# Reconnaissance of the Geomorphology and Glacial Geology of the San Joaquin Basin, Sierra Nevada California

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*A region of exceptional interest to the geomorphologist*

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# ILLUSTRATIONS

# RECONNAISSANCE OF THE GEOMORPHOLOGY AND GLACIAL GEOLOGY OF THE SAN JOAQUIN BASIN, SIERRA NEVADA, CALIFORNIA

By François E. Matthes


## ABSTRACT

Reconnaissance of the San Joaquin Basin, situated in the central part of the west slope of the Sierra Nevada, California, was undertaken in order to extend southeastward the studies made earlier in the Yosemite region, and to test the soundness of conclusions reached in the Yosemite region, regarding the geomorphologic development and the glaciation of that area and to determine their bearing on the history of the Sierra Nevada as a whole.

For these purposes the San Joaquin Basin is, in several respects, the most revealing of the drainage basins of the west slope of the Sierra Nevada. In it, the erosional features are unobscured by volcanic flows except locally. Also, the granitic rocks are exceptionally extensive, and their prevailing massive character has profoundly influenced the topography. For example, the San Joaquin Canyon is consistently narrow, and exhibits neither anomalous Yosemite-like widenings nor, for the most part, the unusual sculpturing characteristic of the yosemites.[1] Also, the resistant nature of the massive granitic rocks accounts for the preservation of an unusually fine record of the successive cycles of erosion, and an extraordinary wealth of clean-cut hanging side valleys. Furthermore, because the granitic rocks are practically continuous to the foot of the range, the ancient erosion surfaces and the array of hanging valleys likewise extend not merely throughout the glaciated upper course of the San Joaquin Canyon but also through most of the unglaciated lower course, to within a few miles of the foothills.

It should be noted, too, that the San Joaquin River, having a southwestward course conformable to the slope of the Sierra block, was subjected to the full rejuvenating impulse of each tilting movement. Its tributaries, on the other hand, have mostly northwesterly or southeasterly courses, at right angles to the master stream as well as to the direction of tilting of the block. The flow of the tributaries, therefore, was accelerated very little by the tilting of the Sierra block. In this contrasting relationship of master stream to tributaries the drainage pattern of the San Joaquin Basin is typical for most of the basins in the central and southern part of the Sierra Nevada, but probably in no other basin is the relationship so well shown.

The salient geomorphologic features of the San Joaquin Basin may be summarized as follows: The San Joaquin Canyon is essentially a narrow, youthful, branching gorge, which has been cut into the floor of a relatively broad, mature valley. The mature valley in turn is flanked by extensive undulating uplands, with a relief over wide areas not greater than 1,000 feet. In places, however, the uplands are surmounted by hills, mountain groups, and imposing mountain crests trending, in most cases, in a northwesterly direction, and having a relief of 1,500 to over 2,500 feet,—ranges forming a part of the so-called High Sierra. At least one mountain crest has peaks that bear distinctively tabular summits.

These features are believed to be the products of four partial cycles of stream erosion, each initiated by a major uplift. They are interpreted as follows:

Expressive of the latest cycle, is the branching gorge or inner canyon of the San Joaquin River and its main branches. This gorge is regarded as being wholly of Pleistocene origin, and is correlated with the "canyon stage" of the Yosemite region. The benches and shoulders which flank the Pleistocene gorge in the lower and middle reaches of the basin, giving the San Joaquin Canyon a 2-storied aspect, are remnants of a mature valley developed in a partial cycle of erosion which preceded the canyon stage. The maturity of this valley is indicated by its broadly flaring cross section and its low, smooth gradient (deduced from the extended gradients of the lateral valleys that were left hanging in the latest cycle of erosion). To have attained its mature character, the valley must have required a period several times as long as that which was required for the carving of the Pleistocene gorge. It may be inferred that the partial cycle of erosion in which the valley was developed embraced all, or nearly all, of the Pliocene epoch. Accordingly, the Pliocene valley of the San Joaquin River may be assigned to the "mountain valley stage" of the Yosemite region.

The undulating uplands into which the Pliocene valley has been cut are erosion surfaces referable to a still earlier cycle. The forms of these uplands are so much more mature than those of the Pliocene valley that there is good reason to assign for their development a correspondingly greater span of time. Furthermore, they are clearly correlative with the uplands of the Yosemite region, and are traceable across the divide and continuous with the uplands of that region. From paleontological evidence found north of Yosemite Valley, in the Table Mountain district between the Tuolumne and Stanislaus Rivers, it appears that the Yosemite uplands, representing the broad valley stage, are of late Miocene age. Accordingly, the uplands of the San Joaquin Basin are also thought to have been produced in a cycle of erosion which began some time back in the Miocene and continued until the latter part of that epoch.


[1] Yosemite comes from "uzumati" or "uhumati," which in the language of the Southern Miwoks meant "grizzly bear." It is said to have been originally the name of the tribe of Indians who inhabited the Yosemite Valley, or at least of that part of the tribe which dwelt on the north side of the Merced River. The name was given to the valley, at the suggestion of Dr. Lafayette Houghton Bunnell, by the Mariposa Battalion, the first party of white men to enter the valley, in 1851.

Finally, the hills, mountain groups, and mountainous crests surmounting the uplands are clearly monadnocks, and the tabular summits (Mount Darwin and Mount Wallace) of the one crest are, from the evidence of the great height to which these summits rise above the uplands, much older than the Miocene erosion surface. These platforms are referable to the most ancient erosion surface recognizable in the Sierra Nevada, thought to be Eocene in age.

The hanging lateral valleys fall into two tiers or sets, the one much higher than the other. Valleys of the upper set are hanging with reference to the mature Miocene erosion surface. Valleys of the lower set are hanging with reference to the Pliocene erosion surface (the flanking benches and shoulders of the San Joaquin Canyon). The 2 sets of hanging valleys attest to 2 rejuvenations of the master stream induced by 2 uptiltings of the Sierra Nevada. Valleys of the upper set were left hanging as a result of the uplift which initiated the mountain valley stage of erosion during the Pliocene; those of the lower set, as a result of the uplift which initiated the canyon stage of erosion during the Pleistocene. The 2 sets of hanging valleys are analogous to the 2 upper tiers of hanging valleys in the Yosemite region.

By the same method employed in connection with study of the Yosemite Valley, the data provided by the hanging valleys of the San Joaquin Basin were used to reconstruct the longitudinal profiles of the San Joaquin River and its 2 branches for each of the 2 stages of erosion indicated. The abundance and distribution of the hanging valleys made possible the reconstruction of the former river profiles throughout a much longer section than in the case of the Merced, and farther down toward the foothills.

The mountain crests surmounting the Miocene erosion surface are features inherited from the system of northwestward-trending ridges that occupied the place of the present Sierra Nevada in Late Jurassic and Cretaceous time. The northwestward-trending valley troughs between these crests similarly are features dating far back into Cretaceous time, and still control the drainage pattern of the tributary streams to a marked degree.

The main drainage divide, at the head of the San Joaquin Basin, does not coincide with the top of the great east escarpment of the Sierra Nevada except at two very short stretches. Evidently the divide is an ancient erosional feature, which parted northeastward flowing waters from southwestward flowing waters long before tectonic movements formed the escarpment. The escarpment is probably in large part of early Pleistocene origin, and is a feature produced as a result of the downfaulting of the Owens Valley graben.

