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SHEETFLOOD EROSION

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DEFINITIONS.

Commonly, running water gathers into streams and corrades channels; exceptionally, running water spreads into sheets of limited or unlimited width, and, by a combination of erosion and deposition, produces plains.

Pure water flowing over a smooth indestructible surface does not move as a uniform film: if the surface is broad the sheet differentiates into parallel streams of greater depth and relatively rapid flow, separated by shallower bands of relatively sluggish flow; and at the same time both streams and intervening bands differentiate into series of transverse waves which move forward more rapidly than the body of the differentiated sheet. The tendency of flowing water to divide into streams is well known; it is undoubtedly by reason of this tendency that running waters commonly flow in streams which cut channels and eventually fashion most of the lands of the earth. The tendency of flowing water to break up into transverse waves is not so well known, though beautifully exemplified in sluices for irrigation or for bringing logs and lumber down from mountains (where it is the succession of waves which prevents the sluice from clogging and equalizes the movement of the floating load); it is of subordinate importance geologically.

Under certain conditions, sand-laden water flowing over an erodable plain tends at first to divide into parallel streams like those of pure water on an indestructible surface, yet, since the streams formed in this way at once begin to scour and overload themselves and thus check their own flow, this tendency is soon counteracted and the water is distributed again; so that the ultimate tendency is toward movement in a more or less uniform film or sheet. This tendency is well known to laymen in those regions in which it prevails, but it seems not to be generally recognized among geologists. Colloquially a moving water-body of this type is sometimes known as a "wash;" but since the term is commonly applied primarily to the product and only secondarily to the agency, and since it is usually restricted to limited, though broad, channels (*e. g.*, in San Francisco wash), it seems desirable to use some other designation for the water-body; and the term *sheetflood* has come into use in notes and in conversation.

Thus there are in nature two strongly contrasted types of moving water bodies, namely, (1) streams, and (2) sheetfloods. The first type is characterized by a tendency toward concentration in narrow and relatively deep bands which quickly cut channels for themselves; the second is characterized by a tendency to spread widely in relatively shallow sheets. The second is logically coordinate with the first as a geologic agent. In a general way streams prevail in humid regions, sheetfloods in arid regions, though streams occur locally in arid lands, while it seems probable that sheetfloods occur under certain conditions in nearly all lands, howsoever humid.

Sheetflood Work in the Sonoran District.

FEATURES OF THE DISTRICT.

Location.—Sheetflooding is characteristic of the broad expanse of plain and mountain in southwestern Arizona and western Sonora (Mexico), stretching from the Sierra Madre to the gulf of California, and lying between Gila and Yaki rivers. In physical characteristics and geologic history this territory forms part of Powell's great province of "Basin

Ranges,"* constituting a considerable part of that portion of the province characterized by "Open Basins;" but the district is so distinctive that, for purposes of description at least, it may be set apart as the *Sonoran district.* It corresponds approximately with the region known among the Mexican inhabitants as Papagueria, or land of the Papago Indians.

The Sonoran district slopes from the high Sierra of Mexico and the Mogollon escarpment at its northern extremity to tide level in the gulf of California. To the casual observer traversing its expanse it seems a region of mountains, for rugged buttes, mesas, and sierras are always in sight and usually dominate the landscape; but more careful observation shows that it is primarily a plains region, since fully four-fifths of its area consists of plains, hardly one-fifth of mountains, and the elongated sierras and scattered buttes are nearly always flanked by vast tracts of lowland. The mountains range up to 6,000 or 6,500 feet above tide in the interior (imposing Baboquivari, southwest of Tucson, measures 6,798 feet) and still greater altitudes toward the Sierra Madre; the intermontane plains rise gently from sealevel to 3,500 or 4,000 feet,† while the buttes and sierras may rise anywhere from 100 to 4,000 feet above the circumscribing plain. The mountains are notably rugged, abounding in lofty precipices, vertical and sometimes overhanging cliffs, knife-edge aretes, and leaning (apparently or actually) picachos, and they rise with remarkable abruptness from the smooth plains, so that, to the casual observer, they seem an archipelago of rocky peaks rising from an ocean of desert sands. Though monotonously smooth, partly by contrast with the rugged mountains, the plains slope gently away from the mountains and merge in flat-bottomed valleys leading directly or deviously toward the sea, so that the entire surface, with the exception perhaps of a few playas near the coast, drains seaward. In the valleys occupied by washes (rivers during the wet seasons, sand wastes during most of the year) the grades may be as low as 20 or even 15 feet to the mile; over the average plain the slope is 50 or 75 feet to the mile, and on the great apron-like foot-slopes pushing among the aretes and lateral spurs of the larger sierras the grade may be 100, 200, even 300 or more feet to the mile.

Climate.—The Sonoran district is excessively hot and arid. Yuma, noted as the hottest station in the United States, is in its northwestern corner, and while records are lacking, it is probable that Caborca and Hermosillo are considerably hotter; the rainfall in the Sierra may reach 15 or 20 inches,

* National Geographic Monographs, vol. i, 1895, pp. 95-98.

† Captain D. D. Gaillard, of the International Boundary Commission, writes: "The sacred peak of the Papago, Baboquivari, is 6,798 feet above mean sea level of San Diego bay. The lowest part of the valley on the east of this peak (called the "Sasabe flat") is about 3,200 feet above the same datum plane, while the lowest part of the valley on the west of the peak (called the "Moreno flat") is only about 2,300 feet above the plane of reference" (official letter dated February 6, 1896).

but the meager records in even the most fertile valleys in the foothills seldom rise above 10 inches, while the average over the interior probably falls below 5, and may be no more than 2 or 3 inches during the year. There are two nominally wet seasons, occurring respectively about midwinter and midsummer. The midwinter precipitation is generally the heavier and the more widely distributed, but both in summer and in winter the greater part of the rainfall occurs in local storms. Snow falls on the Mogollon and the Sierra, remaining half the year on a few of the highest points; to this fact the perennial character of some of the northern tributaries of the Gila and the stronger branches of the Yaki may be ascribed. During the occasional drizzles of the wet seasons the scanty moisture is chiefly absorbed by the sun-baked earth, so that floods do not ensue, though the spring-fed streams may rise by reason of the diminished evaporation; during the moderate storms that occur here and there from year to year torrents are produced which rush tumultuously down the slopes and become potent geologic agents, and during the great storms occurring from decade to decade or from century to century whole plains are flooded; yet so dry are air and earth that the deluge is absorbed within a few miles or scores of miles. Thus, although the entire surface slopes seaward, no living water reaches the sea between the Colorado and the Yaki, 700 miles away.

By reason of heat and aridity the Sonoran district is desert or subdesert throughout; the vegetation is too scant, stunted, and scattered to protect the surface from storms; the meager flora forms little or no humus, and thus there is no soil and little of that chemic action initiated by vegetal growth and decay. Through a combination of biotic conditions of great significance the vegetal life and the sedentary animal life are concentrated in scattered colonies with bare earth between, and the colonies collectively form but a small fraction of the total area. Thus the region is one in which physical agency operates directly, with little aid or obstruction from the biotic agency always present and often predominant in humid districts.

Since the waters of the Sonoran district never reach the sea the territory is complete in itself as a geologic province; the storm waters gather detritus in the mountains and transport it into the valleys, but their agency is limited to shifting the rock matter from one point to another in the same vicinity, and thus degradation and aggradation go hand in hand, and gradation is completed within the district.

Topography.—At first sight the Sonoran district appears to be one of half-buried mountains, with broad alluvial plains rising far up their flanks, and so strong is this impression on one fresh from humid lands that he finds it difficult to trust his senses when he perceives that much of the valley-plain area is not alluvium, but planed rock similar to or identical with that constituting the mountains. To the student of geomorphy this is the striking characteristic of the Sonoran region—the mountains rise from plains, but both mountain and plain (in large part) are carved out of the same rocks. The valley interiors and the lower lowlands are, indeed, built of torrent-laid debris, yet most of the valley area carries but a veneer of alluvium so thin that it may be shifted by a single great storm. Classed by surface, one-fifth of the area of the Sonoran district, outside of the Sierra and its foothills, is mountain, four-fifths plain; but of the plain something like one-half, or two-fifths of the entire area, is planed rock, leaving only a like fraction of thick alluvium. This relation seems hardly credible. During the first expedition of the Bureau of American Ethnology (in 1894) it was noted with surprise that the horseshoes beat on planed granite or schist or other hard rocks in traversing plains 3 or 5 miles from mountains rising sharply from the same plains without intervening foothills; it was only after observing this phenomenon on both sides of different ranges and all around several buttes that the relation was generalized, and then the generalization seemed so far inconsistent with facts in other districts that it was stated only with caution even in conversation. During the 1895 expedition a skilled student of geomorphy (Mr Willard D. Johnson) was added to the party, partly in the hope that observation in this direction might be extended and verified or corrected. Even then the observations and inferences seemed hardly worthy of trust until the shores of the gulf of California in Seriland were examined and the superb section from Punta Ygnacio to Puerta Infierno was found to exhibit clearly the inferred relation. "A quarter of this 15-mile exposure is the current-built point, another quarter cuts butte or range of igneous rock or ancient granite, while the remaining half traverses typical intermontane plain in cliffs of 20 to 50 feet, and fully 5 out of the 7½ miles of the low cliff reveal the substratum of planed granite beneath a torrential veneer, while there is more of alluvium-free granite than of graniteless alluvium."* Sierra de Tonuco, lying a few miles outside the northeastern corner of Seriland,† is a typical mountain mass of the Sonoran district; it is a deeply furrowed block of semi-metamorphic limestone resting on an inclined table of slightly schistoid granite; its crest is perhaps 2,500 feet above the plain, and its upper three-fifths is limestone; its base appears to be heavily burdened with taluses of limestone and granitic debris, but occasional arroyas cut through these aprons and show that they are not of great depth. These rubble-cumbered slopes pass within a fraction of a mile into a lowland plain so

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* National Geographic Magazine, vol. vii, 1896, pp. 127, 128.

