bordering a stream, built of sediment carried by the stream and dropped in the slack water beyond the influence of the swiftest current. It is called a living flood plain if it is overflowed in times of high water, but a fossil flood plain if it is beyond the reach of the highest flood.

Insolation. Exposure to the sun's rays, and hence the effect of the sun's rays on the materials composing the surface of the earth. This is usually spoken of as the effect of changes of temperature and consists of exfoliation and the breaking up of rock and rock fragments.

Land form. The term land form is applied by physiographers to each one of the multitudinous features that taken together make up the surface of the earth. It includes all broad features, such as plain, plateau, and mountain, and also all the minor features, such as hill, valley, slope, canyon, arroyo, and alluvial fan. Most of these features are the products of erosion, but the term includes also all forms due to sedimentation and to movements within the crust of the earth.

Lateral planation. The reduction of the land in interstream areas to a plane parallel to the stream profile, effected by the lateral swinging of the stream against its banks.

Mesa. A Spanish word meaning table. Strictly applicable to those level or nearly level masses of land of relatively small extent which stand distinctly above the surrounding country, as a table stands above the floor upon which it rests. It is loosely applied, however, to any broad, flat surface of moderate elevation which is bounded on at least one side by a cliff or steep slope.

Mountain pediment. A plain which lies at the foot of mountains in an arid region or in headwater basins within a mountain mass. The name is applied because the plain appears to be a pediment upon which the mountain stands. A mountain pediment is formed by the erosion and deposition of streams, usually of the ephemeral type, and is covered with a veneer of gravel in transit from higher to lower levels. It simulates the form of an alluvial slope.

Mountain slope. The sloping surface which forms the side of a mountain; specifically the slope characteristically developed by the processes of erosion in an arid region.

Niche. A cave or reentrant in a rock face or beneath a waterfall.

Peñasco. A Spanish word meaning a large rock. It is commonly used in the Southwest for a projecting rock, such as those isolated by the recession of cliffs or mountain slopes. "Pilar" (pillar) has the same significance.

Picacho. A peak or sharply pointed hill or mountain. Because of the steep slopes of mountains in the desert region, picacho appears as the name of numerous mountains in southwestern Arizona.

Plateau. A table-land or flat-topped region of considerable elevation and extent. A plateau is commonly higher than a mesa and usually more extensive. It may have an undulating surface and from it may rise mountains, or it may be dissected by the cutting of canyons. If a large part of the original surface has been destroyed by streams, it is called a dissected plateau.

Playa. A Spanish word meaning literally shore or strand; a level or nearly level area that occupies the lowest part of a completely closed basin and that is covered with water at irregular intervals and for longer or shorter periods of time, forming a temporary lake. It is generally composed of evenly stratified beds of clay or silt that have been deposited in a temporary lake and that may contain large amounts of soluble salts. The surface is usually devoid of vegetation and may be either hard or soft and smooth or rough. Playas are frequently called "dry lakes," and other terms, such as "alkali flats" or "salinas," are used either in a general sense or to designate playas of special types.

Rain wash. The water from rain, after it has fallen on the surface of the ground and before it has been concentrated into definite streams; the work done by this water in striking the earth's surface and in transporting débris.

Recession of slopes. The moving back or receding of slopes from a former position without change in the angle of slope; comparable to cliff recession.

Regimen of a stream. The system or order characteristic of a stream—in other words, its habits with respect to velocity and volume, form of and changes in channel, capacity to transport sediment, amount of material supplied for transportation, etc. The term is also applied to a stream which has reached an equilibrium between corrasion and deposition or, in other words, to a graded stream.

Rincon. See Cove.

Rock shelter. A shallow cave or reentrant under an overhanging cliff.

Rock waste. Same as rock débris. See Débris.

Rubble. Rough, irregular pieces of broken rock.

Sediment. In the singular the word is usually applied to material in suspension in water or recently deposited from suspension. In the plural the word is applied to all kinds of deposits from the waters of streams, lakes, or seas, and in a more general sense to deposits of wind and ice. Such deposits that have been consolidated are generally referred to as sedimentary rocks.

Sedimentation. The act or processes of deposition of materials from suspension in the water of streams, lakes, and seas. Sometimes extended to cover deposition by wind and ice.

Sheet flood. A flood which spreads as a thin sheet of water over a large area and is not concentrated in channels. Sheet floods are of short duration, generally being measured in minutes or hours, and the water is always muddy. They are characteristic of the alluvial areas of the Papago country.

Sierra. A Spanish word meaning saw; applied to mountains. The typical sierra is longer than it is broad and presents to the observer, when viewed from the side, a jagged crest, which decreases in altitude from a point near the middle toward each end. Its slopes are scored by narrow gorges or canyons, between which are projecting ridges.

Talus. The sloping heap of loose rock fragments lying at the foot of a cliff or steep slope.

Terrace. A plain, natural or artificial, from which the surface descends on one side and ascends on the other. Terraces are commonly long and narrow, and they border seas, lakes, or interior valleys. A terrace may be built up by the deposition of sediment from water, it may be cut by the breaking of waves on a shore or the sweeping of currents, or it may be formed by the dislocation of the rocks in crustal movements. The descent from river terraces toward the river may be very abrupt, especially in arid regions; the ascent on the other side may be only that of an extensive alluvial slope.

Weathering. The effect of atmospheric agents on rocks and the processes by which rocks are affected by these agents.