During the Pleistocene epoch, the higher parts of the San Joaquin Basin were repeatedly mantled with glaciers. As a result, glacial features were superimposed on a landscape inherited from Miocene and Pliocene times. For tracing and mapping the courses of the ancient glaciers, and for determining their farthest limits, reliance was placed on the testimony of glacial deposits rather than on that of sculptural features, and a systematic survey was made of the moraines built by the individual glaciers. On the glacial map constructed from this survey, distinction has been made only between the Wisconsin and pre-Wisconsin stages. However, at several localities the field data appear to warrant future subdivision of the Wisconsin moraines into those of early Wisconsin time and those of late Wisconsin time, corresponding to the Tahoe and Tioga stages of Blackwelder. The pre-Wisconsin moraines are in all respects closely similar to those in the Yosemite region, and are therefore referred to the El Portal stage, believed to correspond to Blackwelder's Sherwin stage at the east base of the range and thought to be not younger than the Illinoian stage of the continental glaciation. No morainal deposits belonging to the Glacier Point stage, the earliest stage of glaciation recognized in the Yosemite region, are shown on the map but a few small, isolated patches of an ancient moraine were discovered in the central part of the basin, and these may well be representative of the Glacier Point stage, in view of their elevated positions.

The San Joaquin glacier system of the El Portal stage was by far the largest system of confluent glaciers in the Sierra Nevada, measuring more than 50 miles in length along the crest of the range, and 30 to 35 miles in breadth. Of the 1,760 square miles comprised in the San Joaquin Basin, almost 1,100 square miles were covered by glaciers. This ice mass, taken together with the ice masses in the basins of Dinkey Creek and North Fork of the Kings River, formed a mer de glace 1,500 square miles in extent. Yet it was not an icecap, strictly speaking, for its surface was broadly concave rather than dome shaped. It consisted of a large number of confluent glaciers that had descended from the surrounding peaks and crests, filled the canyons, and overflowed on to the intermediate uplands.

The glacier system was essentially bilobate, as it comprised two great primary branches that descended Middle Fork and South Fork canyons. The branches united below the junction of the two forks, to form a very broad trunk glacier that overflowed the main San Joaquin Canyon and spread widely over the central part of the basin. The glacier ended in a rather blunt tongue, only a few miles long, which lay in that part of the main canyon separating Chiquito and Kaiser Ridges. The length of the San Joaquin glacier system, measured from the head of the South Fork branch to the terminus of the trunk glacier, was nearly 60 miles; the length measured along the Middle Fork branch was almost 45 miles.

Big Creek basin was occupied by a glacier system of its own. This system attained a length of about 20 miles and an areal extent of about 105 square miles.

During the Wisconsin stage of glaciation, in the San Joaquin Basin as elsewhere in the Sierra Nevada, the volume of ice was considerably smaller than in the earlier stage, and the ice-covered area was, therefore, much less extensive. The San Joaquin glacier system had, of course, the same general pattern as in the earlier stage, for it reoccupied most of the cirques and followed the same valleys and canyons, but it took the form of many discrete glaciers which became confluent only in part. Thus, large upland areas which were ice-covered in the earlier glaciation remain bare throughout the Wisconsin stage.

By far the greater part of the ice which formed in the San Joaquin Basin was again part of a bilobate system, and this pattern was the more pronounced because the ice was largely confined within the canyons or broad valleys. The trunk glacier in the main canyon, formed through union of the Middle Fork and South Fork glaciers, was only a short and feeble tongue. The maximum length of the San Joaquin glacier system, measured from the head of the South Fork to the terminus of the trunk glacier, was 47 miles; the length measured along the Middle Fork branch was 32 miles.

A number of glaciers, which in the El Portal stage were tributary to the San Joaquin glacier system, in the Wisconsin stage fell short of joining that system, and throughout their existence remained separate ice bodies or became confluent only with adjacent glaciers. This was the case with the Granite Creek glacier, the Big Creek glacier system, and the many relatively small glaciers on Chiquito Ridge, Kaiser Ridge, and other ridges.

## INTRODUCTION

This report is based upon a reconnaissance of the upper basin of the San Joaquin River conducted in 1921, 1923, and 1927. By the upper basin (or what will hereafter, for convenience, be termed the San Joaquin Basin) is meant the mountain course of the San Joaquin River, situated in the central part of the west slope of the Sierra Nevada (fig. 1.) The San Joaquin Basin lies between the drainage basins of the Merced and the Fresno Rivers, on the northwest, and the drainage basin of the Kings River on the south. This report does not include the level plain at the west foot of the range which is traversed by the lower or valley course of the San Joaquin River—the San Joaquin Valley, as it is generally called, or the southern part of the Great Valley of California; neither does it include the drainage basins within the Sierra Nevada of the other rivers which join the San Joaquin River on the plain.

Like each of the adjoining basins and those of the other master streams of the west slope of the Sierra Nevada, the San Joaquin Basin is a natural geomorphologic unit that can advantageously be treated by itself.

The reconnaissance with which this report deals was undertaken for a 2-fold purpose: first, to extend geomorphologic and glacial studies made in previous years in the Yosemite region southeastward, as a first step toward connecting that region with the as yet isolated area, 100 miles distant, in the basins of the Kern, Kaweah, and Kings Rivers, which had been investigated some years before by Lawson (1904, 1906) and Knopf (1918); and second, to test the soundness of conclusions which the author had previously reached in the Yosemite region regarding the geomorphologic development and the glaciation of that region, and to determine their bearing on the history of the Sierra Nevada in general.

From preliminary map studies, it was expected that the San Joaquin Basin would prove to be a key area for the interpretation of the central and southern parts of the west slope of the Sierra Nevada, and this inference was fully confirmed.

The San Joaquin Basin, up to the time when these investigations were undertaken, had not been previously studied systematically. Very little was known of the geology of the area beyond the fact that its rocks are mostly granitic, except near the crestline of the range where metamorphic rocks prevail. Only one hasty reconnaissance had been made through it, namely, by Brewer's party of the California Geological Survey in 1864; but that initial exploration, as is evident from Whitney's report (Whitney, 1865) as well as from Brewer's original journal (Brewer, 1930) had yielded, besides a sketch map by Hoffman, only a few scanty geologic notes. To one who reads between the lines, it is plain that the party suffered many hardships not mentioned in its report, and that the overcoming of physical obstacles, and the ultimate safety of its members became problems of paramount importance to which scientific studies had to be largely sacrificed. Their reconnaissance is to be regarded primarily as of historic interest.

In the reconnaissance of 1921 the writer, therefore, found himself essentially in a virgin field. However, some conception of the outstanding landmarks of the basin had been gained previously from graphic articles published in the Sierra Club Bulletin and illustrated by excellent photographs; and by far the most valuable advance information about the region was obtained from the topographic maps that had been published about a decade previously by the U. S. Geological Survey.