† Map of Seriland, op cit., pl. xiv.

smooth that, except where outlying granite buttes rise from its expanse, it may be traversed by wagons in any direction; yet for 5 miles from the mountain base on northeast, north, west, south, and southeast the wheels grind over granite half the time, while on the east the alluvial veneer appears barely to conceal the granite over an area larger than that occupied by the sierra. In the northeastern portion of the Seriland map over a dozen buttes are shown rising sharply from the subdesert plain, and though these lie almost in the delta of Rio Bacuache, analogy with similar buttes a few miles further northeastward, which were carefully examined, indicates that they are not scattered island summits, as their appearance suggests, but merely knobs rising from a baseleveled plain of granite traversed somewhere by an ancient valley a few hundred feet deep. Again, 5 miles southeast of Puerta Infierno the tide-carved coast cuts a typical granitic butte a hundred feet high and as many yards across, rising sharply from the inclined foot-slope of Sierra Seri, yet the rugged-faced knob is seen to surmount a granite pediment nearly half a mile across in the line of section.

It is to be remembered that the surface and structure of the district are known only through two expeditions, each traversing it twice; but so far as the observations go they indicate that the vast plains diversified by scattered sierras and buttes do not represent an alluvium-buried mountain land so much as a planation level with a few monadnocks still surviving.

Geology.—The structural geology of the Sonoran district is too little known to warrant detailed description. In a general way the rocks appear to be (1) ancient granites, (2) partially metamorphosed limestones, shales, etcetera, and (3) moderately old igneous sheets with associated tuff beds.

The granite is sometimes quite schistose, again massive and homogeneous, frequently cut by veins and dikes. Where it reveals structure the trends are approximately meridional. Originally (so far as can be judged) it was a floor on which the sedimentaries were laid unconformably; now it is deformed chiefly by upbending into meridional ridges with culminating nodes forming the nuclei of sierras. There are no data concerning its age except the structural relation showing it to antedate the clastic strata.

The limestones, shales, and other clastics are apparently of considerable aggregate thickness, limestones predominating in the south and shales in the north. Commonly they are highly inclined; often they are folded, somewhat Appalachian-wise, into meridional ranges greatly reduced by degradation. Sometimes, as in Sierra de Tonuco, and also in Sierra de Caborca (where the trend is locally latitudinal), the limestones seem to be only slightly inclined. Commonly the rocks are decidedly metamorphosed, the limestones into marble, the shales into phyllitic and other schists, slates, etcetera; yet sometimes, as in the sierras just noted the alteration is slight. In Sierra de Caborca the limestone is highly silicious (intermixed and interlaminated with silicious silt) and weathers brown, highly vesicular, and ferruginous, so as to be mistaken locally for lava. Collectively the clastic rocks seem to be corrugated extensively, and the harder beds, together with the nucleal granite ridges and nodes, form the scattered sierras characteristic of the district; but the region has suffered profound degradation whereby much, probably the greater part, of the clastic mass has been carried away. Locally, in certain of the sierras, the topographic configuration expresses the structure, as Johnson's surveys admirably show; throughout the plains and fully half of the mountain area (*i. e.*, in nine-tenths or more of the district) there is no visible relation between structure and configuration. No general faulting and monoclinal deformation such as is considered characteristic of the Great Basin was detected. The age of the clastics has not been determined, but there is some reason for correlating them with the sedimentaries of eastern Mexico and certain of the metamorphics of California, and regarding them as Jurassic and Cretaceous.

In parts of the district igneous rocks and tuffs prevail, concealing the ancient granites and the clastics and forming most of the buttes and lower ranges as well as portions of the greater sierras; and elsewhere similar materials are found here and there, sometimes throughout considerable areas. Sometimes the igneous rocks are apparently involved with the clastics, and in general they seem to have suffered degradation conformable with that of limestone and schist and granite, so that the origin of the greater part of them would seem to date back nearly to the close of the principal deposition period. Occasionally newer looking and less eroded lavas and tuffs are found, and in the western part of the district there are coulees and lapilli beds, particularly about the volcanic peak Pinicate; but modern or even late Tertiary vulcanism would seem to be quite local and exceptional.

Hydrography.—Viewed as a unit, the Sonoran district is a great plain sloping from the high Sierra to the sea and relieved here and there by minor ranges and masses usually trending in north-south directions; but viewed in greater detail it may be considered by the student, as it is by the Indian, Mexican, or American layman, as an assemblage of drainage basins or "valleys." In a general way the "valleys" lie between the parallel ranges, those north of the subcontinental divide (which coincides approximately with the international boundary) sloping toward the Gila, those beyond the divide sloping southward; but in passing westward each "valley" lies lower than its neighbor, and in the western part of the district the ranges are often interrupted and the " valleys " open one into another directly toward the sea, while in all portions the larger water-lines frequently trench the sierras and unite two or more " valleys " in a single drainage basin. Typically the " valley " is simply a vast elongated plain tilted sharply upward into bounding sierras on both sides and around one end; the plain is slightly concave, and if the slope exceeds say 15 or 20 feet per mile, its center is marked by a " wash "—a torrent perhaps a mile wide after the great storm, a sterile sand waste at other times; and the upturned rim is carved by labyrinths of barrancas, many of which unite at the mountain base to form shallow arroyas meandering the plain, but seldom reaching its center. Thus the typical " valley " is waterless save during storms, and its ephemeral waterways are multitudinous in the bounding mountains and few or none in its flattened interior. In the eastern part of the district, where the parallel ranges are higher and lie closer together, some " valleys " carry permanent streams northward and southward from the subcontinental divide toward, and at storm time into, geographically great but hydrographically puny rivers—the Gila in Arizona, and the Altar (or Asuncion, or Pitiquito, or Magdalena, or San Ygnacio) and the Sonora, as well as the northern branches of the Yaki, in Sonora. These " valleys " occupied by permanent rivers are not typical for the district, in that they are rather broadly flattened V-shape than concave in profile; yet they vary from normal valleys in that water is scanty or absent in the depths and increases with the ascent of the waterways and culminates well toward the summits. Such " valleys," or the greater waterways by which they are connected, ultimately trend westward through the bounding ranges and down the general slope toward the sea—a bourne which they (excepting a tributary or two of the Gila and two more of the Yaki well toward the high Sierra) never reach. So the important constituent elements of the district are valley-plains, bounded by barranca-scored mountains and sometimes faintly inscribed with drainage lines which are nominally rivers but actually sand wastes during 360 days of the average year; and the mountain is far subordinate in importance to the valley-plain, while the " river," though a necessary descriptive term, is little more than an empty name.

The general topographic relation of " valley," mountain, and " river " is modified and often masked by a subordinate relation growing out of a northeastward migration of the divides. It is to this migration that the westward deflection of the principal rivers is due, and it is to the same cause that the union of neighboring " valleys " into irregular basins must, in most instances, be ascribed. So common is this tendency that, except in the foot ranges of the high Sierra, few of the drainage basins are complete and symmetric; few of the outlying sierras have escaped trenching by the retrogression of arroyas opening westward or southwestward, and many of the divides, main as well as minor, have been shifted from the rims well into the interiors of the valley-plains.

