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THE GALIURO MOUNTAINS, ARIZONA.

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"All our results in geology are tainted by the tacit assumption of simplicity that does not exist."—*G. K. Gilbert.*

GENERAL STATEMENT.

The following interpretation of the Galiuro mountains in southeastern Arizona as a tilted and dissected fault block, a typical Basin Range, is based on the work of several earlier observers and extended by the present writers who, as teacher and graduate student at the University of Arizona in the spring term of 1929, have visited the range at several points, in its northern third.

The topographic map of the state, 1 : 500,000, shows the mountains, trending northwest-southeast, to be 50 or 60 miles in length and 10 or 15 in width. The crest is from 4,000 to 6,000 feet in altitude in its highest part, with a rather abrupt descent to the southwest; on that side it falls off by some 3,000 or 4,000 feet to the valley of San Pedro river which leads northwestward, about parallel to the range front and 8 or 10 miles from it, along a broad intermont trough. The valley floor stands at about 3,200 feet altitude opposite the southeastern end of the range and at about 2,000 feet a little beyond the northwestern end, where it joins the valley of the Gila. The town of Winkelman lies near that junction. Mammoth, the dwindling village of an abandoned mining district, lies in the San Pedro valley 20 miles above Winkelman. Benson, 55 miles farther up-stream in the same valley, is enlivened by the crossing of the Southern Pacific railroad.

The Galiuro range is extended southward by the smaller range of the Little Dragoon mountains, and also southeastward by the Winchester mountains; but the present essay is not concerned with these extensions. The Santa Catalina and Rincon mountains lie southwest of the San Pedro trough. The Pinaleno or Graham mountains lie beyond an apparently similar but somewhat higher and narrower trough on the northeast, which is continued far southeastward in the Sulphur Springs trough, where much of the drainage disappears in a broad playa without outlet.

Two close-placed stream valleys, those of Copper creek and Mulberry wash, heading within the Galiuro range, lead southwest to the valley of San Pedro river; they separate the northwestern third of the range from the southeastern two-thirds. The northwestern third is cut into sixths by the deep canyon of Arivaipa creek which carries drainage from the detrital trough on the northeast through the range to the San Pedro. Our observations are limited chiefly to the neighborhood of these branch valleys.

The geological map of the state represents the greater part of the range as occupied by "older volcanic rocks," believed to be Tertiary andesites for the most part; various underlying crystalline and Paleozoic rocks are indicated along the western side of the range in the northwestern third of its length. According to members of the State Bureau of Mines the under-rocks include inclined sheets of rhyolite associated with ancient quartzites, both being unconformably covered by the capping andesites. As to the two prongs in the southeastern part of the range: the smaller or southern prong, making part of the Little Dragoon mountains, is mapped as consisting of ancient crystallines and paleozoic strata; the larger, southeastern prong, making the Winchester mountains, is mapped as showing only Tertiary lavas: a brief inspection of the farther end of the last-named mountains showed their structure to be disorderly. The troughs adjoining the Galiuro range on either side are occupied by more or less indurated detrital deposits, chiefly of Pleiocene or Pleistocene age. The deposits of the southwestern trough are trenched along its physiographic axis—that is along the line defined by the meeting of the detrital slopes from the Galiuro mountains on one side and from the Santa Catalina and Rincon mountains on the other—by the above-mentioned shallow valley of the San Pedro, a true valley of erosion in contrast to the broad, detritus-filled trough of displacement in which the valley is excavated.*

* The broad, flat-floored depressions which lie between the mountain ranges of Arizona are nearly always called "valleys" by their occupants, although they are in most cases aggraded troughs or basins. It is, of course, difficult to effect a change in the use of the popular old word, valley, but in

EARLIER ACCOUNTS.

Few and brief are the accounts of the Galiuro mountains in geographical literature. The earliest is by W. P. Blake,[1] who states that "the Galiuro range consists of ancient rhyolites... The planes of flow, instead of being nearly horizontal as usual, are vertical over a large area, and have a nearly uniform north and northwesterly trend to which the direction of the range and its chief valleys conform. Over a considerable part of the range the rhyolite crops out in jagged peaks ... There are also horizontal beds of highly crystalline lava and of volcanic tufa and breccias, remnants of which are found in table mountain summits and in detached eroded masses filling some of the ancient valleys in the vertical rhyolite, but now cut through by erosion ... The rhyolite intrusion may be assumed to have taken place along a longitudinal line or plane of break and faulting following the great syncline between the two uplifts of the Archean granites, gneiss and schists of the Santa Catalina and the Graham or Pinaleno mountains." The "horizontal beds of highly crystalline lavas" here mentioned are presumably the andesites which cover so much of the range, usually with a gentle eastward slant. Blake goes on to say: "The peculiar and strongly marked vertical structure [of the rhyolite] may be due to lateral pressure along the course of the break and not to lateral or original horizontal flowing." His cross section, here copied in part in Fig. 1, represents horizontal beds of lava on both sides of the range, unconformably overlying the apparently eroded edges of the vertical rhyolites. This inter-

this essay we propose to limit its application to longitudinal depressions excavated under the erosional leadership of streams. The nearly level surface of aggraded basins or troughs will be called by the fitting name of plain or dissected plain; the piedmont marginal slopes of such plains may be called bajadas (bahadas). The case recalls a dispute that is sometimes heard as to whether whales are fish. They are still properly enough fish in the original sense of that old English word; a sense that survives in spite of the introduction of a scientific classification which places whales with mammals. A zoologist may fairly enough limit his own use of the word, fish, so that it shall not include whales; but he cannot easily lead popular usage to give up the original sense of the word. Similarly, a physiographer may limit his own use of the word, valley, so that it shall not include the plains of aggraded intermont basins, but he cannot prevent the popular use of the old word as a name for such plains; witness the well-established name, Valley of California.

[1] Blake, W. P., The geology of the Galiuro mountains, Arizona. Eng. and Mining Journ. 73, 546-547, 1902.

pretation of the range structure seems to us improbable, unless it represents a more southern section than we have seen. The assumptions that the Galiuro range occupies a great syncline between the upheaved Santa Catalina and Pinaleno mountains, and that the rhyolites rose through a break or fissure along the depressed synclinal axis seem unwarranted.

Campbell has given a brief account of the northwestern part of the range.[2] He notes that "overlying the shales and sandstones just described [mostly deformed paleozoic beds?] is a great mass of Andesyte which doubtless was poured out

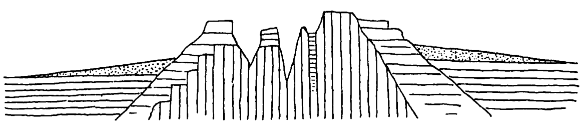

Fig. 1. Rough copy of Blake's section of the Galiuro mountains.

as surface flows in the synclinal basin..." These flows "conceal much of the older topography... Over most of the basin the zone of transition from sedimentary to igneous is marked by a thick bed of [Cretaceous] conglomerate, consisting of a matrix of andesitic tuff cementing well-rounded boulders [chiefly granite, quartzite, and limestone] of all sizes from a few inches to ten or more feet in diameter... In its maximum development it [the andesite] probably has a depth of not less than 1,000 feet... The Tertiary history of the range is complicated, consisting of great erosion intervals in which large masses of gravel were produced [in the adjoining depressions or troughs?] ... they do not in any respect resemble the underlying Cretaceous conglomerate." Faulting is not mentioned.