Those parts of the San Joaquin Basin shown on the Mount Lyell, Mount Morrison, Kaiser, and Mount Goddard quadrangles were largely covered by the reconnaissance surveys. In addition, the foothill country shown on the Friant, Academy, and Dinuba quadrangles was given a cursory examination. Thus the San Joaquin River and its tributaries were traced from the peaks on the crest of the Sierra Nevada down to the mouth of the rock-cut canyon where the river begins its alluvial course over the sediments of the Great Valley of California.

The fieldwork consisted partly in analyzing the features of the landscape into elements belonging to successive surfaces of erosion, and partly in the systematic tracing and mapping of the moraines that mark the farthest extensions of the Pleistocene ice in each of the two well-defined and clearly distinct glacial stages. No means were found within the compass of the San Joaquin Basin for determining the age of any of the surfaces of erosion, owing to the absence of fossiliferous deposits. Nevertheless, the ages are not wholly indeterminate, for it was possible to correlate the erosion surfaces of this area with those previously recognized in the Table Mountain region of the Stanislaus basin (fig. 1), where fossils are present in the Tertiary stream deposits, and where the age of at least one erosion surface has been tentatively determined. No attempt was made to identify and map

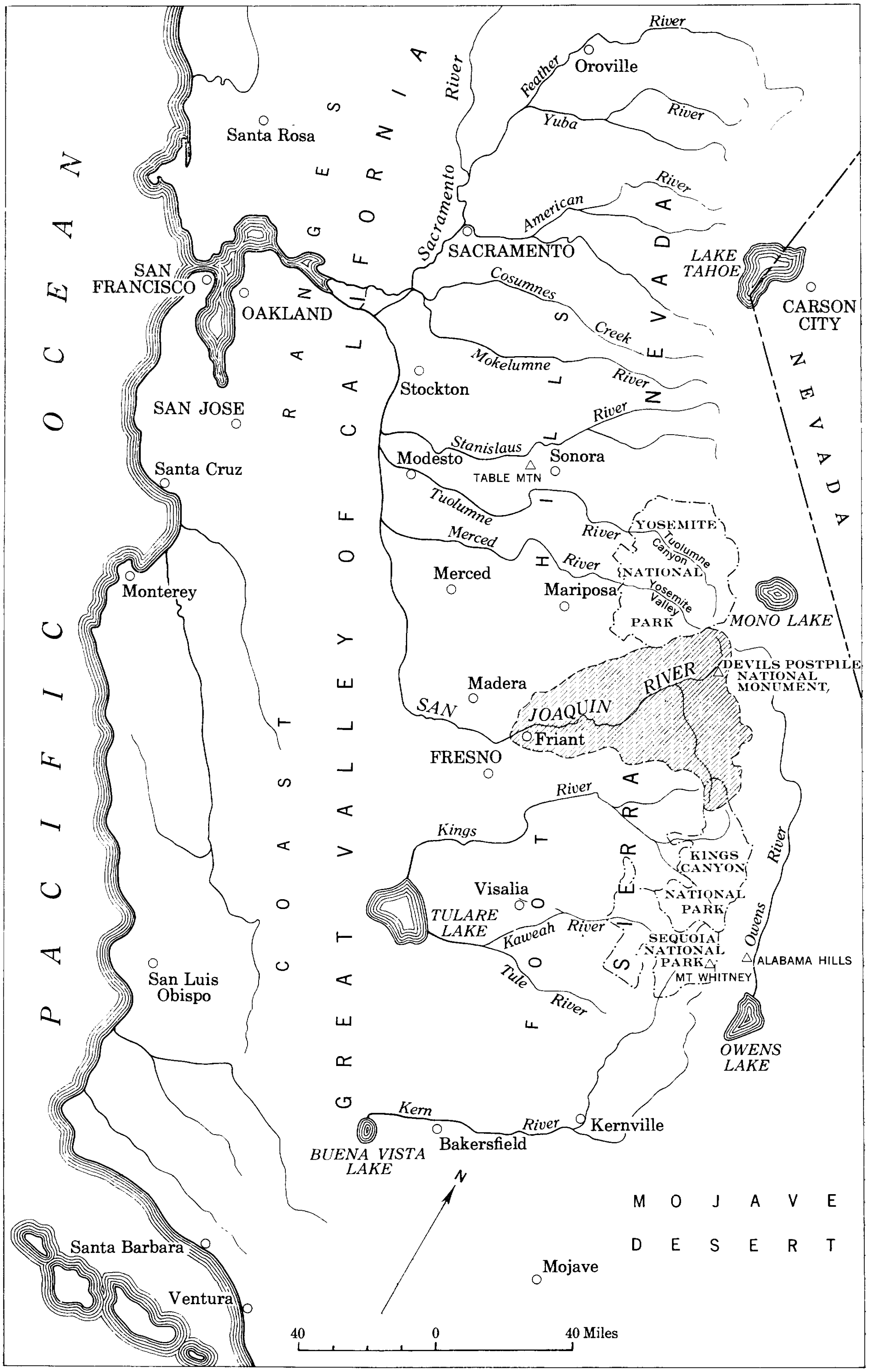


FIGURE 1.—Index map showing location of the San Joaquin Basin.

the different types of igneous rocks that constitute the great batholith of the Sierra Nevada and which form the prevailing country rock of the area, and no petrographic studies were undertaken in connection with the reconnaissance. Some attention was given, however, to the more important bodies of metamorphic rock, which are scattered here and there, and to the volcanic rocks, which consist of many small local flows of Tertiary and Quaternary age.

The author's investigations did not cover the San Joaquin Basin completely, and consisted mainly of a reconnaissance of its geomorphologic and glacial features. The foothill belt, in particular, received only minor attention, but as it was not practicable in the time available to cover all parts of the basin with equal thoroughness, and as the foothill belt presents a set of geomorphologic problems of its own, deserving special investigations, it seemed best to present the studies made in their present incomplete form.

## ITINERARY OF EXPEDITIONS

In the summer of 1921 (July 8–October 1), the author, with a small party, made a preliminary reconnaissance across the entire breadth of the rugged San Joaquin Basin and back, traveling on horseback and equipped with a pack train. Starting from Yosemite Valley, he entered the San Joaquin Basin by the little-frequented Fernandez Pass and thence descended into the valley of Granite Creek (pl. 1). Using Clover Meadow as a headquarters, the entire basin of Granite Creek and the so-called Jackass district to the south were explored. Crossing the North Fork of the San Joaquin River, the party then traveled successively to "77" Corral, to Reds Meadow and the Devils Postpile, and to Mammoth Pass; and finally up the Middle Fork of the San Joaquin River to its headwaters at Agnew Pass and Thousand Island Lake.