Geologic development.—The observations of the two expeditions by the Bureau of American Ethnology yielded certain inferences concerning the structure, geomorphy, and geologic history of the district, and these in turn yielded certain generalizations; and as a supplement to the empiric description they are worthy of statement for the purpose of making clearer the features of the district, though it is to be remembered that they constitute a series of field hypotheses, probably valid in the main though requiring elaboration and minor modification with further field-work. The first inference is that the clastic rocks represent a thick and practically continuous series of deposits laid down on a granitic floor, the series growing finer and more calcareous southward. The second inference is that about the close of the period of deposition vulcanism was initiated, whereby considerable sheets of lava and tuff were produced. The third inference is that toward the close of the period of vulcanism extensive deformation occurred, chiefly as east-west compression, with consequent development of meridional corrugations, and it is deemed probable (though there is little explicit evidence on this point) that the cycles of (1) deposition, (2) vulcanism, and (3) deformation occurred in this order, yet overlapped to such an extent that deformation perhaps began before deposition entirely ceased and while sporadic vulcanism also persisted. The fourth inference is that the massif produced in this way stood at moderate altitude for a long period, including approximately the Eocene and the earlier half of the Neocene; that a large part of its volume was degraded; that the surface was planed to an approximate baselevel, relieved by ridges and masses of the monadnock and catoctin types, usually of harder layers but sometimes marking broader divides, and that during this vast period the drainage basins were outlined and developed. It is deemed probable that during much or all of this period the precipitation was greater than now, so that the district throughout was one of degradation, and so that the drainage basins were of the normal dendritic type, veined by rivers occupying broad yet essentially V-shape valleys; and it is considered probable also that the basin-limiting sierras were less rugged than now. The final inference is that the period of symmetric degradation was terminated by general southwestward tilting due to uplift in the northeastern portion—the uplift that resulted in the making of the Sierra Madre in Mexico and the high plateaus in the United States, and in the birth of Colorado river; that this geographic change was accompanied by a meteorologic change, chiefly diminution of precipitation to such extent that the rivers shrunk and ceased to carry detritus or even to flow into the sea, and that the storm freshets flowing northeastward were paralyzed while those flowing southwestward were relatively stimulated (both in high and cumulative degree because of the delicate adjustment between pecipitation and absorption), so that every divide in the district began migrating northeastward. It is deemed probable that the tilting began somewhat gradually late in the Neocene, and thus that the transformation in the face of the district took place rather slowly. It is also deemed probable that essentially the present attitude has now been maintained for a long time, though the tilting is doubtless yet in progress at a slow rate. It may be noted that the records of neighboring districts, so far as known, are consistent with that interpreted for this district.

STREAM EROSION IN THE DISTRICT.

Charactor of streams.—The current maps of the Sonoran district commonly represent a considerable number of rivers gathering from many tributaries in the mountains and flowing northward into the Gila or southward and westward into the Altar and Sonora or directly into the gulf. Better maps based on actual surveys, such as those of the General Land Office in the United States, show multitudes of small streams flowing down the mountain slopes and either ending on the plain or uniting in rivers which wander toward some principal waterway and end blindly; but the general maps express hypotheses based on the behavior of streams in humid lands, and even the best maps represent the sand washes produced by great storms in lieu of permanent water. In the more elevated eastern part of the district, and during the rainy seasons, especially that of winter, when the storm water in the mountains is supplemented by melting snows, most of the sand washes are, indeed, converted into streams, which, although shallow, are rapid and even torrential, and carry vast volumes of sediment-charged water down the slopes; but throughout most of the territory the sand washes are hardly wetted during the normal rainy season, and are transformed into torrents only during great storms or cloud-bursts occurring at intervals of years or decades. So the map representing sand washes as rivers is misleading unless its purely conventional character is clearly understood. Although the aggregate stream length represented in such a map is considerable, perhaps several times greater than the aggregate length of the streams actually flowing on a given date during the wettest season, yet during the dry season the aggregate length of actual water lines is reduced to a minute fraction of the aggregate length of sand wash, and nearly all of the channels are dry. So the stream of living water is an exceptional, indeed an exceedingly rare, feature in the Sonoran district, and is hardly known save in its more elevated eastern portion.*

Sources of streams.—The sources of stream water are, as usual, three—(1) melting snow on the high Sierra and the Mogollon, (2) ground-water appearing as seepage or springs in the deeper valleys, and (3) the product of rains. The first of these sources might be neglected, save that it contributes (*a*) directly to the longer rivers, San Pedro and Santa Cruz in Arizona, and Altar, Magdalena, Bacuache, Sonora, San Miguel, and the main and minor branches of the Yaki in Sonora, and (*b*) indirectly through ground-water to these and other streams during a part of the year.

The ground-water is of considerable importance as a source of streams, partly since its flow is moderately steady, and its tendency is thus to maintain the stream as such and to enable it to continue corrasion and transportation, albeit feebly, throughout the year. In the mountain gorges the ground-water commonly emerges as permanent or temporary springs, while in the alluvium-lined valleys it simply seeps through the sand, generally below the surface, though sometimes in a slender streamlet winding through the broad sand wash. Among the rocks of the mountains the ground-water movement is conditioned as in humid lands, but in the broader valleys it is conditioned by a variety of factors, including the conformation of the alluvium-lined basin with its various arms and interruptions, as well as by the rate of evaporation, etcetera. Thus the alluvial mass and the adjacent hard rocks are wetted or saturated during the rainy season, and the water percolates down the slopes along lines generally corresponding with those of surface drainage; and wherever the surface drainageway is exceptionally deep, there the ground-water most frequently emerges to flow for rods or miles, or until evaporated or reabsorbed by the sands. So it happens that water may often be found by digging in the dry sands of a wash; that a nominally permanent stream may appear, disappear, and reappear half a dozen times in the course of a day's journey down a single storm-fashioned wash, and that the rippling streamlets lengthen during the night and in cool or cloudy weather and shrink during the day and the heat, when evaporation culminates.

It is by reason of this relation between land surface and ground-water surface, in conjunction with the characteristic migration of divides, that a considerable part of the Sonoran district is habitable by man, for it is in the narrow gorges produced by the retrogressive erosion trenching the

* The bounding rivers, Gila and Yaki, are maintained by tributaries from without the district.

ranges that the ground-water reaches or approaches the surface so that settlements can be maintained.

The chief source of stream water is the sporadic storm, especially the thunder-gust or cloud-burst, which fills old channels and gouges out new ones, though the flow may last but a few minutes, and seldom continues more than a few hours. In the sierras the slower drizzles produce stream floods which sometimes find their way out on the valley-plains, though the drizzle on the plain commonly does no more than wet the surface or produce feeble sheetfloods; and on the broader plains only a relatively small part of even the heaviest rainfall ever collects in streams.

In brief, the streams of the district are strikingly short and small in proportion to the area, and only less strikingly few and feeble in proportion to the scant precipitation.

Streamways and stream-work.—In the sierras the permanent streams are slender threads of water slipping over ledges, now gathering in tinajas,* and again disappearing in fissures or gravel pockets at the bottoms of rugged barrancas; and the barrancas dividing narrow aretes are exceptionally parallel and close laid, while it is the combes or amphitheaters in which the barrancas head, in conjunction with the peaks in which the aretes join the crests, that produce the characteristic sierra profile. Most of the multitudinous barrancas are supplied only by storm torrents, and these usually end about the base of the sierra, the margin of the valley-plain; it is only the deeper and longer barrancas that send arroyas or permanent channels far enough over the plain to unite with other waterways in dendritic systems; and it is partly for the reason that most barrancas end at the plain that their remarkable parallelism is maintained. Outside the sierras the typical channel is at first a rugged or flat-bottomed barranca cut in the country rock; it soon diminishes in depth and increases in width and becomes lined with boulder beds; still further down stream it changes into a broad, steep-banked arroya cut in alluvium and burdened with gravel beds or sand sheets; and it finally ends in an alluvial fan, usually of imperceptible slopes miles in length and furlongs in width. If the stream is permanent it is, in its low-water stage, but a thin ribbon of water rippling over the rocks of the upper course or the sands of the middle course. The streamways are notable, first, for high grades, and, second, for the width of their channels, which may exceed that of the Ohio, or even that of the Mississippi, for a stream less than 50 miles long; but during most of the year nine-tenths of the few streamways are broad wastes of barren sand, the most forbidding lines of the desert, often littered with skeletons of famished stock.

* Natural bowls, or water-pockets; defined in Science, new series, vol. iii, 1896, p. 494.

The character of the channels expresses well the characteristics of stream erosion: In the sierras the storm torrents gather loosened rock masses (there is little disintegrated detritus and still less decomposed rock matter on the steep slopes), hurl them down the cliffs and hurry them through the barrancas, bursting them asunder and knocking loose other masses on the way; toward the base of the sierras the larger boulders lodge, to be removed and reduced during later storms, while the pebbles and finer debris are swept further. Then general or local conditions either spread the torrent into a sheetflood, or else maintain the stream character; and in the latter case cobbles and pebbles are laid down after much trituration, the sand is carried far, scouring the channels as it goes, and finally nothing coarser than silt is borne by the diminishing flood, which is constantly robbed by dry earth below and drier air above; the silt burdens the flood without giving much aid in corrasion, and it gradually expands either into a labyrinth of interlacing channels or into a sheetflood, when evaporation and absorption rapidly sap the strength of the torrent until it ceases to be. It is significant that despite the high declivity of the barrancas the freshet torrents are often surprisingly clear, evidently by reason of the dearth of comminuted and lixiviated detritus, so that the streams are often underloaded and thereby enfeebled as erosive agents.