Jones, searching for manganese in Arizona, briefly reports its occurrence in massive limestone about 10 miles northeast of Mammoth in the neighborhood of Copper creek,[3] but makes no statement as to the general structure of the range.

Darton, under whose supervision the geological map of the state was prepared, describes the Galiuro range as including

[2] Campbell, M. R., Conglomerate dikes in southern Arizona. Bull. Geol. Soc. Amer., 33, 135-138, 1904.

[3] Jones, E. L., Jr., Deposits of manganese ore in Arizona. U. S. Geol. Surv., Bull. 710-D, p. 169, 1920.

"high mesas and ridges," and as consisting of "a great thickness of Tertiary volcanic rocks with some included beds of tuff, ash and conglomerate, for the most part dipping gently eastward. They present to the west a bold escarpment in which the underlying rocks appear."[4] This geologist gives several local and somewhat detailed sections of the under rocks, but does not discuss the origin of the range and makes no mention of a fault along its southwestern base.

Ross, viewing the northern part of the Galiuro range from the east, says that it appears "to be built up largely of Tertiary lavas." He also notes that the "Tertiary volcanic rocks are extensively faulted," and that the intermont depressions formed in part by faulting are "filled with the sandstone and conglomerate of the Gila formation."[5] This reference to faulting is one of the very few that we have found in earlier writings.

UNDER-STRUCTURE OF THE RANGE.

The older rocks mentioned by Darton as lying under the Tertiary lava flows include a variety of coarse and fine-grained crystallines as well as a rather heavy series of more or less deformed Paleozoic strata. We have not attempted to differentiate these rock masses, but have directed our observations chiefly to determining the nature of their surface when they were buried by the andesitic outpourings. Similarly, we have not attempted to determine either the chemical composition of the magma or the mineralogical constitution of the magma-supplied lavas which now cover so large an area of the range, but have accepted the statements of members of the State Bureau of Mines to the effect that diabase, rhyolite, and altered basalt occur among the underlying crystallines and that the covering ash beds, breccias and lava sheets are andesites.

Form of the Sub-Lava Surface. The general relation of the underlying and overlying rock masses is shown in a longitudinally compressed diagram in Fig. 2. The irregularly bedded andesites appear to be of greatest volume through the middle of the range, where they may measure 1,200 or 1,500 feet in thickness. There, and as far southeastward as we

[4] Darton, N. H., A résumé of the geology of Arizona. Univ. Ariz. College of Mines, Bull. 119, 1925; see p. 272-274.

[5] Ross, C. P., Geology ... of the Arivaipa and Stanley mining districts ... Arizona. U. S. Geol. Survey Bull. 763, 1925. See pp. 29, 44, 52.

could see, the whole of the west-facing scarp seems to be formed of them, as drawn in Fig. 3; but inasmuch as the cobbles and gravels on the benchland over the San Pedro valley hereabouts contain many fragments of an altered basalt of deceptive flinty appearance, we infer that the basal slopes

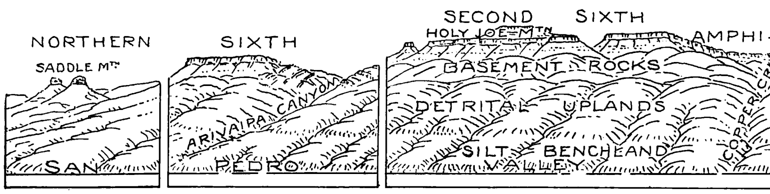

Fig. 2. Compressed diagram of the Galiuro mountains, looking northeast.

of the escarpment consist of that rock, although it is not shown there on the geological map.

In the neighborhood of Mulberry wash the basement rocks, hidden farther southeast, rise in massive, rounded, gray-green hills to half or more of the scarp height, and the lava cover decreases in thickness correspondingly. In the space around

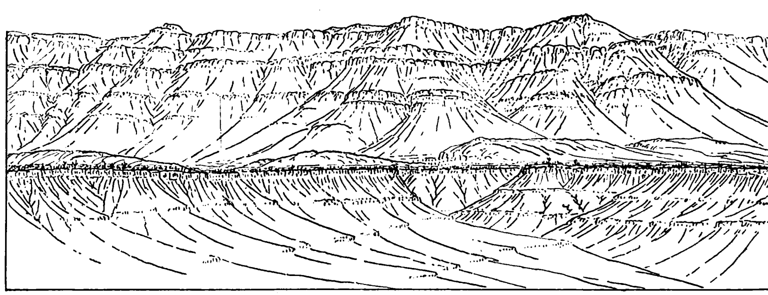

Fig. 3. Escarpment of heavy lava flows, mid-length of the Galiuro mountains, looking northeast. Low lava slabs rise in middle ground. Dissected detrital deposits in foreground; the valley is eroded in gravel-covered silts, here consisting largely of diatomaceous earth.

the heads of Mulberry wash and Copper creek, the well-dissected hills and mounts of the underlying crystallines, mostly of light gray color on the weathered slopes which are often covered with granite-like weathered boulders, reach so much greater height than farther south that the lava sheets appear not to have covered them; and it is apparently for this reason that the thinned edges of the sheets here withdraw 3 or 4 miles from the general line of the range front in an amphitheatral entrant.* It is true that the tops of even the highest crystalline-rock hills in this area are now hardly as high stratigraphically as the base of the thinned lava cover; but that defect of height is, like the deep-cut valleys between the

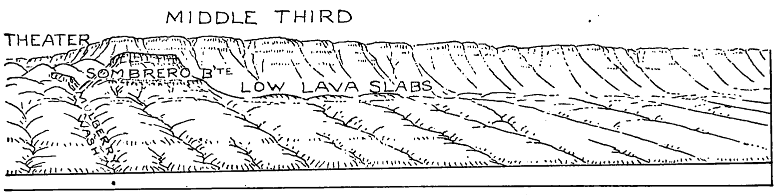

Fig. 2, continued.

hills, attributed to erosion after the range block was uplifted.