The party, doubling back, followed the Middle Fork southward to Fish Valley, ascended the upland toward Pincushion Peak, and cursorily examined the basin of Silver Creek. Then it descended into the valley of the South Fork of the San Joaquin River and followed it up to the Lower Hot Springs, where a side trip was made into Vermilion Valley[2] and up the canyon of Mono Creek. Resuming its journey up the South Fork, the party traveled to Blaney Meadows and examined the area around Selden Pass, then continued up Evolution Valley, and using this as a base, explored Evolution Basin as far as the Muir Pass, as well as the rugged country around Mount Darwin, the Glacier Divide, and Mount McGee. The return was made down the South Fork to Blaney Meadows, over the Hot Springs Pass to Long Meadow, where the country at the head of Big Creek was covered; then on to Huntington Lake, northward over Kaiser Ridge, and down Kaiser Creek to Daulton Ranger Station. Scarcity of grass due to prolonged drought made it impracticable to keep the pack train in this area and compelled the party to hasten across the San Joaquin River to Placer Ranger Station. After a brief halt there, to examine the more accessible parts of the Chiquito Creek basin, the march continued in a northwesterly direction by Beasore and Mugler Meadows to the Chiquito Pass, where the Merced Basin and the Yosemite National Park were reentered on October 1.

In the spring, and early summer (July 3–30) of 1923, the lower part of the San Joaquin Basin, which is traversed by several roads, was visited by automobile. From Fresno, a reconnaissance was made through the foothills and up the grade from Tollhouse to Shaver Lake, Big Creek, and Huntington Lake. The return trip was made through the lower San Joaquin Canyon, which that year for the first time had been made accessible by the opening of automobile roads built by the Southern California Edison Company to connect its chain of power stations. During the remainder of the field season a second pack train expedition was made from the Yosemite Valley through the roadless western and central parts of the San Joaquin Basin, examination of which had to be abandoned in 1921 owing to lack of pasturage for the pack train. On this second trip, conditions were more favorable, and time was spent in the large tract stretching from Kaiser Ridge northward to the junction of the South Fork and Middle Fork of the San Joaquin River.

In 1927 (June 27–September 18) opportunity was had for a supplementary and somewhat more detailed examination of a limited area immediately surrounding Huntington Lake and extending southward to the valley of Dinkey Creek. This additional work seemed particularly desirable in view of the great hydroelectric developments centering about Huntington Lake, and the rapid transformation of the surrounding region into one of the major summer tourist centers of the Sierra Nevada. (See later paragraph on "Economic and Social Use," page 12.)

## INVESTIGATIONS SUBSEQUENT TO FIELDWORK

Since this reconnaissance, a number of noteworthy studies have contributed to the geologic knowledge of the central and south-central parts of the Sierra Nevada. Those of special significance to this report may be briefly mentioned. Hans Cloos and Ernst

[2] This valley is now occupied by Lake Thomas A. Edison.

Cloos (Ernst Cloos, 1933) have applied their technique of structure analysis to various parts of the Sierra batholith. Mayo (1930, 1934, 1935, 1937, and 1941; Locke, Billingsley, and Mayo, 1940) has extended these studies throughout the central and southern Sierra Nevada, including the San Joaquin Basin, by his regional investigations of the structures of the intrusive rocks and their relations to the metamorphic rocks. Erwin (1934, 1937) has made an intensive study of the metamorphic rocks and associated mineral deposits in the region at the head of the Middle Fork of the San Joaquin River. Blackwelder (1932) has studied the evidences of successive glaciations on the eastern flank of the Sierra Nevada. Macdonald (1941) has investigated the metamorphic and igneous rocks in the foothills belt of the western Sierra Nevada between the Kings and the San Joaquin Rivers. Webb (1946) has presented new evidence for the events in the evolution of the Middle Kern Basin, and has revised some of Lawson's earlier interpretations. The author (Matthes, 1930a, 1933a, 1933b, 1937, 1950b) has followed up geomorphologic studies in the Yosemite, Tuolumne, and San Joaquin Basins by related investigations in the basins of the west-slope rivers in the southern part of the Sierra Nevada, and by more intensive investigations at selected points along the eastern flank of the range, from the vicinity of Mono Lake southward to the Alabama Hills (fig. 1). As this report is being completed, Birman (1954) has published, in abstract, the results of a recent, detailed study of the glacial record along the South Fork of the San Joaquin River and its tributary, Mono Creek.

## ACKNOWLEDGMENTS

During the summer of 1921, the writer was ably assisted in the field by Mr. Francis Cameron. The writer also wishes to acknowledge his indebtedness to officials of the Southern California Edison Company and the Forest Service of the U.S. Department of Agriculture for their courtesies in connection with this reconnaissance. Certain data in this report have been taken, with the permission of the Vanguard Press, from the chapter entitled "A Geologist's View" which the writer contributed to "The Sierra Nevada: the Range of Light" (Matthes, 1947). Data have also been taken, with the permission of the University of California Press, from the writer's volume, "The Incomparable Valley: A Geologic Interpretation of the Yosemite" (Matthes, 1950b). Grateful acknowledgment is made to Mr. Charles S. Denny, whose painstaking and critical review of the manuscript led to many constructive suggestions which were adopted.

## GEOGRAPHIC SKETCH

### LOCATION AND EXTENT OF AREA

The San Joaquin Basin is one of the largest of the many basins on the west slope of the Sierra Nevada, whose rivers drain into the Great Valley of California (fig. 1). It lies immediately southeast of the scenic central part of the range, which is mostly in Yosemite National Park. In its outlines, the basin is roughly comparable to a wedge-shaped leaf (fig. 2). Broadest at the crest of the range, it narrows southwestward to a point at the foothills.

The most northerly point of the basin, near Agnew Pass (pl. 1), is at latitude 37°44′; its southernmost point, in the foothills below Friant, is at latitude 36°55′. The basin extends from longitude 118°39′ at Mount Wallace westward to longitude 119°47′ in the foothills west of the San Joaquin River.

The northwestern part of the basin lies in Madera County, the southeastern part in Fresno County. The San Joaquin River is the boundary between the two counties from the foothills to a point near the center of the basin; from this point the boundary extends northeastward in a straight line to the crest of the range. The entire basin is included in the Sierra National Forest save its southern foothills and the scenic area at the southeast corner of the basin which includes Evolution Valley, Evolution Basin, and Goddard Canyon, and their confining crests; these are parts of the Kings Canyon National Park.

On the northwest, the San Joaquin Basin adjoins the relatively small drainage basin of the Fresno River, which reaches only about half-way up the west slope of the Sierra Nevada. Above this, it adjoins the larger drainage basin of the Merced River, which extends all the way to the crest of the range. The San Joaquin Basin is walled off from the Merced Basin by a chain of lofty crests and peaks.

On the south the San Joaquin Basin borders the drainage basin of the Kings River, which is slightly smaller. The two basins are separated by a long line of serrate peaks which, toward the lower levels, give way to irregular, plateaulike uplands.

On the northeast—that is, at its extreme head, which is throughout determined by the main drainage divide on the crestline of the Sierra Nevada—the San Joaquin Basin abuts upon the east front of the range, which drains into Owens Valley and the lesser basins at its head, except for a short stretch at the extreme north end, which drains into the basin of Mono Lake.