The streamwork in the district is notable partly in that it is exceptional in occurrence, partly in that it is reduced and rendered subordinate by the tendency of the streams to pass into sheetfloods with diminishing declivity; for most of the barranca torrents are transformed at once on reaching the valley-plain, while the sand-lined channel of the typical arroya is but a sheetflood of limited width. So strong indeed is the tendency toward transformation that it is only in the few streams of permanent supply and in the valley-plains oversupplied by exceptionally extensive drainage basins that definite channels are maintained.

SHEETFLOODING IN THE DISTRICT.

Character of sheetfloods.—In distribution the streams are mainly confined to the sierras, including the Sierra Madre and the higher foot-ranges as well as the lower outlying ranges and masses and the isolated mesas and buttes, and are local and exceptional in the valley-plains, while half the vast valley-plain area is the area of sheetflooding. Although there is a general increase in precipitation with altitude throughout the district, the cloudburst and drizzle usually affect both sierra and valley-plain; and in such cases the plain is flooded by the direct rainfall as well as by drainage from the sierra. The character of the flooding is known from direct observation, from indirect observation on flotsam, and from consistent lay testimony.

During the 1894 expedition a moderate local rain occurred while the party were at a Papago rancheria near Rancho de Bosque, some 15 miles north of the international boundary at Nogales; the rainfall was perhaps one-fifth of an inch, sufficient to moisten the dry ground and saturate clothing despite the concurrent evaporation, and was probably greater in the adjacent foothills of Santa Rita range. The road was sensibly level, having only the 20-feet-to-the-mile grade of Santa Cruz valley; it ran across the much stronger slope from the range toward the river, and an arroya embouched from low terraciform foothills not more than 200 or 300 yards up the slope. Thus the arroya opened not on a perceptible fan but on a sensibly uniform plain of sand and silt with occasional pebbles sloping perhaps a 150 feet to the mile. The shower passed in a few minutes and the sun reappeared, rapidly drying the ground to whiteness. Within half an hour a roar was heard in the foothills, rapidly increasing in volume; the teamster was startled, and set out along the road up the 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, and loaded with twigs, dead leaflets and other flotsam; it was seen up and down the road several hundred yards in either direction or fully half a mile in all, covering the entire surface on both sides of the road, save a few islands protected by exceptionally large mesquite clumps at their upper ends. 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 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 diminution in depth in the direction of flow being less rapid than the diminution in velocity. The front of the flood was commonly a low, lobate wall of water 6 to 12 inches high, sloping backward where the flow was obstructed by shrubbery, but in the open curling over and breaking in a belt of foam like the surf on a beach; 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 on-coming torrent rushing over previously wetted ground. Within the flood, transverse waves arose constantly, forming breakers with such frequency as to churn the mud-laden torrent into mud-tinted foam; and even when breakers were not formed it was evident that the viscid mass rolled rather than slid down the diminishing slope, with diminishing vigor despite the constant renewal from the rear. Such were the conspicuous features of the sheetflood—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 only a few miles away. A special feature soon caught attention: On looking across the flood it was seen from the movement of waves and flotsam that the rate of flow was generally uniform, a little more sluggish about the mesquite clumps, a little swifter over the interspaces; but now and then a part of the sheet (usually between and below mesquite clumps or slight elevations by which the current was made to converge) began to move more rapidly, when almost immediately the flotsam would shoot forward at twice or thrice the ordinary rate, the flood surface would sink toward the upper end and swell toward the lower part of the rush line, while the roar would rise above the rustling tumult of the more sluggish waters; within 50 feet or 50 yards the swelling rush would be churned into foam and rise several inches above the general level of the flood, and then the waters would diverge and slacken and quickly mingle with the general sheet; sometimes the crest of a delta or fan would show through or above the water at the lower end of the rush, and would push up stream through growth chiefly at its upper end; but in any event the whole process of the gathering and respreading of the waters commonly lasted but a few seconds, or perhaps a minute or two, and left but a faint trace in unusual rippling of the flood. So common were these rushes that two or three or even half a dozen might be within the field of vision at the same time—some just starting, some dying 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; then the torrent began to disappear at the margin, the flow grew feeble in the interior, the water shrank and vanished from the margin up the slope nearly as rapidly as it had advanced, 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 not conspicuous, though significant. The most striking effect was the accumulation of flotsam, chiefly twigs and branches, against the upper sides of clumps of shrubbery, ant-hills, ground-squirrel mounds, and other elevations; and from these the extent of the flood could be traced even beyond the limits of vision, showing that its width was at least one and perhaps two or three miles, and that it nearly blended with other similar floods emerging from neighboring barrancas in the mountains and arroyos in the foot-slopes. A less striking effect was the accumulation of a nearly continuous film of sediment, chiefly fine sand or silt, hardly distinguishable after drying from the general surface deposit, with which it undoubtedly soon blended. This film was usually an inch or less in thickness, though sometimes it lined depressions to depths of several inches. A highly significant effect was found on examining the track of one of the more violent rushes within the flood: At the upper end this was a gully reaching two feet in depth and one or two yards in width, newly gouged in the gravelly and sandy silt of the plain; at the lower end it was an elongated delta or fan, composed chiefly of sand but containing occasional pebbles (which were not borne by the sheetflood, and must accordingly have been washed out of the gully). A score of other gullies and deltas were seen, some well developed, some nearly obliterated, and it seemed clear that the well developed examples were only those produced toward the end of the freshet, the earlier examples having been masked or obliterated by the later flooding. These distinctive marks of the sheetflooding were distributed as extensively as the flotsam heaps, and in like manner were found on the plains below neighboring arroyos

On traversing a characteristic torrential apron stretching southward from the southern end of Baboquivari range toward the great arroyo known as Rio Seco, in northern Sonora, the track of a still more extensive sheetflood was crossed, its traces (apparently some months old) being the characteristic accumulation of flotsam or drift lodged against shrubbery and elevations, and the equally characteristic gullies terminating in fans. The route lay almost directly across the slope, three to five miles from the base of the mountain; and the sheetflood-plain was so smooth that, with a little care in avoiding the occasional gullies, the wagon passed over it at a rapid trot, save in crossing a single sand-lined arroyo eight or ten feet deep and twenty yards across, the torrent marks indicating that the entire plain had been flooded for a width of nearly or quite ten miles to a depth exceeding a foot and not exceeding a yard, save in the central arroyo and one on either side (down which the drainage from the barrancas had evidently flowed streamwise after the force of the torrent was spent). This plain is a typical torrential apron of the Sonoran district; its slope, five miles from the mountain base, is perhaps 150 feet to the mile, increasing to 200 feet near the mountains and perhaps 300 in the reentrants between projecting spurs, while toward Rio Seco the inclination diminishes to 100 feet to the mile or less where the surface passes by a low crenulate escarpment into the broad wash of the pseudo-river, itself sloping probably 40 or 50 feet to the mile. The deposits of the plain as revealed in gullies and the marginal and central arroyos are gravelly and even bouldery sands near the mountain, grading into silty sands toward Rio Seco. These deposits have the customary air of great depth, yet, as shown in the walls of the barranca (the main head of Rio Seco) passing the frontier post of Sasabe and the lesser barranca near the Indian village of Poso Verde, they are usually but a yard or two in thickness for several miles from the mountains and rest on an eroded surface of non-decomposed mountain rocks.

Later the 1894 expedition passed up the broad valley extending northwestward from Hermosillo between two outlying ranges for about 100 miles. The greater part of this valley is a single torrential plain tilting up laterally into the bounding ranges and rising gradually northwestward from an altitude of perhaps 100 feet to over 2,000, where it seems to drown the mountains, save a few peaks rising sharply from its gentle surface; the regularity of the valley and its apparent lining being interrupted in four or five places by sharp-cut drainage-ways which have retrogressed through the westerly bounding range. About midlength of the valley (south of the tanque known as Agua Nueva) the route crossed obliquely the trail of a sheetflood, marked by flotsam and gullies, several miles broad. In this case the nearest upslope mountains were 20 or 30 miles away and not more than 2,500 feet higher than the flood-marks, while the surface inclined for 50 miles directly to the lower reach of Rio Sonora, which is never wet save by local showers or the storm freshets descending from the Sierra Madre during midwinter or midsummer rains. Accordingly it seemed clear that the sheetflood had been confined to the plain—that the waters of a single storm had accumulated, rushed down the 1:25 slope for ten or more miles, and then disappeared through absorption and evaporation.

During the exceptionally humid autumn of 1895, the second expedition experienced a single rain, or rather a succession of showers, not sufficient to produce either streams or sheetfloods, on the gentle slopes of Altar valley about the settlement and entrenched buttes of San Rafael de Alamito, where camp was pitched for several days. Yet this plain was marked for an area of at least 100 square miles by bunches of flotsam and driftwood lodged against the sparse shrubbery. The area was altogether out of reach of possible floods in Altar wash, to which, indeed, the marks did not extend, and the slope and direction of flow were nearly at right angles to its line. Except the geographically insignificant buttes, there were no mountains within a dozen miles in which the torrent might have gathered; and when the party ascended the 30-mile slope toward the Altar-Sonora divide the torrent-marks were found to diminish and gradually disappear in such manner as to demonstrate that the waters had gathered mainly, if not wholly, on the plain itself, and then rushed down toward, but apparently not quite to, the sand wash of the Altar. Where the flotsam was accumulated most abundantly the slope was probably 50 feet to the mile or less; and the fan-ended gullies were few and small, becoming more conspicuous further up the incline where the flotsam was less abundant.