In the ten-mile length between Copper and Ariviapa creeks, the lava cover advances in a bold cliff-fronted escarpment for something more than half that length, as shown in Fig. 4, but its thickness there is apparently much less than that of the heavy lava beds to the south. According to information received from Messrs. Wilson and Tenney of the Arizona

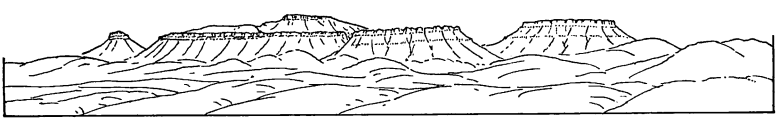

Fig. 4. Tabular lava caps of the Galiuro mountains between Arivaipa canyon (to left) and valley of Copper creek (to right). The highest summit is Holy Joe mountain, 6,145 feet. The rolling hills consist of basement rocks; the foreground is dissected detritus.

Bureau of Mines, the floor on which the eruptives here rest unconformably is "hilly," and the hollows between the hills, some of which consist of inclined and much eroded quartzites and rhyolites, have been evened up by deposits of andesitic ash and breccia before the heavier andesitic flows were spread out in a broadly continuous cover. It is important to note, however, that the crystalline rocks of the under-mass, most of which are probably intrusive, have forms of mature or

* We replace "re-entrant," as the opposite of salient, by the shorter word, "entrant," which the New Oxford Dictionary defines as "one who or that which enters."

late-mature erosion, as far as they have been determined. None of them appear to have been intruded after the eruption of the covering andesites, but on the contrary so much earlier that they had been greatly eroded before the eruption of the cover took place.

The steep walls of Arivaipa canyon and the adjoining highlands on either side are occupied chiefly by heavy quartzites and other members of the ancient Apache group, more or less inclined and outcropping in bold, ungraded cliffs, along with sheets of intrusive diabase. Here the pre-lava surface was probably even higher than in the Copper-Mulberry entrant, for none of the covering lava sheets appear on the adjoining highlands or on their back slope as far up-stream as we could see from a point well inside of the canyon; but Ross, who has

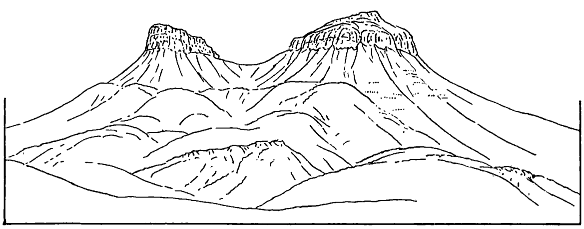

Fig. 5. Lava-capped peaks of Saddle mountain, isolated from the north end of Galiuro mountains, but apparently of similar structure and history. Hills of basement rocks in middle distance.

examined the ranges next to the northeast, states that Arivaipa creek, on leaving the trough on that side of the Galiuro range, enters its canyon through "resistant beds of Tertiary volcanics,"[6] which must therefore flank the northeastern side of the range here as elsewhere, and which presumably dip beneath the detritus of the trough to which the range there slants down.

But although absent from the range crest on either side of Arivaipa canyon, the lava beds reappear in good force, though not so heavy as in the middle of the range, a few miles farther north in its first sixth and there again form a frontal escarpment, but the range crest is here 1,000 or 1,500 feet lower than in the second sixth. Farther on, two isolated knobs, Fig. 5, appear to mark the most northern extension of the

[6] Op. cit., p. 12.

andesite cover; farther north still the deep transverse gorge of the Gila is eroded in rocks of altogether different nature, belonging to another mountain mass.

In view of these various facts it is concluded that the under-rocks of the Galiuro range had not been worn down to a smooth lowland before the lavas were erupted upon them, but that they then still retained a hilly or sub-mountainous relief, measuring 500 or 1,000 feet in 10 or 20 miles. Nevertheless, as compared to the relief which must have been developed in an early stage of the erosion cycle that was introduced by the presumably Mesozoic deformation of the under-rocks, the deformed structures were at least well subdued when the lava deluge took place. The sub-lava surface does not therefore seriously impugn the correctness of Powell's early generalization to the effect that the Great Basin was, before the upheaval of the existing ranges, "a comparatively low plain, constituting a base level of erosion to which the region had been denuded [after its Mesozoic deformation] in Mesozoic and early Tertiary time when it was an area of dry land."[7]

EVIDENCE OF BLOCK-FAULTING.

Although various departures from the prevailing northeastward dip of the covering lava beds may occur, especially in the southeastern part of the range where summits of full crest height are mapped several miles back of the frontal scarp, it still appears probable that the compound Galiuro mass, consisting of a complex and hilly under-mass beneath a relatively simple but heavy lava cover, has been, since the lava cover was poured out, disturbed by up-faulting along the western base line of the range where the lava beds now, as a rule, form so strong a scarp; also by tilting to the northeast where the lava beds, in the northern half of the range at least, appear to slant down into a detritus-filled trough. It is, however, possible, that down-faulting as well as down-tilting may be responsible for the disappearance of the lavas along the northeastern border of the range, especially in the southeastern part where its border on the state geological map is somewhat irregular. Faulting along that border appears assured farther southeast in the Winchester mountains.

[7] Powell, J. W., Geology of the .... Uinta mountains. Washington, 1876; see p. 32.

There is no indication whatever that the inferred up-faulting of the Galiuro block was associated with the intrusion of any of the underlying crystallines; for two long intervals of time appear to separate the period in which even the latest intrusion made its way into the under-mass from the period in which the block faulting took place: the first of these intervals having been occupied with the erosion of the under-mass into its moderate, pre-andesite relief, and the second interval having been occupied with the outpouring of the heavy lava cover.

The chief evidence of faulting is as follows: Before the up-tilting of the compound mass into its present northeastward slant, the covering lavas must have lain lower than now and in an essentially level attitude. If the entire volume of the compound mass were then the same as at present, it must have terminated southwestward along nearly the same face that we now see in the long range scarp. Such a termination is, in view of the great thickness of the lavas, highly improbable. Hence we conclude that in their original extent, the lavas and the underlying rock mass must have had a greater extension to the southwest, though not necessarily so great as their many miles of extension in other directions.

In view of this conclusion, two suppositions may be made as to the upheaval of the compound mass. It may be supposed, first, that its entire volume was upheaved with eastward slant (or with any desired deformation), thus raising a huge mass of rocks where the San Pedro depression now exists, and that that huge mass of rocks has since then been removed by erosion. Or second, it may be supposed that a northwest-southeast fault divided the original volume of the compound mass into two parts, one of which was uplifted into the present position of the range block, while the other was relatively depressed along the site of the San Pedro trough. These suppositions are both, geologically considered, eminently possible. But if the first supposition be adopted, it would be necessary to follow it by a further supposition; namely, that the erosional removal of a great part of the broad uplifted mass gave the remainder the long scarp of fairly simple outline that it now possesses, without strong salients and deep entrants; and this is not reasonable. On the other hand, if the second supposition is adopted, the long and simple scarp results naturally enough; not that the ravined scarp as we now see it, Fig. 3, is the unaltered fault scarp, but that a moderate measure of erosion on the original scarp would wear it back to the actual scarp.