From the crestline to the foothills the basin measures 65 miles in length; it is 54 miles wide, measured along the crestline of the range; and its area comprises

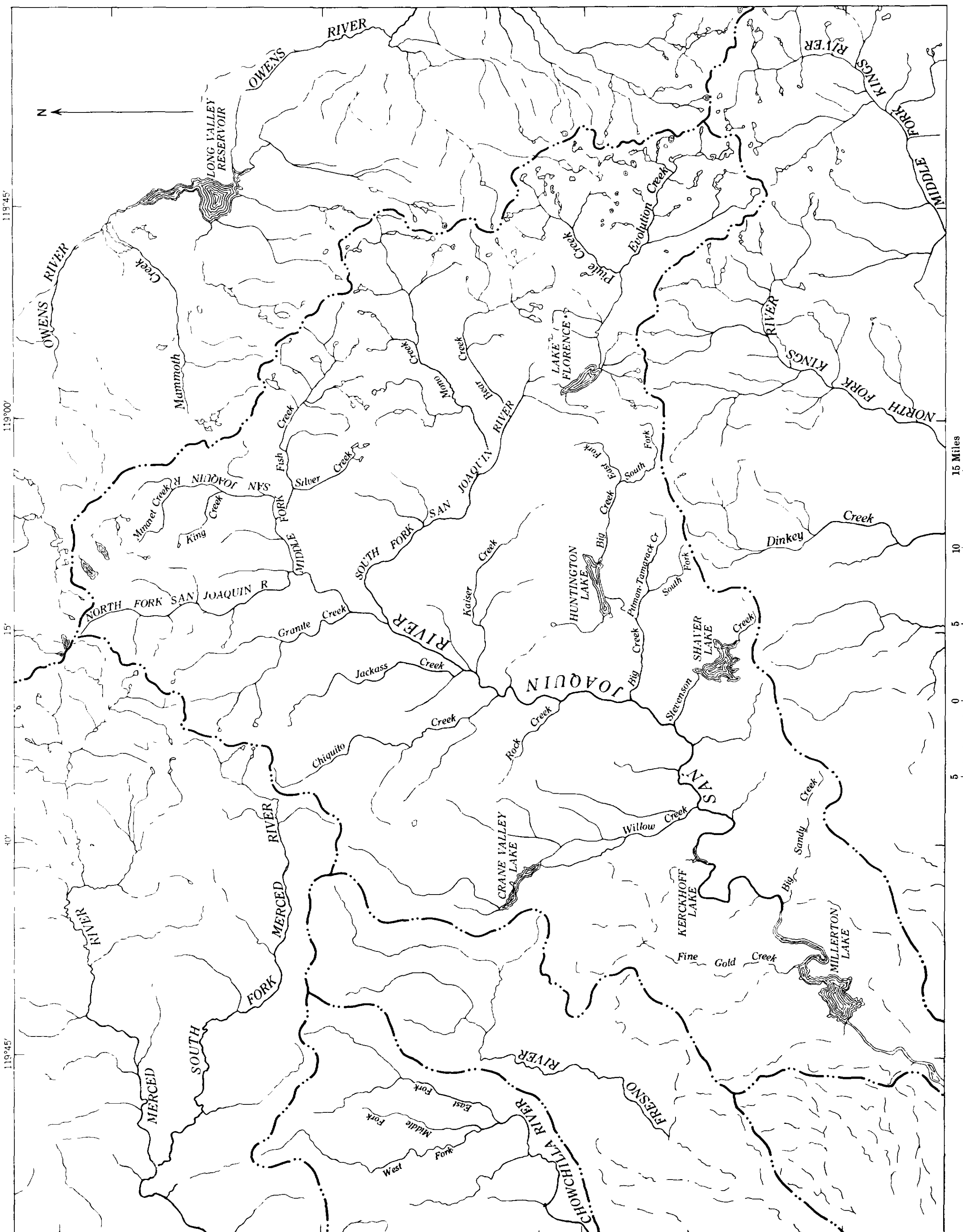


FIGURE 2.—Drainage map of the San Joaquin Basin and surrounding region.

1,760 square miles. The outlines of the tract are fairly regular, the salients and indentations in its sides being for the most part small and roughly compensating. The only significant departure from the wedge shape, mentioned previously, is a projection 10 miles in length at the southeast corner.

### DRAINAGE AND TOPOGRAPHY

The outlines of the San Joaquin Basin have been compared to those of a wedge-shaped leaf, and similarly the drainage lines may be likened in a general way to the venation of that leaf. The San Joaquin River, in its upper course known as the Middle Fork, forms the crooked midrib, running southwesterly. The North Fork extends up into the principal left lobe, at the north; the South Fork into the much larger right lobe, at the southeast; and other smaller tributaries each into a minor lobe.

Thus the San Joaquin River, like nearly all of the great master streams of the Sierra Nevada, pursues mainly a southwesterly course down the west slope and transverse to the crestline of the range. Most of its tributaries, on the other hand, pursue northwesterly or southeasterly courses, approximately at right angles to it and unaffected by the general southwestward slope of the range. The preponderance of these longitudinal elements in the drainage net will be apparent from a glance at the drainage map, figure 2.

The longest and most important of the longitudinal streams is the South Fork of the San Joaquin, which flows northwestward throughout its course save in the 3-mile stretch immediately above its junction with the Middle Fork, where it turns southwestward. The South Fork is 52 miles long—17 miles longer than the Middle Fork; for that reason and because of its greater volume, it might well be regarded as the true upper course of the master stream. Several of its tributaries have northwestward-trending courses, in whole or in part. Such are Evolution Creek, Piute Creek, and Bear Creek—the two last named flowing northwestward in their upper courses and then making a right-angle turn to the southwest in their lower courses. Other tributaries of the San Joaquin that flow mainly in northwesterly directions are Kaiser Creek, Big Creek and its branch Tamarack Creek, Stevenson Creek, and Big Sandy Creek. Tributary to the Middle Fork is Fish Creek and its branch, Silver Creek.

Among the southeastward flowing streams are to be counted the upper course of the Middle Fork itself, from the vicinity of Agnew Pass to Pumice Flat; Minaret Creek, King Creek, the North Fork of the San Joaquin (which heads on Rogers Peak) and several of its tributaries; Granite Creek and its forks; Chiquito Creek and several of its tributaries; Rock Creek; and Willow Creek.

The above list includes all of the major affluents of the San Joaquin, with the exception of Jackass Creek and Fine Gold Creek, which flow mostly in southerly directions; but even these streams have long southeastward-trending stretches and branches, and taken as a whole, trend east of south rather than west of south.

The San Joaquin Basin reaches all the way from the foothills to the crestline, and has the full hypsometric range of the Sierra Nevada, which at this latitude is considerably more than 13,000 feet. The two extremes in altitude are the bed of the San Joaquin River at the foothills, 5 miles below Friant, which is only 285 feet above sea level, and the summit of Mount Humphreys, on the crestline, which attains 13,972 feet. A straight line drawn between these two points, which are 63 miles apart, slopes at an angle of 2°21′, or at a mean rate of 217 feet to the mile (equivalent, approximately, to a 4 percent grade). This inclination is representative in a general way of the central part of the Sierra Nevada, and is intermediate between the slope of the northern part, which is only 1°24′, or 128 feet to the mile (2.4 percent), and that of the culminating part, in the latitude of Sequoia National Park, which, measured from the foothills to the Great Western Divide, is 4°30′, or 416 feet to the mile (7.9 percent).