The 1895 expedition skirted the western and southern bases of Sierra de Tonuco, just outside the area mapped as Seriland; and along the southwestern margin, near Rancho de Tonuco, the steep mountain side passed within a fraction of a mile into fairly smooth plain, sloping perhaps 150 feet to the mile. Numerous water-cut gullies and fans of exceptional size were found. Most of these were apparently some years old; and the deltas and fans contained quantities of angular and subangular boulders, sometimes reaching a foot in diameter. The deeper scorings here revealed a sheet of fragmental debris, evidently drift from the neighboring sierra, rarely reaching five feet in thickness, composed of little-worn gravel with occasional boulders embedded in a matrix of loam or silt; this rested on a sharply-eroded surface of granite or black marble not at all decomposed. The mantle was variable in thickness, averaging probably less than a yard over considerable areas, and frequently disappearing, leaving the rock to form the surface. About the rancho the alluvium thickened locally, and the ground water circulating on the subjacent rock surface was tapped by a well 40 or 50 feet deep; but even here, in the line of natural flowage from the deepest barranca of the sierra toward Encinas desert, where the slope was least, the usual gullies terminating in low fans abounded, some having been evidently produced by the latest storm. On the steeper slopes adjacent a number of low circular or elliptical mounds, apparently made up chiefly of angular boulders, were noted; and comparison of the evidently older with the manifestly young indicated that these were remnants of ancient gully-fans modified, rounded, and relatively raised above the mean surface by subsequent erosion, though in a few cases the boulder mounds were half buried by finer silt deposited about their flanks.

The 1894 expedition traversed Baboquivari or Moreno valley (west of Baboquivari range), crossing the course of "Fresnal creek" as shown on the excellent official map of Pima county, Arizona; and though the line of the "creek" was not traceable (the wash having been obliterated in consequence of local failure of rains during recent seasons), a considerable flotsam-marked area was found in the eastern part of the valley, below the Papago Indian villages collectively known as Fresnal. Here, too, in the shadow of the high and remarkably rugged granite range and its dominant peak, boulder mounds similar to those adjacent to Sierra de Tonuco were observed, and in two or three instances low buttes, together with the more considerable eminence known as Fresnal hill, were noted as apparently the product of continued circumdenudation, initiated about accumulations produced in the manner inferred in the Tonuco region. In this valley, too, it was observed that sometimes gullies of considerable dimensions are produced well out on the plain; in one instance the waters of a storm (apparently a local thunder-gust) had scooped out a basin 25 or 30 feet wide, 10 or 12 feet deep, and 250 feet long, then dammed its lower extremity with silty debris, and, finally, as the flow slackened, lined it with impervious silt which held water for months, and so located a Papago settlement; and cases were reported in which basins or tinajas of this character, refilled from season to season for some years, drew about themselves agricultural rancherias of Papago Indians, who built houses and planted fields around the banks in order that they might enjoy the priceless gift of their most potent deity.

In southwestern Arizona the sheetflood is well known to the Indians and to those Mexican and American rancheros who chance to be favorably situated, and they are well and expensively known to railway corporations, who sometimes have five miles or more of track washed out by a single storm perhaps sweeping over a smooth plain without a single waterway before, and with only a few new-made gullies after, the catastrophe. In essential features the local lay testimony is everywhere alike; there is a storm with exceptional precipitation, the water simply floods the surface in a muddy torrent or "wash" stretching as far as the eye can reach, the ground is swept of loose débris, and even of surface sands, while flotsam and sand heaps are piled up here and there; and in a few minutes, or perhaps a few hours in the lower valleys, the flood slackens and almost immediately disappears.

Such is the character of the sheetflood, as determined from direct observation, lay testimony, and the evidence of effects; and were it needful this evidence might be many times multiplied.

Conditions requisite for sheetflooding.—The main (perhaps the sole) source of the sheetflood is storm-water, comprising that shed from the mountains and that falling directly on the intermontane plains; and since the mountains are low and form only a small fraction of the surface, it seems clear that the chief source is the storm of the plains.

The first requisite for typical sheetflooding, then, is precipitation so rapid as to exceed immediate absorption by the dry earth and immediate evaporation in the drier air (for usually, in the Sonoran district, the precipitation horizon is some yards or hundreds of yards above ground, and the lower strata of the air are so hot and dry as to take up much of the falling and a part of the fallen moisture); and this involves several attendant conditions: One condition is that the temperature shall be high and the capacity for aqueous vapor great, in order that a large quantity of water may be produced when precipitation occurs; and this condition is amply met in the highly heated Sonoran district. An attendant condition is that the precipitation shall be rapid; and this also is met by the subtropical climate and wind-disturbing topography of the district. A third condition is that the soil shall be readily pervious only in limited degree or to limited depths; and this condition is met on the lightly veneered baselevels adjacent to the mountains, where the mantle only is porous and the under rocks sound and hard; it is not met in the deeper central portions of the valleys, where the permeable sands are of considerable depth. There are also other conditions which need not be noted in detail.

The second requisite is that there shall be abundant detritus, whereby the moving water may be readily loaded to the full limit of its capacity; and this requisite also involves several conditions: An important condition is absence of sward or turf to hold the earth-particles in union; this condition is fulfilled by the bare sands and naked rocks making up nine-tenths or more of the Sonoran surface. It is probable that another condition resides in chemical inertia of the mechanically comminuted rock-matter in the dry, coupled with some chemic activity promoting miscibility when wetted; and this condition is found in the friable sands and silts of the region, which form a tenaceous mud on saturation and a viscid slime on flooding. A third condition is dimensional heterogeneity in the debris, so that every part of the sheetflood may be loaded to its full capacity, whether its movement be swift or slow; and this condition is fully met on the upper plains, where silt, sand, gravel, and boulders in all sizes and shapes are intermingled, though it is less perfectly met in the valley interiors, where the materials are more completely assorted. Other conditions exist, but they are apparently of minor importance.

A third requisite is that the slope of the surface shall be of a certain somewhat variable value (not yet determinate save empirically as say 75 to 200 or possibly 300 feet per mile). The optimum or most efficient slope is evidently conditioned by thickness of the detritus mantle, which would appear to be considerable on the higher slopes, less on the lower slopes, and so great as to be an obstruction toward the valley interiors; by coarseness of the detritus, which always is greatest on the higher slopes; by dimensional heterogeneity, which in like manner culminates on the higher slopes; by porosity and friability, and by various other conditions. With slopes above the limit of efficiency, sheetflooding does not occur; the detritus is simply swept away, and the under-loaded storm-waters gather into streams, which carve channels. When the slope is below the limit of efficiency, the mechanism becomes clogged, the declivity and consequent velocity do not permit the incipient stream to overload itself quickly, and there is a tendency to assume the habit of streaming rather than that of sheetflooding. The various conditions of slope requisite for sheetflooding are strikingly met in the Sonoran district; two-fifths or more of its area consists of vast torrential aprons lightly veneered with detritus resting on baseleveled rocks, the inclination ranging between 75 and 250 feet per mile.

The final requisite for sheetflooding is that the volume of water, the mass of available debris for loading it, and the slope (and hence the velocity) shall be so interrelated and balanced that every part of the sheetflood may be loaded to its capacity, and that any temporary or sporadic increase in velocity may be quickly checked by overloading and consequent reduction of velocity. The conditions affecting this requisite are multifarious, probably beyond analysis, but it may be suggested that an important—perhaps the essential—condition is a progressive paralysis or weakening of the torrent due to the constant absorption and evaporation of its liquid element, the solid element remaining to burden immediately the falling or inflowing water. This condition is fully met in the parched air and burning sands of Papagueria.