The second supposition appears so much more reasonable than the first that it is here adopted. The range is therefore regarded as, in essence, a tilted fault-block and the adjoining troughs are regarded as having been down-faulted or down-tilted. During and since the up-faulting the range block has shed a great volume of detritus into the adjoining depressed troughs, as will be further told below.

Let it be noted that the above evidence for block faulting is not provided by an orthodox geological repetition of a series of stratified formations, for the down-faulted mass is invisible. It is found simply in the structure and form of the up-faulted mass along its southwestern face which, although transecting various rock structures, preserves a fairly steep scarp along a simple northwesterly course for about 50 miles. This physiographic evidence of faulting is, however, very similar in its nature to orthodox geological evidence; for when a geologist finds a series of strata repeated in the same order in two adjacent areas, he infers that they have been separated by a fault accompanied and followed by erosion, because he cannot believe that the two parts have been formed independently; he is forced to the conclusion that they are displaced and eroded parts of an originally single and continuous mass. Similarly a physiographer infers a fault when he sees a series of rocks outcropping in a fairly continuous and nearly rectilinear scarp, because he cannot believe that such a scarp represents either their original extent, or the margin of an erosional retreat from their original extent. They must, when formed, have had a greater extension; and as the erosion of their greater extension cannot have produced a scarp of so simple an alignment, the scarp must have originated by faulting, although it may now be somewhat modified by post-faulting erosion.

Neither of these methods of fault determination is infallible. If a single stratum of commonplace composition is repeated, its repetition may not be unreasonably ascribed to a recurrence of similar and ordinary conditions of deposition; it would be unsafe to assert that faulting has taken place in such a case. Likewise, if post-faulting erosion has caused a considerable irregularity in an initially regular fault scarp, the fault can not be safely identified as such on physiographic grounds alone. In a region of faulted structure where a great amount of post-faulting erosion has taken place, the only available evidence of faulting may be wholly of a geological nature. On the other hand, recent faults in massive rocks, in which no repetition of identifiable structures are detected, can be determined only by the physiographic evidence of their still-visible scarps. Thus Baulig has recently shown, in a refined study of the Central Plateau of France,[8] a region largely composed of massive crystalline rocks, that a number of scarp-producing faults occur there which had not been recorded on the large-scale geological map of the region, because the geologists who made the map had had no experience in the physiographic recognition of young fault scarps. Neither the geological nor the physiographic method of fault-finding is therefore always successful or always correct; but in the case here under consideration the physiographic method is believed to be trustworthy. It would be pleasing if the fault, as determined physiographically, were confirmed by independent geological evidence; but unfortunately we have found no such evidence.

LOCAL EXPOSURE OF THE BLOCK FAULT.

Where the deep-cut valley of Copper creek passes from the mountain rocks into the piedmont deposits—now dissected in consequence of their post-depositional upheaval—a small but very clear exposure of the main, block-making fault is seen. It strikes northwestward and is steeply inclined from the mountain into the trough. The adjoining rock is the altered, fine-grained basalt, to which allusion has been made above as probably constituting the basement on which the heavy frontal lavas of the mid-range rest; it is dark bluish where freshly worn in the stream bed, but becomes gray where weathered; it is more resistant than the coarser crystallines farther upstream in the mountain mass, for there the creek is fairly well graded and the valley is submaturely opened; while here close to the fault the valley narrows to a steep-sided gateway, and the creek on passing through the gate cascades to a lower level. The solid rock is adjoined by 15 or 20 feet of crushed rock or "gouge," along which a short transverse gorge is worn northward. An apparently undisturbed mass of stratified, red-weathered gravels and cobbles stands in an abrupt face next west of the crushed rock.

[8] Baulig, H., Le plateau central de la France .... Paris, 1928.

The road that leads from Mammoth to certain mines in the valley heads of Copper creek makes nearly all of its distance from the San Pedro valley to the fault line on the ascending slope of the silt benchland and the gravel uplands, below which Copper creek is incised to a depth of 50 or 100 feet in the silts and to a depth of from 500 to 800 feet in the gravels. Near the fault line it descends by a dug-way on the north side of the deep valley, and after making a short detour into the fault gulch, enters the gateway in a rock cut about 30 feet above the stream bed, as in Fig. 6.

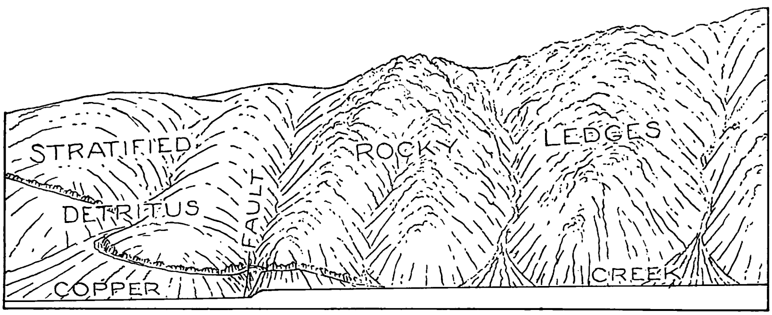

Fig. 6. Diagram of fault between basement rocks of Galiuro mountain block and uplifted detrital deposits; north side of Copper creek.

It must be inferred from this exposure of the fault, the discovery of which was a gratifying confirmation of the inference we had previously formed, that the displacement upon it was long continued while erosion of the up-faulted block and deposition in the down-faulted trough were in progress; but at least 800 feet and probably 1,000 feet or more of the total uplifting was accomplished without faulting after all the gravels now seen in the piedmont uplands were laid down; and while the later uplifting was in progress, the earlier deposited gravels shared in the erosional dissection that had previously operated on the mountain mass alone.

THE DETACHED SLAB OF SOMBRERO BUTTE.

Next south of Mulberry wash, a detached and cliff-rimmed slab of the mountain lavas, known as Sombrero Butte, Fig. 7, stands a mile or more forward from the main escarpment. The slab measures about two miles in length, and half a mile or more in width. Its highest cliff-making lava sheet inclines gently eastward at a distinctly lower stratigraphic level than that of the main crest. The depression between the slab and the range front is occupied by hills of massive crystallines. The slab of the Butte is therefore interpreted as down-faulted with respect to the range block; or better said, it is incompletely up-faulted and the failure of up-faulting appears to measure 500 feet or more. All the cliff-making outcrops in the Butte from the capping cliff to the canyon bed are lava sheets; weaker beds presumably occupy the intermediate, waste-covered slopes; hence the volcanic rocks here exposed

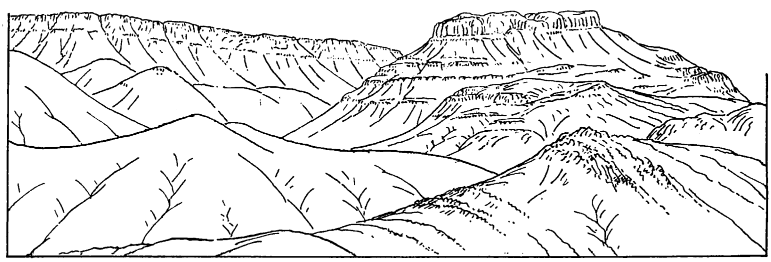

Fig. 7. Sombrero butte, a detached lava slab, looking southeast from a basement mount north of Copper creek. The canyon of Mulberry wash cuts off the tabular mass in middle ground from the butte. Main lava scarp of the Galiuro range in the left background; basement mounts and hills between Mulberry wash and Copper creek in left foreground.

have a total thickness of perhaps 1,000 feet. A narrow canyon is cut through the slab near its northern end by Mulberry wash. The lava beds in this cut-off terminal portion of the slab dip gently southward, as if because of drag in the incomplete up-faulting. The main lava sheet, exposed in a strong cliff by which the Butte is encircled at its top, is strongly jointed, giving it at a distance a columnar appearance; but a near view shows the joints to stand nearly parallel, with a north-south trend, thus dividing the lavas into vertical slices rather than columns.