Most of the mountain crests are on the upper slope of the San Joaquin Basin—that is, in the part commonly termed the "High Sierra." The middle slope is by contrast signally devoid of serrate crests, being predominantly a region of plateaulike uplands that have a general southwestward slant and bear scattered hills and knobs of moderate height. Less impressive scenically, but equally interesting to the student of landforms, are these undulating, billowy uplands, which aggregate about a hundred square miles in area. They are sharply trenched by the San Joaquin River and its main branches, which have cut impressive canyons more than 2,000 feet deep; but the upland surfaces themselves are drained by tributary streams which follow, mostly, broad shallow valleys. From the mouths of these valleys, the tributaries generally descend abruptly into the deep canyons, by cascades and even waterfalls. So characteristic of the region is this situation that the San Joaquin Basin might be termed a "land of hanging valleys." Though it does not possess an array of spectacular waterfalls such as distinguish the Yosemite region, it does have a wealth of beautiful cascades. In some places, as south and southeast of Shaver, the upland persists to within a few miles of the foothills and there breaks off in steep bluffs of considerable height. The foothill belt, again, contains short northwestward-trending ridges and detached mountains 1,000 to 1,500 feet high.

The mean inclination for the entire San Joaquin Basin is, however, considerably less than 2°21′, for the crestline itself varies more than 4,700 feet in altitude. At one point, Minaret Pass (not marked on Mount Lyell quadrangle, but situated directly east of Pumice Flat, in the upper Middle Fork Canyon), the crest descends to an altitude of 9,200 feet. A line drawn from this lowest point on the main divide to the western foot of the range, slopes at an angle of only 1°35′, or at a rate of 147 feet to the mile (2.8 percent). The mean inclination for the entire basin is probably not far from 1°54′, or 174 feet to the mile (3.3 percent).

These figures, however, take no account of the actual configuration of the San Joaquin Basin, which is diversified by boldly sculptured, serrate mountain crests, plateaulike uplands, and deep valleys and canyons.

The mountain crests include a few that trend southwestward, down the slope of the Sierra Nevada, but most of them, including those that are especially prominent in the configuration of the basin, trend northwestward, parallel to the axis of the range and at right angles to the course of the San Joaquin River, thus interrupting and accidenting the general southwestward slope. These crests, ranging from 2,000 to more than 2,500 feet in height, rise high enough above the adjoining uplands and valleys to be called mountain ranges. The persistent trend of these crests has affected the arrangement of the tributary streams, which, as previously emphasized, show a remarkable tendency to flow in southeasterly or northwesterly directions, at right angles to the general direction of their master stream.

From the foregoing description it is evident that the San Joaquin Basin on the whole does not in any sense slope gradually and continuously down to the level of the Great Valley of California. It differs markedly in that respect from the more gently sloping northern parts of the Sierra Nevada which afford grades for railroads and highways. The configuration of the San Joaquin Basin is such that a person who would travel in a straight line from the main divide down to the foothills, instead of having a fairly continuous descent, would find himself obliged to make repeated arduous climbs and steep descents. The canyon of the San Joaquin is too rugged to serve as a convenient avenue for travel, and as a consequence, the main routes are on the uplands on either side of the canyon and over the transverse ridges. Some conception of the irregularities in the slope of the San Joaquin Basin may be gained from the profile in figure 3 which is plotted without vertical exaggeration.

Among the topographic anomalies in the San Joaquin Basin one is especially noteworthy. This is the sag in the crestline of the range at Minaret Pass, a peculiar feature that differentiates the San Joaquin Basin from all other parts of the Sierra Nevada, except the basin of the Feather River near the northern end of the range. The pass is more than a mere notch in the otherwise remarkably continuous crest of the mountain block. It is a 5-mile stretch of low altitude that includes also Mammoth Pass (9,300 feet) at its southern end. Mammoth Mountain is an ancient volcano located in the middle part of the sag. The dwindling of the main drainage divide here is accentuated, moreover, by two other unusual circumstances: by the breaking down of the generally precipitous eastern escarpment of the Sierra Nevada in this section to a slope of moderate declivity only about 1,000 feet in height; and by the presence, 6 miles to the west, of one of the most impressive of the longitudinal crests, the Ritter Range, whose lofty summits, more than 12,000 and 13,000 feet in altitude, far overshadow the low and subdued main divide (fig. 4).

## CLIMATIC CONDITIONS [3]

The San Joaquin Basin, being centrally situated in the Sierra Nevada, shares in the climatic conditions and life zones that are typical for the west slope of the range.

Like every other mountain range of great height and extent, the Sierra Nevada is itself a "climate maker"; that is, in large measure it is the author of its own weather conditions and controls those of the regions to the leeward. Lying parallel to the Pacific coast, it forms a barrier over which the vapor-laden winds that blow in from the ocean must rise. As they are forced up to high levels, they are chilled and discharge their condensed water vapor. This heavy precipitation on the Sierra Nevada explains the general barrenness of the Great Basin. The air currents are fairly wrung dry as they pass over the range.

About 18 percent of the total annual precipitation falls in autumn, about 53 percent in winter (mostly snow), 26 percent in spring, and less than 3 percent in summer.

[3] This section has been based on the following sources: Erwin, 1934, p. 17–18; Matthes, 1930a, p. 10–11; Matthes, 1933a, p. 27–28; Russell, 1938, p. 73–84; Russell, 1947, p. 323–340.

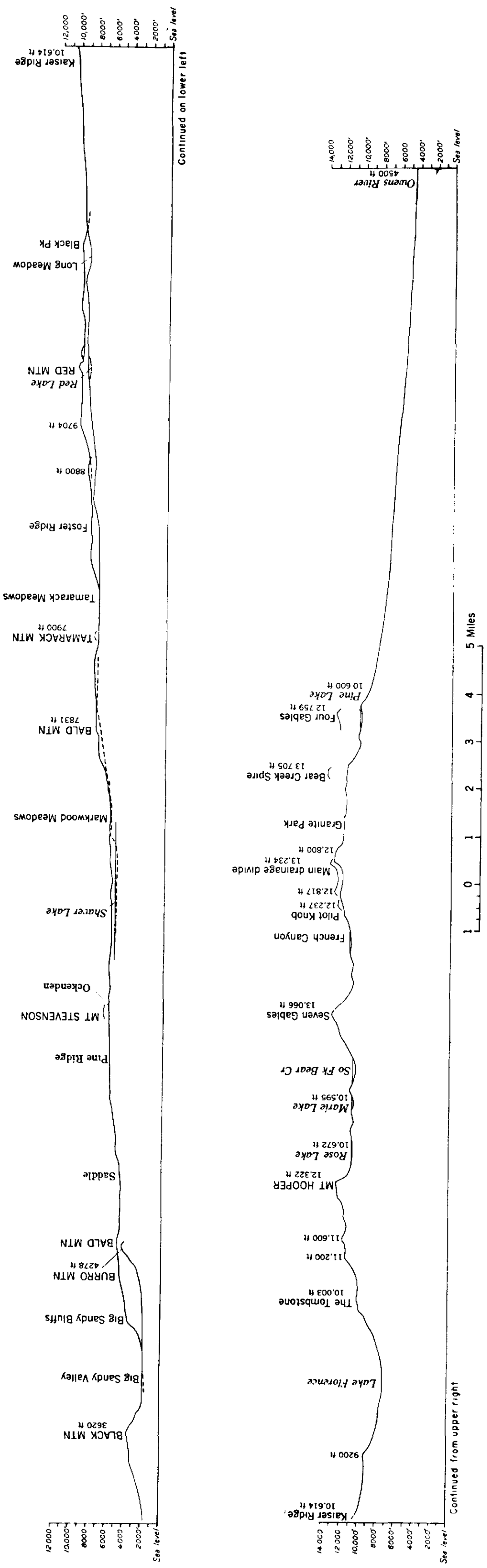


FIGURE 3.—Profile across Sierra Nevada, from Big Sandy Valley over Kaiser Ridge-Florence Lake-Mount Hooper-Seven Gables-Main Drainage Divide near Granite Park to Owens River.