On juxtaposing the requisite and qualifying conditions of sheetflooding, they are found in harmony with the distinctive characteristics of the greater part of the Sonoran district, and when the characteristics are compared with the conditions observed in special localities the harmony is rendered still more complete. It becomes evident that the sierras and buttes lie outside the domain of sheetflooding, since their slopes are too steep and their detritus too scanty; that the mountain-born streams on reaching the torrential plains must become quickly diverted and attenuated into sheetfloods, provided their volume be sufficient; that the light shower falling on the baselevel plain is absorbed, while the heavy shower must spread into a moving film and the cloud-burst into an irresistible sheetflood, sweeping all before it; and that the final feeble flow, whether from distant barrancas or local seepage in depressions, must resume the habit of the stream, pushing down toward the sea until the waters are finally lost.*

Erosive work of sheetfloods.—It may be affirmed from observation, both direct and indirect, and from necessary inferences concerning land-forms

* Reference is due to the work of Mr Willard D. Johnson during the second expedition, and to his opinions concerning the somewhat anomalous topographic features of the Sonoran district. Although sheetfloods were not witnessed during this expedition, Mr Johnson had opportunities for studying flotsam records, and in the course of his admirable topographic surveys he was much in contact with the features of the sand washes forming the fans or deltas of Rio Sonora, Rio Bacuache, and other principal drainageways. His conception of the Sonoran flood was commonly expressed by the term "interlacing drainage," consisting of a multitude of broad, shallow, and swift streams, approximately parallel in course, constantly divaricating and reuniting in such manner as to leave numerous islands, which were from time to time invaded and swept away. This conception is undoubtedly accurate so far as the lower reaches of the waterways are concerned, and it doubtless applies also to what the writer would consider as the lower or peripheral zone of sheetflooding proper, where there is a tendency toward the resumption of stream habit. Unfortunately Mr Johnson's observations and conclusions are not yet published; circumstances have prevented even the completion of his map, excepting the portion including Seriland; but important results may be anticipated.

and structure, that the sheetflood is an efficient agency (1) in transportation, (2) in corrasion, and incidentally (3) in deposition. Its efficiency is enhanced in the Sonoran district by various conditions, comprising all those essential to the existence of this form of water body, and including notably the local tendency toward the production of disintegrated and comminuted detritus rather than residua over the surface of mountain and plain—vegetation is too meager to produce appreciable quantities of humus acid, water is too scanty to aid materially in chemic action, frost is too rare and superficial and the included water too minute to rend the rocks effectually. Its efficiency is limited by the rarity of rainfall in sufficient quantity to produce flowage in any form—over the greater part of Papagueria, where the mean annual precipitation is probably no more than three to five inches, many tracts of 1,000 square miles or over are missed by the midwinter and midsummer storms of one or more years, the freshet-making storm may be three or five years in coming, and the great mantle-moving torrents are apparently separated by decades or centuries.

The efficiency of the sheetflood in transportation was amply shown by the relatively trivial torrent at Rancho de Bosque, which was literally a thin mortar of mud rather than water, and the well-preserved traces of sheetflood work in other localities gave unmistakable indications that great quantities of detritus were collected and transported. Inferences as to the behavior of greater sheetfloods rendered necessary by analogy and by the distinctive topographic configuration indicate with strong probability that the volume of material transported by the debacle increases in a higher ratio than the volume of water, so that the entire detrital mantle may be saturated to the point of mobility and carried down the slope in a sort of mud-flow peculiar only in its magnitude and in the dimensional heterogeneity of the moving particles.

The efficiency of the sheetflood in corrasion is made manifest by consideration of its mechanism: The velocity of flow must be considerable, else the flood is absorbed and evaporated; the water must be laden to its full capacity with abrasive material, else it runs clear and gathers into streams. This material, whether fine or coarse, is exceptionally hard and sharp rather than softened and rounded by decomposition, and the internal currents in the shallow sheet are such as constantly to batter and scour the subjacent surface as the mass half rolls and half slides across it. The inference from the character of the sheetflood is consonant with the necessary inference from the character of the baselevel surface. Over dozens or scores of square miles in carefully examined localities, hard rocks like those of the mountains, and with no sign of decomposition, are planed almost as smooth as the subsoil by the plowshare, with nothing either in configuration or in covering to indicate that streams have flowed over them, and extended consideration has yielded no other suggestion as to the eroding agent than that found also in analogy with the observed sheetflood. Moreover, these planed surfaces are not rare or exceptional; they occur under a definite law of distribution (with respect to sierras on the one hand and alluvium-lined valleys on the other) in all parts of the Sonoran region; their area may be estimated as two-fifths of the entire tract, or over 100,000 square miles. The efficiency of the sheetflood as a corrading agent is connected with its efficiency as an agent of transportation, for the rapid corrasion constantly furnishes material to be carried down the slopes, and this material in turn is available for cumulatively increasing the effective work of the agent.

The efficiency of the sheetflood in deposition would appear to be subordinate. In the miniature examples observed, a relatively considerable sheet of sediment was indeed laid down, yet it was no more than might be taken up and carried further down the slope by the next torrent, so that deposition in this case would seem to be little more than the mark of decadence; and in the various torrential plains on which the traces of past sheetfloods were found the conspicuous marks were those of degradation rather than aggradation. So far as the characteristics of the sheetflood are susceptible of analysis, too, it would seem that this form of flowage cannot maintain its distinctive attributes unless the detritus mantle is of limited thickness, so that deposition may be considered as essential and characteristic only to the extent of supplying abrasive materials for the next debacle within the sheetflood zone proper, while the external or peripheral deposition would appear rather to represent ordinary delta-building or stream-work. It is significant in this connection that many of the valley-plains (*e. g.*, San Luis valley, east of Baboquivira range) are much more strongly diversified by waterways and their attendant bluffs in their medial portions than half way up the gentle slopes toward the bounding mountains.

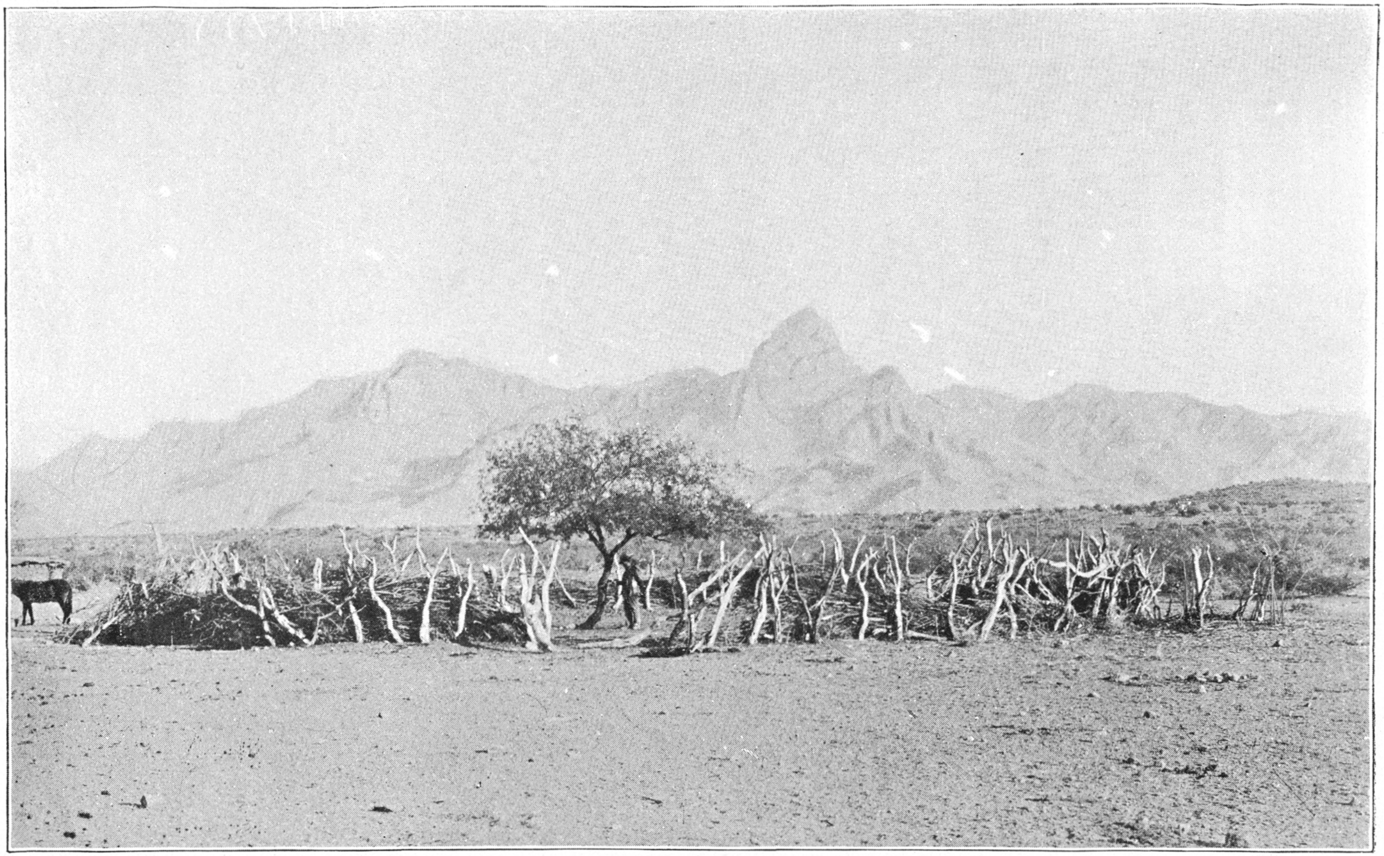
When the functions of sheetfloods are combined, it is found that their tendency is to recede or retrogress from the valley interiors, as these are progressively clogged with sediments, toward and into the bounding ranges; and this retrogressive cutting is one of the most significant features of the erosive process, partly in that it tends to produce anomalous profiles, passing abruptly from steep mountain side to nearly flat plain, in lieu of the gently sloping concave profile characteristic of stream-work. When the torrent filling the mountain barranca embouches on the plain, the first effect of the slackening in flow is the discharge of the detritus in a fan, which of itself tends to spread the water; and this fan protects the subjacent rock from corrasion. The slackened torrent may, indeed, divide on the fan surface into a number of streamlets divaricating over the contiguous part of the plain, but these are subject to the same law as the main stream and are continually divided and subdivided as they move down the diminishing incline; and thus the ultimate effect is to distribute the water widely and plane the fan into gentle curves, blending with the adjacent baselevel and sharply discordant with the mountain slope. As the process continues, the fan of one episode, particularly if produced by an exceeding torrent, may resist the powers of succeeding freshets, and thus initiate a butte in the line of the barranca, like Fresnal hill; and in some cases the salients between adjacent barrancas are cut through by the divergent floods in such manner as to form outlying buttes or cusps in line with the aretes ribbing the sierra, like some of the isolated buttes rising from the eastern apron of Sierra Seri, and the granite picacho with its half-mile pediment in the Seriland section near Puerta Infierno. The immediate consequence of this retrogression is the cumulative sharpening of the inflection in profile marking the base of the mountain; and it is noteworthy that the smaller mountain remnants on the flatter plains are (other things equal) steeper and more rugged than the greater mountain masses, as illustrated by Sierra de Tonuco and the little buttes in the northeastern part of Seriland in comparison with the high Sierra.