A fault by which the slab is separated from the piedmont gravels is fairly well shown at its northern end in a cut of the Mulberry-wash road; judging by a weathered crevice, the fault plane trends about north-south, and dips 65° to the west. The lower beds of lava are much shattered near the fault. The little mining village of Sombrero Butte lies in the open valley of Mulberry wash next upstream from its canyon in the Butte slab. The fault which separates the slab from the main range block must lie in a valley that branches southeast from that of upper Mulberry wash at the village and follows the inner base of the Butte, for to the east of this branch valley is a hill of massive crystalline rock covered with cobbly detritus of local weathering.

A few miles south of Sombrero Butte, the piedmont detrital uplands are interrupted for a mile or more by a series of low lava knobs, which appear to represent a group of still less up-faulted slabs. We had a view of them from the gravel uplands nearer the San Pedro valley, as in Fig. 3. Sombrero Butte is not shown on the state geological map, but these lower knobs are represented by an isolated color patch.

EROSION OF THE UP-FAULTED RANGE.

The face of a recently uplifted fault block may present a fairly continuous rock scarp, trenched only by narrow gulches and almost free from talus at its base. Such a scarp, 500 or 1,000 feet in height, is to be seen along certain stretches of the enclosing Funeral range on the northeastern side of Death Valley. With more advanced erosion, the gulches widen into valleys and consume a large part of the original scarp, leaving only triangular, spur-end facets between the valley mouths; the facets are undoubtedly somewhat the worse for wear, and therefore slant back at a less steep angle than that of the original fault-scarp slope; and by this time, large and well-formed detrital fans are built forward from each valley mouth upon the lower ground of the relatively down-faulted area. An excellent example of an up-faulted mountain mass in this rather early stage of dissection is offered by a part of the Wasatch range of Utah, 50 or 60 miles south of Salt Lake City; Spanish Fork canyon is cut next to the south. At a still later stage, the spur-end facets are rounded off, so that even the farthest advanced ends of the spurs have retreated more or less from the fault line; and in this stage the physiographic evidence for faulting is not so manifest as in earlier stages; but if the spurs still end on a fairly even line, in spite of being composed of unlike rocks, upfaulting may be reasonably appealed to as a cause of their alignment.

Such is the case in the bold, west-facing escarpment of the House range of western Utah, from which Gilbert appears to have first gained the idea of a fault-block mountain range in 1872, and to which he returned nearly 30 years later for more detailed study. His first sight of the range had led him to note briefly that "it marks a N-S crack, . . . the eastern lip of which is uplifted." In 1901 he was impressed with the manner in which the resistant strata lying nearly horizontal along the middle of the range, the weak overlying shales that slant obliquely southeastward, and farther on the resistant covering limestones that decline to the southern end of the range, are all limited by the same gently sinuous line along the western base. His note book of that year describes the range as a "conspicuous example of uplift along a fault—as distinguished from survival from erosion. It is incredible that the erosion of White valley [the intermont depression to the west] should have left this great façade. The time spent in development of such a breadth of valley [10 or 15 miles] would have sufficed also to give the mountain a mature topography" which it does not possess.[9]

Like the House range and many other fault-block ranges in the Great Basin, the Galiuro range no longer preserves any visible part of a fault scarp in its western face. The heavy lava beds which form the high escarpment along the mid-length of the range are dissected by many steep-pitching ravines, Fig. 3, which may be confidently regarded as somewhat extended into the initial back slope of the up-faulted mass by obsequent growth at their heads, whereby their original short consequent courses on the rising and steeply inclined fault face have been somewhat lengthened. The short and steep-pitching spurs between the ravines are well-rounded and retain no semblance of terminal facets. Evidently the visible escarpment has retreated by a considerable measure from the potential fault face. We have not seen the northeastern or back slope of the lava cover, which Darton describes as for the most part dipping eastward, but it is said by those who know it to be "very rough," presumably because of erosion by consequent streams. However, as above noted, it is possible that the back slope departs, especially in its southeastern half, from the simple form of a tilted block.

The less heavy lava capping which forms the bold, tabular, cliff-rimmed crest along the second sixth of the range between Copper and Arivaipa creeks, Fig. 4, has probably retreated two or three miles from the fault plane, as may be inferred from Fig. 8, in which the southern lava table of Fig. 4 is

[9] Biographical Memoir of Grove Karl Gilbert. Mem. Nat. Acad. Sci., 21, 1927, pp. 55, 245.

drawn on a larger scale; here the underlying rocks are rather broadly laid bare in flanking mounts of subdued form, but not so broadly as in the Copper-Mulberry entrant, Fig 9, near by on the southeast, for, as already noted, it is thought that in that entrant the pre-lava hills were so high that they were not covered by the lava flood. Strong as the retreat of the fault-block crest has been, nowhere along the range base have we discovered any sign of a piedmont rock pediment, such as Bryan has described as characteristic of certain Arizona ranges,[10] and such as is described and well figured by Ross along the southern base of the steep-faced Santa Teresa

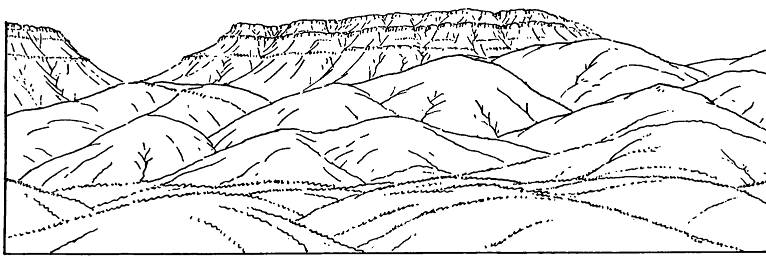

Fig. 8. Tabular lava cap north of Copper creek, about 6,000 feet altitude. Hills and mounts in middle ground are of basement rocks; foreground, dissected detrital uplands.

mountains,[11] beyond upper Arivaipa valley to the northeast of the Galiuro range, where the pediment is cut in granite or quartz monzonite at an altitude of 5,000 feet, or such as we have seen along the west base of the Little Dragoon mountains to the south. Hence it must be supposed that the Galiuro range has not advanced so far in its post-elevational evolution as these pedimented ranges. It appears, however, to have a time ago reached the fan-dented stage;[12] but in consequence of the further elevation that it has suffered since the attainment of that stage, with the result of causing the dissection of its piedmont gravels, it should not be described as now fan-dented. It is noteworthy that the mounts and hills carved in the basement crystallines, where they have been stripped of the lava cover, have little or none of the ragged

[10] Bryan, Kirk, The Papago country, Arizona. U. S. Geol. Surv., W. S. Paper 499, 1925.
[11] Op. cit.
[12] Davis, W. M., The Basin Range problem. Proc. Nat. Acad. Sci., 11, No. 7, 387-392, 1925.

angularity that is commonly associated with arid erosion, but are smoothly rounded, as in Figs. 8 and 9.