Thus the summers are remarkably dry. Rainless periods of 2 or 3 months are the rule, though occasional thunderstorms may occur, especially in the High Sierra. Camping without tents is a common practice, and the higher parts of the range have such an enjoyable and healthful summer climate that they have become a mecca for vacation seekers.

Torrential rains are uncommon and floods on Sierra streams are generally the result of unusually rapid melting of snow, rather than of heavy rainfall. The Sierra is almost free of violent storms. Large windfalls of trees, such as result from gale-velocities, are comparatively rare.

The extreme heavy snowfall of the Sierra Nevada results from the coincidence of maximum precipitation with the season of lowest temperature—a coincidence that also explains the persistence of a deep snow cover until late spring or even later. Winter snows exceed those of any other part of the United States, except for the Olympic Mountains and the northern Cascade Range. According to United States Weather Bureau records, the annual snowfall at stations on the Southern Pacific Railroad, at altitudes between 6,000 and 7,000 feet on the west slope, aggregates 30 to 40 feet in depth. Records of more than 60 feet are fairly common above a 6,000-foot altitude. Snowfalls of 5 feet within 24 hours, and over 32 feet within a single month, have been reported. At Huntington Lake the depth of the snow cover in February and March, in some years, is nearly 10 feet, and from other localities depths almost twice as great have been reported.

The Sierra Nevada is not, of course, equally favored with moisture in all its parts. The annual precipitation increases with elevation, on the western slope, at rates varying from 0.75 to 1.33 inches for each 100 feet of vertical ascent, up to altitudes of 5,000 to 6,500 feet, above which the rate slightly decreases. Thus the bulk of rain and snow falls on the middle part of the west slope, and the foothills and lower slope partake in large measure of the semiarid conditions that prevail in the Great Valley. The higher peaks and crests above the forest zones are also relatively dry, the air currents having discharged most of their content of water vapor before reaching those heights. The High Sierra, it is true, retains its snow cover much longer in spring and summer than the middle slope, but that is due primarily to the lingering cold. The east front of the range also is arid compared with the west slope.

From altitudes of 11,000 feet upward, the precipitation, even in summer, consists largely of snow or hail, and the temperature in the shade seldom rises much above the freezing point. Snowdrifts abound until far into midsummer, and perennial bodies of old, hard snow and even a few small glaciers occupy the shaded, steep-walled recesses among the higher peaks.

### LIFE ZONES AND VEGETATION

The unequal distribution of snow and rain on the Sierra Nevada, together with the wide range in temperature from the torrid foothills to the wintry crest, give rise to several distinct climatic belts or zones, each of which has its characteristic forms of vegetation and animal life (Matthes, 1930a, p. 10–11; 1933a, p. 28–29). These zones are broadest and most distinct on the west slope of the range, and are readily recognized when one ascends the San Joaquin Basin.

The semiarid foothill belt, hot and dry in the summer but rainy in the winter, corresponds to what biologists term the "Upper Sonoran life zone." Its vegetation consists characteristically of thin grass, bushy chaparral (an aggregate of small-leaved bushes among which the red-stemmed manzanita (*Arctostaphylos*) is especially prominent), scattered evergreen oaks, and digger pine (*Pinus sabiniana*).

Toward the 3,000-foot level this vegetation becomes denser and finally merges with the majestic forests of the Transition life zone. Here flourish the yellow pine (*Pinus ponderosa*), the Jeffrey pine (*Pinus jeffreyi*), the sugar pine (*Pinus lambertiana*), the incense cedar (*Libocedrus decurrens*), the white fir (*Abies concolor*), and the Douglas fir (*Pseudotsuga taxifolia*), all valuable lumber trees attaining great size and height. Dispersed among them, in groups or groves, stand the "big trees" (*Sequoia gigantea*), but no groves of this species have been reported from the San Joaquin Basin, though the Fresno Grove and the celebrated Mariposa Grove lie just north of its boundaries and the McKinley (Dinkey) Grove just south of them, (Sudworth, 1908 and Jepson, 1910).

The Canadian life zone, from 7,000 to 9,000 feet in altitude, is characterized by large stands of lodgepole pine (*Pinus murrayana*) and groves of white fir and red fir (*Abies magnifica*). Between altitudes of 9,000 and 11,000 feet is the Hudsonian life zone, in which only the hardiest species of trees can thrive. The distinctive trees of this zone are the western white pine (*Pinus monticola*), the alpine hemlock (*Tsuga mertensiana*) and the white-bark pine (*Pinus albicaulis*), which grows in curiously storm-twisted, recumbent, and even prostrate forms up to the extreme timberline. Above this line, in the Alpine life zone, the mountain sides and peaks rise apparently barren of vegetation, but actually even here there is a surprising wealth of

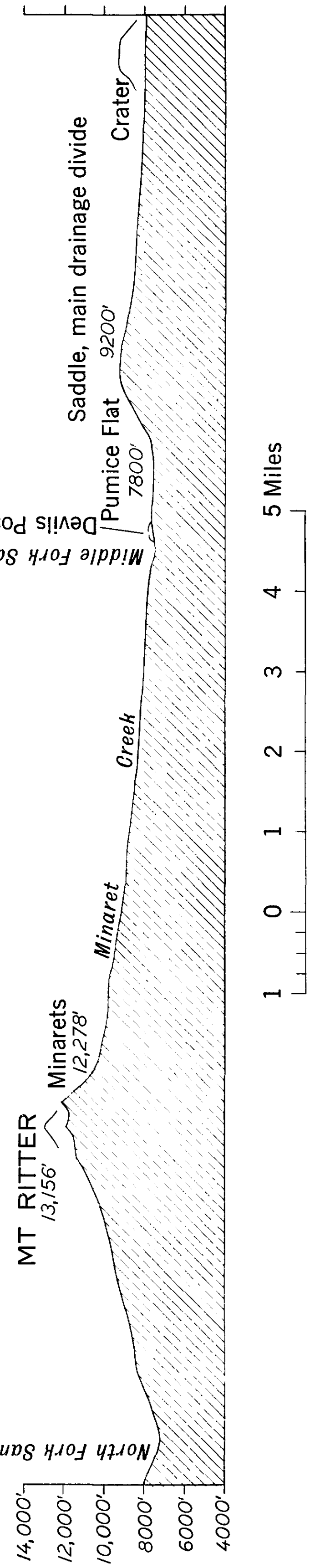


FIGURE 4.—Profile extending from the canyon of the North Fork southeastward through Mount Ritter and across the crest of the Sierra Nevada. The profile, drawn without vertical exaggeration, emphasizes the anomalous lowness of the main drainage divide in this section as compared with the greatly superior altitude of the Ritter Range.

small plants, many of which bear brightly colored flowers.