In brief, it may be affirmed, with so much confidence as the conditions of observation during two expeditions warrant, that the general effect of sheetflooding in the Sonoran district is to carve baselevel plains, lightly veneered by the carving material, about the medial altitudes; that these plains tend ever to retrogress into the mountains, and thereby steepen their slopes and render them exceptionally rugged; and that the anomalous topography of the region is not susceptible of explanation by other agencies.

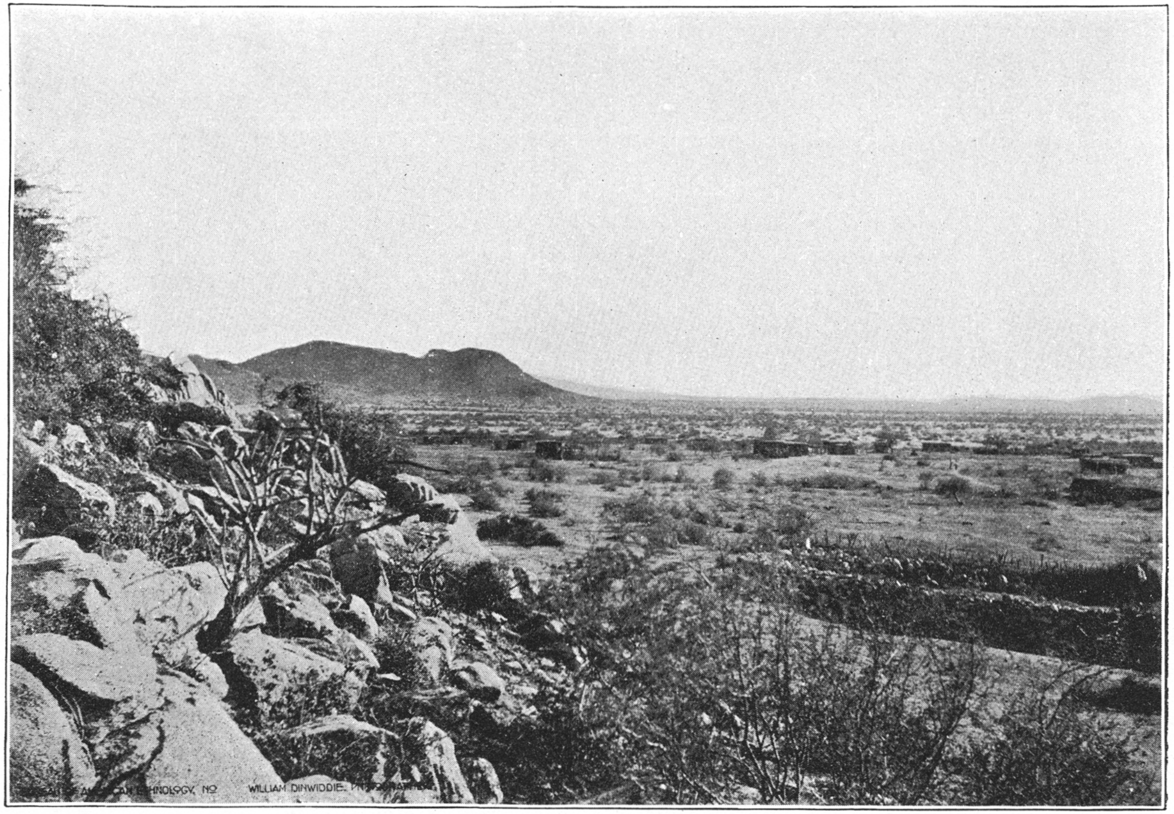
It would be of interest to consider the natural history of sheetflooding in the region, and to obtain thereby a distinctive geomorphic record which might be compared with the stratigraphic record in reading the geologic history of the southwestern portion of the continent; but the time for this study has not yet come.

Sheetflood Work in other Districts.

While the requisite conditions for sheetflooding are especially favorable in the Sonoran district, and while the effects of the process are proportionately conspicuous, it is not to be supposed that the process is confined to the district—indeed it may be suggested that the process will be found a main or minor one in various districts, particularly those



BABOQUIVARI PEAK, LOOKING EASTWARD FROM FRESNAL



POSO VERDE PLAIN, LOOKING SOUTHEASTWARD

whose climate and configuration approach those of Papagueria. It may be noted as probable, also, that even in the more humid provinces a process analogous to that of sheetflooding may exist; for wheresoever rain falls the waters gather into a moving film before rivulets and streams are formed, and this film must be a more or less active geologic agent. Finally, it may be noted that certain obscure phenomena of various waterways which, like the Susquehanna and other Piedmont rivers in parts of their course, tend to corrade their channels laterally rather than vertically, appear to be akin to those of sheetflooding.

Explanation of Plates.

Plate 10.—*Baboquivari Peak, looking eastward from Fresnal.*

The summit of the peak rises about 4,500 feet above the plain in the foreground. So far as seen, the rocks of the range are ancient granites, passing into dark-colored schists near the western base. The conspicuous features of the sierra are steepness, ruggedness, and the dearth of taluses and foothills; the peak has never been climbed. The baselevel plain forming the foreground and middleground is exceptionally irregular, rising toward the right into a smaller counterpart of Fresnal hill (which is located directly in the rear of the point from which the photograph was taken). The surface deposit of the plain, as shown in the immediate foreground, consists of granitic debris in the form of angular boulders and pebbles, sharp sand, and silt; it usually ranges from two to five feet in thickness. The under-rocks of the plain, as shown in a deep arroya and its tributary gulches just beyond the field on the left, are dark schists and granitoid materials, similar to those forming the adjacent base of the sierra. The view illustrates the abrupt transition from mountain side to plain. The air-line distance to the nearest salient is about three miles and to the crest of the peak about five miles.