In spite of the liberal measure of erosion that the up-faulted range block is seen to have suffered in consequence of its uplift and in spite of the diversity of rock structure upon which the erosion has acted, the range front is still fairly rectilinear all along its many miles of length. Hence the view of the range that one may gain on ascending the dissected detrital slope on the southwestern side of the San Pedro trough and looking back across the axial valley, somewhat as in Fig. 2, is indeed instructive. The Galiuro escarpment, as thence seen, ordinarily extends out of sight in the desert haze to the northwest and the southeast; and although consisting

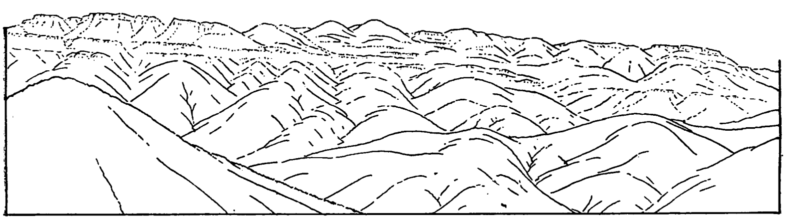

Fig. 9. Lava cap of Galiuro mountains, dipping gently northeast, on the north side of the Copper creek-Mulberry wash entrant. Upper valley of Copper creek in middle ground between hills and mounts of basement rocks. Whether the rounded cone at mid-skyline is basement rock or lava has not been determined.

of deformed and resistant quartzites along part of the face of its first sixth, of divers massive crystallines along its second sixth, and of heavy lava beds through its mid-length and farther south, the most striking feature of its western face is its long and simple continuity.

While this fine escarpment is in sight it is well to recall Gilbert's description of the similar southwest-facing escarpment of the Natanes plateau, a lava-capped mass of gently inclined paleozoic strata 55 miles farther northeast. He said that in its high face "instead of the scalloped figure, made up of convex curves, that results when erosion controls, we have a straight line, interrupted only by angular embayments where it is intersected by water-ways; and the steepest cliffs . . . are along the rectilinear front, which faces a broad, streamless valley. This character maintains for twenty miles, and is unquestionably due to a fault—a fault . . . of not less than 2,000 feet throw."[13] At the same time one may recall to advantage the sprawling, lava-capped mesa spurs of the San Mateo plateau around the maturely dissected volcanic cone of Mt. Taylor in western New Mexico; for there, where erosion has evidently enough been in control since the lava sheets were long ago outspread upon a peneplain of gently inclined strata, the high-standing spurs end in large convex curves which are conspicuously developed between the deep-set and widely-opened valleys that have been excavated between them.[14] When one thus recognizes the actual accomplishment of advanced erosion in one lava-flooded district, its small accomplishment in another may be better appreciated. We had the satisfaction of seeing both the Natanes and the San Mateo plateaus while our work on the Galiuro range was in progress.

DETRITAL DEPOSITS IN DOWN-FAULTED TROUGHS.

Intimately associated with the erosion of up-faulted mountain blocks is the removal of the detritus that they yield and its deposition in the adjacent down-faulted troughs. We have not seen the trough on the northeastern side of the Galiuro range, but its deposits, now dissected by the upper waters of Arivaipa creek, are described by Ross as consisting in large part of "conglomerate of various grades of coarseness," in which "all the older formations are represented among the pebbles."[15] That trough continues far southeastward, under the name of Sulphur Spring valley, to the Mexican boundary; but through all that 100 miles of distance it has a smooth, undissected floor, and a large part of it is occupied by an extensive playa. Two wells, 1,095 and 1,050 feet deep, in its southernmost part penetrated clay and consolidated gravel, and gravel and sand, without reaching rock; another, near the southeastern end of the Galiuro range, 1,200 feet deep, penetrated "granite" in the last 10 feet; a fourth near by went 970 feet in clay.[16] Meinzer gives an excellent account of this trough, which he regards as "one of the broad débris-

[13] Gilbert, G. K., U. S. Geogr. Surv. west of the one hundredth meridian (Wheeler Survey), 3, p. 528, 1873.

[14] See Geological Map of New Mexico, 1:500,000. U. S. Geol. Surv., 1928.

[15] Op. cit., p. 30.

[16] From an unpublished thesis on "Deep-well logs," by L. A. Smith of the University of Arizona, 1927.

filled valleys" that characterize the Basin Range region; he notes that Arivaipa creek is capturing drainage area from the playa basin by headward erosion.[17]

The San Pedro trough on the southwest of the Galiuro range is also continued southeastward, between other ranges, to the Mexican boundary; and the San Pedro river has excavated its valley in the trough deposits through all this length of over 100 miles in a remarkably direct course. We have repeatedly examined the detrital deposits in this trough at various points along the northern third of the range, as well as toward Benson on the south where they are exposed in exceptionally high bluffs on the southwest. Their materials are coarse, sub-angular, and well cemented near the range base in the valleys of Copper creek and Mulberry wash; finer and better rounded farther forward; and are followed by fine silts near in the middle of the trough; but inasmuch as the whole body of deposits has been more or less deformed, it would not be safe to assert that the visible silt beds are the true stratigraphic equivalent of the coarser beds near the mountains.

It was briefly noted above, in connection with the exposure of the main fault where it crosses Copper creek, that erosion and deposition appear to have accompanied the up-faulting of the range block, this naturally expectable procedure being there well authenticated. The same conclusion is confirmed by the uplifted and higher-standing piedmont deposits of the rolling uplands which we examined where they bank up against the mountains one or two miles north of Copper creek and where they are now 800 feet or more above the level of the creek bed. Abundant blocks of a nearly black, coarse-crystalline diabase are found there; they are evidently derived from the mountain mass, for they increase in size up 3 or 4 feet and also in number on approaching the mountain slope; and there exceptionally large blocks of shattered and re-cemented quartzite, up to 10 or 12 feet in diameter, are occasionally seen. On the graded side-slope of a valley that passes from the mountain rocks to the outwashed gravels, the black diabase blocks were weathered out in two gently inclined horizons at half and whole height (about 75 and 150 feet) above the valley bottom. Along the mid-length of the range the detrital

[17] Meinzer, O. E., and Kenton, F. C., ... Sulphur Spring valley, Arizona. U. S. Geol. Surv., Water Supply Paper 320, 1913.

deposits are uplifted to less altitude and dissected to less depth.

The thickness of the detrital deposits in the San Pedro trough must be greater than the 800-foot depth of Copper creek valley. The deepest boring in the trough is the "county well" at Benson, 1,505 feet in sand and gravel.[18] It should be recognized, however, that the gravels, sands and clays encountered in various deep wells may not all have been deposited after the mountain-making disturbances of their region; for it has been learned that, in parts of Nevada and southeastern California at least, such deposits were laid down on the land surface—the "Powell surface"—with a considerable thickness previous to the dislocation that produced the mountain ranges of to-day, and that they therefore shared those dislocations. Hence some of the trough deposits may be of this earlier origin.

The silts that occupy the middle belt of the San Pedro trough are much less consolidated than the gravel beds near the mountains. They have a visible thickness of 50 or 100 feet in many side valleys. Thin beds of gypsum are of common occurrence in them; and it may be therefore inferred that they were laid down in local and shallow playas or salt-lake basins, during the uplift and dissection of the mountains on the northeast and southwest and the resulting aggradation of their trough; also that at the time of their deposition the north-flowing San Pedro river of to-day had not been organized.

As the detrital deposits accumulated in the down-faulted trough they must have assumed the form of gently inclined piedmont fans, heading in every mountain valley and stretching forward in long slopes of gradually lessening declivity to the playa flats; and the adjacent fans must have become laterally coalescent, thus constituting normal bahadas; the larger fans may have formed low divides on the trough floor, separating local playas. The detrital deposits no longer preserve their original form, as is told below.

BLAKE ON THE SAN PEDRO SILTS.

A good example of the change from earlier to later geological views with the progress of exploration and investigation is found in the departure of the above interpretation of the

[18] See footnote 16.

San Pedro silts from that given by Blake hardly 30 years ago.[19] He wrote of "the former lake-like sheet of water which we have good evidence filled the greater part of this valley [intermont trough] in late Tertiary or Quaternary time. This evidence is chiefly the presence on both sides of the valley of unconsolidated red clays and sediments in horizontal beds of great thickness, often terraced by river erosion." The silts that we have seen are yellowish or gray, except that, in a gulch parallel to Mulberry wash and 6 or 8 miles southeast of it, hence about 15 miles southeast of Mammoth, the silts are white. These were known to Blake and found by him to consist of volcanic glass and diatoms; and as a specialist whom he consulted pronounced the diatoms to be mostly marine, he concluded that the "valley thus appears to have been occupied by sea-water. It was open on the north to the great open valley of the Gila and Salt rivers. ... The phenomena bear testimony also to the great epirogenic uplift since the Miocene. ... It appears most probable that the height of the water was about 4,000 feet above [present] tide. ... A depression of four thousand feet would submerge the greater part of southern and southeastern Arizona ... leaving only a few widely separated islands above the Pliocene sea." Blake's fullest account of the silts is contained in a special article.[20] Neither a large lake nor an arm of the sea can now be believed to have occupied the San Pedro trough. Mr. Albert Mann, diatomist of the Carnegie Institution of Washington, informs us by letter that the description of diatoms as "marine" does not necessarily mean that they grew in the sea; they may have occupied saline or strongly mineralized water, such as inland playa-lakes might provide, in contrast to fresh water.

A considerable number of fossil vertebrates have been found in the silts near Benson, farther up-stream in the San Pedro trough. These, according to Gidley,[21] include proboscideans, edentates, rodents, birds, and turtles, regarding the preservation of which this ecological paleontologist gives an excellent account, based in part on interpretations by Kirk

[19] Blake, W. P. Lake Quiburis, an ancient Pleiocene lake in Arizona. Univ. Ariz. Monthly, 4, 1902, 107-108.

[20] Blake, W. P., Arizona Diatomite. Trans. Wisc. Acad. Sci., 14, 109-111, 1903.

[21] Gidley, J. W., Fossil proboscidea and edentata of the San Pedro valley, Arizona. U. S. Geol. Surv., Prof. Paper 140-B, 1926.

strikingly unlike the Wasatch and Oquirrh ranges of Utah and the Funeral and Panamint ranges which border Death valley in southeastern California. The later up-faulting of the Galiuro block was accompanied by an up-dragging and dissection of the previously deposited piedmont detritus; while the later up-faulting of the other four ranges, after mature valleys had been carved in their first up-faulted mass and large piedmont fans had been outspread from the valley mouths, was accompanied by a down-faulting and burial of the fans.[22]

It may well have been in association with this disturbance of the detrital deposits that the small local, centripetal drainage systems of the playas, now represented by the gypsum-bearing silts of the San Pedro trough, were replaced by the long San Pedro river, which has eroded a valley usually of small depth and half a mile or more in width along the trough-floor; but in the "Narrows," some miles below Benson, the valley has been cut deeply into the gravels, which rise in great, sharply dissected cliffs on the southwest toward the Rincon mountains. The present course of this wet-weather stream is of unequal dimensions along its length; for while a large channel, 30 feet or more in depth and over 150 feet in width, has been excavated in the flat valley floor in the neighborhood of Benson (this large channel having been filled to overflowing in the destructive flood of September, 1927), the channel is much shallower and wider at Mammoth where the stream sprawls in broadly braided fashion when it receives rain enough to run. Much of the valley floor or flood plain outside of the sandy channel is occupied by groves of mesquite and groups of cottonwoods; smaller parts are cleared in irrigated fields of alfalfa; mesquite, cottonwood, and alfalfa vie with each other in the brilliancy of their springtime verdure, while the benchlands and uplands still have only a dull gray-green, largely determined by creosote bush, with gray patches of thorny "cholla."

In consequence of the disturbance and dissection of the detrital deposits, the finer waste of the Galiuro mountains is no longer detained in the adjacent troughs, as it was for ages during the earlier up-faulting of the range block; it is now swept down by the side streams to the San Pedro, by the San Pedro to the Gila, and by the Gila to the Colorado

[22] See footnote 12.

and the Gulf of California. This is true also for the northwestern part of the northeastern trough; for there the Arivaipa has, as above told, cut its valley hundreds of feet deep in the detrital deposits up-stream from the entrance into its cross-range canyon.

It is remarkable that, for several miles north of Copper creek, the well-cemented gravel deposits and the mountain rocks appear to offer similar resistance to erosion. No persistent gulch or bluff follows their contact along the fault trace; and the many well-opened valleys that traverse the trace do not change their form where they cross it.