Plate 11.—*Poso Verde Plain, looking southeastward.*

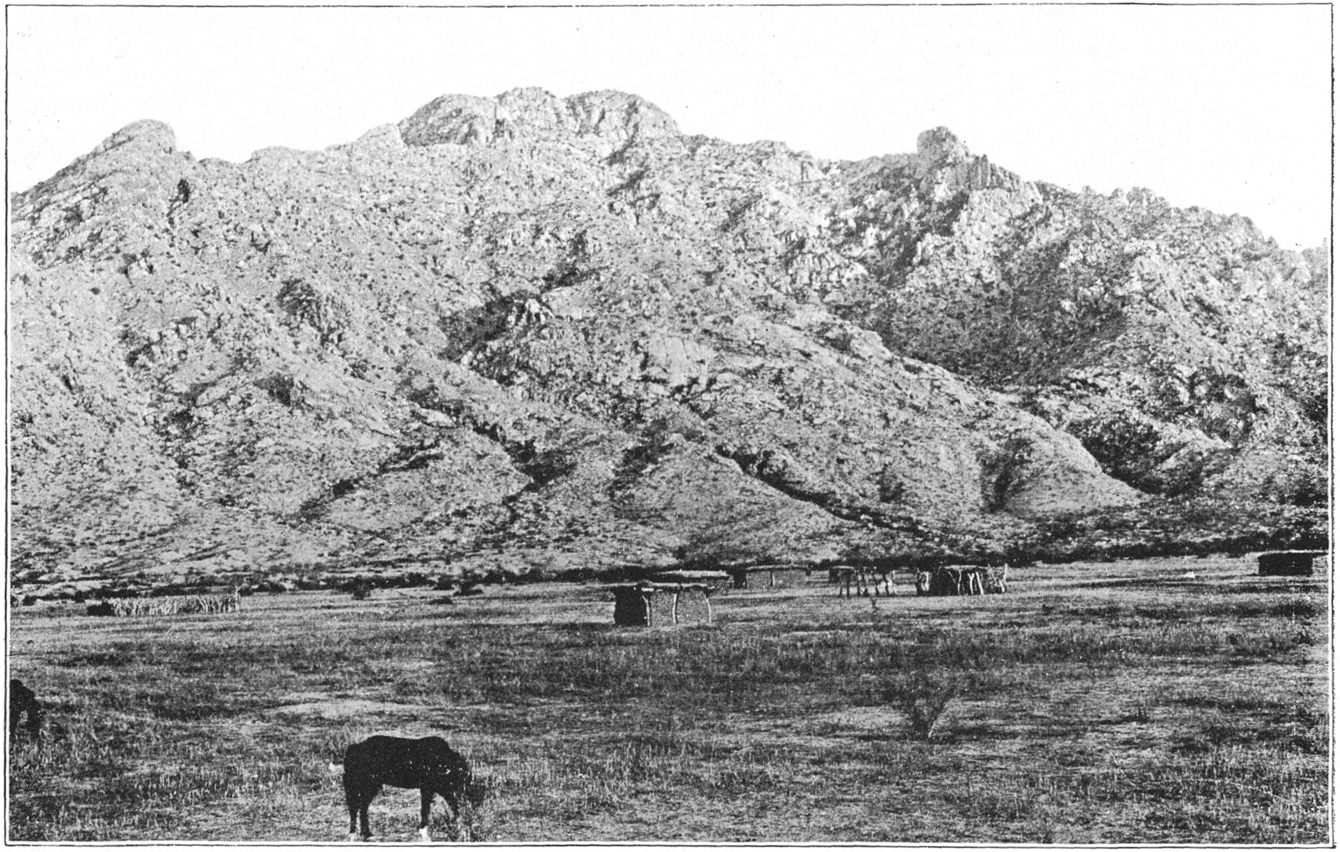
The middleground represents part of the Papago Indian village of Poso Verde and, immediately beyond, the arroya forming the extension of a barranca heading in the mountains on the left. The central part of the picture shows the great torrential plain sloping southward to Rio Seco, on which sheetflood traces were found in 1894. The immediate foreground illustrates the usual relation between mountain-side and plain, the mountain rocks consisting of granite and the plain deposits of granitic debris. At this point the debris mantle is exceptionally thick (15 to 18 feet), as shown by the excavation about the spring supplying the village, but a few hundred yards down the slope toward the left granites are exposed within five feet of the surface of the plain, and the great arroya in the middleground bottoms on granite often rising nearly to the surface. The mountain spur forming the horizon left of the center is less rugged than usual, and its curved profile blending with that of the plain is exceptional—it is a nearly isolated mass affording little space for the gathering of waters, which are free to spread widely on approaching the plain. This salient is 7 or 8 miles, and the range faintly shown beyond 30 or 40 miles distant.

PLATE 12.—*Coyote Mountain, looking eastward.*

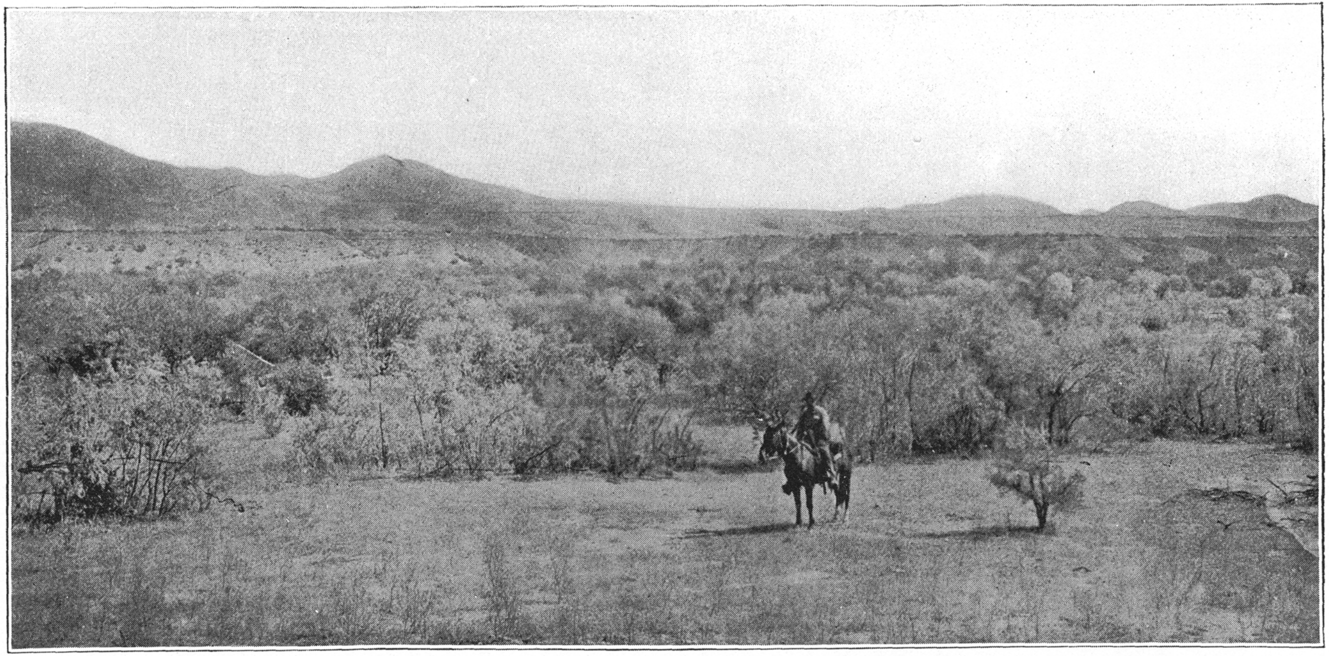
Coyote mountain is an en echelon extension northward of Baboquivari range. The prevailing rocks are gray granites, with schists toward the base and on the adjacent plains. The altitude of the crest is probably about 5,500 feet, or 3,000 feet above the Indian village (Coyote) in the foreground. The conspicuous features, as at Fresnal, are steepness, ruggedness, and the small dimensions of taluses, fans, and foothills. The mountain face shown is practically inaccessible, and has never been climbed. Several low fans are shown, particularly at the right and somewhat left of the center; these have the form of alluvial accumulations, but actually consist of sharply carved mountain rocks, veneered thinly with granitic loam and gravel littered with great boulders. The plain in the foreground is thoroughly typical; the surface deposit is granitic debris, averaging less than a yard in thickness (so far as could be determined from several exposures), resting on the planed edges of rocks similar to those of the mountain. The view shows well the sharp transition from rugged mountain to smooth plain.

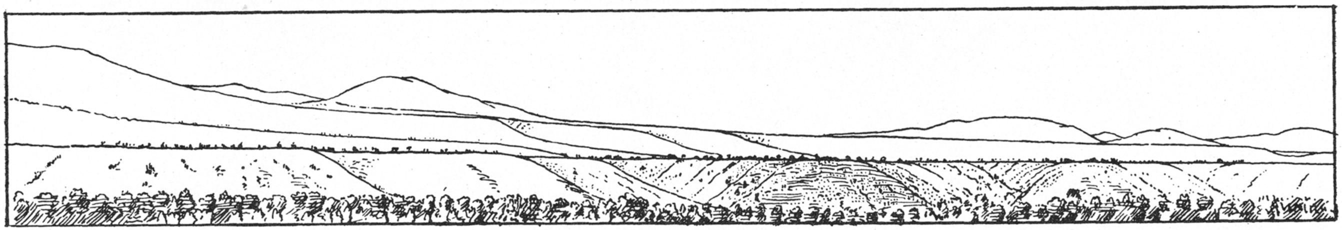
PLATE 13.—*Torrential Aprons of Papagueria.*

The view represents the eastern side of the valley of Rio Magdalena, about twenty miles above Imuris. The mesquite-clothed foreground is alluvial, though under-rocks crop out occasionally and appear in terraciform bluffs. The great aprons forming the background have the appearance of alluvial fans, such, e. g., as those described by Drew in northern India (Quarterly Journal of Geological Society, vol. xxix, 1873, p. 441, et seq.), yet analogy with all of the plains examined indicates that they are in greater part baseleveled mountain rocks thinly veneered with alluvial deposits. They were not visited. The sierra in the right background was somewhat doubtfully identified as belonging to the main Sierra Madre, in which case it is seventy-five or a hundred miles distant. Since the locality approaches the high Sierra, the slopes are steeper than those characteristic of the lower plains; the altitudes range from some 2,000 feet in the foreground valley to 3,500 in the aprons and 5,000 and upward in the nearer sierras.



COYOTE MOUNTAIN, LOOKING EASTWARD





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Notes