Direct evidence of deformation may be seen in the detrital beds, especially in the silts, as one ascends the road along the bed of Mulberry wash to the village of Sombrero Butte. The silt beds frequently dip 3°, 4° or 5°, less often 8°, 10°, 12°, or 14°; and eastward dips toward the mountains are about as common as westward dips toward the San Pedro valley. The steepest dip seen was in a small flexure, where the silts slant eastward 23° for a length of about 15 feet between a broad extent of horizontal silts on either side. The gravels beds farther up-stream in this valley frequently dip 3°, 5°, or 7° away from the mountains. The bed of the wash slants only 1° or 2°; but it is strewn with cobbles all the way to San Pedro valley, and hence into the medial belt of silts. Yet when the marginal deposits of cobbles and gravels were forming, the streams seem not to have been able to sweep coarse detritus forward as far as the medial silt beds. This gives independent evidence of a post-depositional upheaval of the detrital deposits, as already inferred from the height to which they mount on the range flank as well as from the depth to which they are there trenched by the streams that originally built them up.

The rapid rise of several hundred feet from the gently inclined, gravel-covered benchland of silt adjoining the San Pedro valley to the higher-standing detrital uplands, above noted, may be due to a local flexure or fault which there accented the upheaval of the detrital deposits, but we saw nothing in the sides of Mulberry wash to confirm this idea.

Deformation of piedmont detrital deposits is not uncommon in this region. It is seen in certain areas along the southwest side of the San Pedro trough, where the detrital outwash from the northeastern slopes of the Rincon and the Santa Catalina mountains is not only well dissected but rises here and there

Bryan. The "bone-bearing patches of greenish clay represent the marginal and fresh-water springs that are characteristic of the borders of salt lakes. . . . The [fossil] localities thus probably constituted the chief watering places for the animals of the region, and here, naturally, occur their fossil remains. That these areas were once boggy water holes is supported by the condition and arrangement of the bones they contain"; and then follow suggestive details showing that the entombed animals came to their death "by being hopelessly mired." It is concluded that the lakes, to become saline, must have existed at least "a few thousand years" and that the marginal springs "must have had similar periods of existence."

It therefore appears probable that the lakes or playas, in which the San Pedro silts were accumulated, occupied shallow basins such as still exist in the long Sulphur Spring trough, next to the northeast, and such as might have been defined by the unequal inwashing of sediments as detrital fans were built forward from the trough sides. The development of the San Pedro river with a continuous northwestward gradient and the erosion of its valley through the sites of all these extinct lakes is next to be considered.

DEFORMATION AND DISSECTION OF THE TROUGH DETRITUS.

The heavy piedmont detrital deposits that flank the Galiuro range have lost the smooth surface and the gently concave slope that they must have acquired during their aggradation. The account of the northern part of the northeastern trough by Ross makes it clear that the upper waters of Arivaipa creek have cut a large valley in the detrital deposits previously accumulated there; the valley is in part of box-canyon form, and is 1,500 feet deep where it enters the range. The undissected divide at an altitude of about 4,000 feet between the head of this valley and the long Sulphur Spring trough floor to the southeast "is so low and smooth that a traveler might well pass from one valley to the other without realizing it." It is significant that the state geological map shows two 7-mile patches of recent detrital deposits on the highlands of the Galiuro range at altitudes of about 4,000 feet, one on either side of the deep cross-cut canyon of Arivaipa creek. If these deposits are, as their map-color indicates, of the same nature as those in the adjoining troughs, they would suggest that the uplift of the range block was delayed at its northwestern sixth until after it was well advanced farther southeast; and also that Arivaipa creek then took a transverse course from the northeast to the southwest trough and there laid down the cross-cover of gravels, before the northwestern part of the range block was raised; and that it afterwards held this course in spite of the raising. In other words, that the creek is consequent on the earlier uplift of its area and antecedent to the later uplift.

The dissection accomplished in the southwestern or San Pedro trough is as a rule less deep than in the northeastern trough, yet it is so strong that there is no question it has been caused by an uplift of the gravels along the range margin at least. The present ascent from the San Pedro valley at Mammoth, altitude about 2,500 feet, to the mountains by the Copper creek road is made somewhat irregularly; at first for two or three miles over a gently inclined, gravel-covered benchland of silt at an altitude of from 2,600 to 3,000 feet; then, after a more rapid rise, across uplands of gravel and cobbles for 5 or 6 miles until altitudes of 4,000 feet are reached at the junction of these detrital uplands with the rocks of the mountain flanks. The higher detrital uplands are maturely dissected and the lower-lying silt benchlands are submaturely dissected by the open and dry valleys of many wet-weather streams. The valleys are as much as 600 or 800 feet deep below the uplands near the mountains, and as little as 50 feet below the benchlands at the side of San Pedro valley. Near the range mid-length and farther south the altitude of the detrital uplands next to the range and the depth of their dissection seem to be of smaller measure than in the northern third of the range; but these San Pedro trough deposits are well dissected all along the trough length.

In view of the above facts there seems to be no escape from the conclusion that the detrital deposits have been uplifted since they were laid down, especially along the mountain border, as if dragged up there with the rising mountain block; and also that their dissection is a consequence of their uplift; they have, indeed, since their uplift was initiated, shared the erosional fate of the mountain block. This gives strong support to the idea already presented that the deposition of the gravels was contemporaneous with the earlier stages of the upfaulting, and that their dissection was contemporaneous with the later stages when the range block probably gained the final 1,000 feet of its uplift. In this respect the Galiuro range is in irregular mounds, distinctly above the slope of less disturbed areas. At the eastern base of the Rincon mountains, the gravels rise, as above noted, unusually high above the San Pedro and are deeply dissected by its branches. Deformation is seen also along the northwestern side of the Santa Catalina mountains, where a north-flowing stream from one of the inner valleys (Cañada del Oro) turns and runs southwestward for several miles in very abnormal fashion along or near the mountain base among dissected gravel hills of unsystematic form, and at a level 200 or 300 feet below the broad detrital benchland which appears to represent its original piedmont fan. The senior author has suggested that the gentle undulations of the Tucson intermont plain may be due to a slight warping of the detrital deposits that underlie it;[23] new support for this suggestion is now found in the visible warping of the detrital deposits of the San Pedro trough.

CONCLUSION.

In review of all that precedes it is believed that the Galiuro mountains may be rather confidently accepted as a "Gilbert block"; that is, as a tilted and more or less eroded fault block, with its basement of deformed "King mountain" rocks worn down to a hilly, pre-faulting "Powell surface" and covered by one of the most extensive lava "Louderbacks" that has been found in the Great Basin; but it is believed also that many details in the structure and the history of the mountains remain to be deciphered, for our conclusion would surely be tainted with error if we should assume that the whole story of the mountains could be reduced to the simplicity of the account that we have here given of it.

University of Arizona,
Tucson, Ariz.

[23] Davis, W. M., Channels, valleys and intermont detrital plains, Science, 66, 272-274, 1927.