### ECONOMIC AND SOCIAL USE

All of the San Joaquin Basin, except the southwestern foothill section and the Evolution Valley region, is included in the Sierra National Forest. The basin is of great importance for its water resources and as a recreational, lumbering, and grazing area. Most of the information in this section was furnished by the Office of the Supervisor, Sierra National Forest, Northfork, California. Maps of the Sierra National Forest, available from the Forest Service on scales of both one-quarter and one-half inch to the mile, show most of the features mentioned.

Within recent decades, mainly since this reconnaissance was made, a remarkable development of human activities, both economic and social, has taken place in the basin. Hydroelectric power is now being generated on a large scale. The hydroelectric development of the Southern California Edison Co., which utilizes the Shaver Lake, Huntington Lake, and Lake Florence reservoirs (fig. 2) is the largest project of this company, and is reputed to represent a total outlay exceeding the cost of the Panama Canal. Crane Valley Lake and Kerckhoff Lake serve a project of the Pacific Gas and Electric Co. Work in progress, leading to the construction of new plants, is also increasing the outlay of existing plants by adding to present storage facilities.

The entire flow of the San Joaquin River is being utilized for downstream irrigation in the highly productive San Joaquin Valley. Average annual runoff is close to 1½ million acre-feet, all covered by downstream water rights. At Friant (see Friant quadrangle), just outside the Sierra National Forest, is Millerton Lake (fig. 2), which is formed by Friant Dam, a part of the Central Valley irrigation project of the U.S. Department of the Interior.

The building of roads in connection with these projects has opened to the public a large area of rugged, mostly forested mountain country at lower and middle altitudes, that was previously inaccessible except by steep rough trails. There has followed a great influx of vacationists whose numbers have grown as opportunities for recreation have increased. During the 1949 season there were about 990,000 recreational visitors to that part of the Sierra National Forest within the drainage of the San Joaquin River.

The San Joaquin Basin, although on the whole less notable for its mountain scenery than the Yosemite region to the north, and less deeply gashed by canyons than the Kings River Basin to the south, nevertheless includes some of the finest alpine scenery in the Sierra Nevada. The extreme southeastern corner of the basin, embracing Evolution Valley and Basin, and Goddard Canyon, is included in Kings Canyon National Park, established by act of Congress on May 4, 1940.

The Forest Service, in order to preserve the wilderness state of typical mountain and forest areas, has set apart a number of tracts of national forest land that will be left in their natural condition, without roads and other permanent recreational developments. Two such areas have been established in the Sierra National Forest, and both include extensive parts of the San Joaquin Basin. The Dana-Minarets Wild area, of 87,140 acres, lies immediately north and northwest of the Devils Postpile National Monument. The High Sierra Wilderness Area, of 393,945 acres, extends along the crest of the range from the Mammoth Lakes southward to the Kings Canyon National Park. Through these wilderness areas passes the famous John Muir Trail in its course from Tuolumne Meadows, in Yosemite National Park, to Mount Whitney, in Sequoia National Park (Starr, 1953). Mountaineering enthusiasts who visit the upper San Joaquin Basin over this trail or its approaches, afoot with knapsack, or on horseback with packtrains, make excursions from their basecamps into the surrounding areas, and climb peaks of the Evolution group, the Ritter Range, and other alpine sections of the High Sierra (Voge, 1954).

An area of 39,000 acres which almost surrounds Huntington Lake and lies mostly to the north of that lake, was designated the Huntington Lake State Game Refuge in 1931. In this area, set aside for the protection and propagation of wild life, firearms may not be discharged for any reason.

The Devils Postpile National Monument, justly celebrated for its remarkable development of columnar structure in basalt (Matthes, 1930b), brings visitors into the otherwise little frequented country in the Middle Fork Canyon of the San Joaquin River. This monument, administered by the Superintendent of Yosemite National Park, lies at an elevation of 7,000 to 8,000 feet, is about 2½ miles long and ½ mile wide, and has an area of 798½ acres.

Mineralization has occurred in the metamorphic rocks of both the foothills zone (Macdonald, 1941, p. 267–270) and the Minaret mining district, in the Ritter Range region at the north end of the San Joaquin Basin (Erwin, 1934, p. 10–11, 61–78), but there has been virtually no mineral production of significance. The Minaret district, in particular, has been extensively prospected, and ore bodies have been found containing iron, lead, zinc, copper, and silver, as well as minor amounts of molybdenum, tungsten, and bismuth.

On the upper slope of Iron Mountain, in this district, is a body of magnetite that has long attracted the attention of miners and that possibly would be profitable to exploit if it were more accessible to roads and markets.

The notable economic and social developments, together with the increasingly great popular interest in the San Joaquin Basin, give added interest to the geomorphological features which are described and interpreted in this report.

## ROCKS

Before taking up the detailed consideration of the landforms in the San Joaquin Basin, it will be desirable to consider first the nature of the rock materials from which these forms were carved. For this report, the subject may be treated briefly, and mainly from the geomorphological point of view, with emphasis on facts related to the development of landforms. Only incidental reference is made, therefore, to structure and to petrologic details.

The rocks of the San Joaquin Basin belong mainly to the three general classes that occur throughout the greater part of the Sierra Nevada (fig. 5); namely, the granitic rocks that make up the vast compound batholith of Late Jurassic or Early Cretaceous age; the metamorphosed sedimentary and volcanic rocks of Paleozoic and Mesozoic age into which the granitic rocks of the batholith were intruded; and the volcanic rocks of Tertiary and Quaternary age that lie unconformably upon these older rocks as a discontinuous, surficial veneer.

Further mention should be made of the glacial deposits of Pleistocene age in the higher parts of the basin (described in the chapter on glaciation); the alluvial deposits of Quaternary age which underlie many upland meadows and form narrow flood plains in the lower stream channels, notably that of the San Joaquin River, below Friant; and, finally, the sediments of Tertiary age, terrace gravels of Quaternary age, and alluvial fans of Quaternary age at the west border of the range, where the crystalline complex of rocks of Paleozoic and Mesozoic age constituting the Sierra block passes from view beneath the floor of the Great Valley.[4]

### GRANITIC ROCKS

Of the three main classes of rocks in the region, the granitic rocks are by far the most abundant. They occupy the greater part of the basin, their outcrops extending, with only a few important interruptions, from the crestline of the range to the western foothills. Even the outlying island hills that project above the sediments of the Great Valley of California, in front of the range, are composed largely of granitic rocks.

The term "granitic," as used in this report, includes a considerable variety of undifferentiated plutonic rocks, mainly of siliceous types. Besides granite, granite porphyry, and micropegmatitic granite, they include chiefly quartz monzonite, quartz diorite, granodiorite, and gabbro. In this reconnaissance the writer made no attempt systematically to distinguish and map these rocks, but this has since been done by Calkins (1930, p. 120-129) for the nearby Yosemite region and by other geologists for parts of the San Joaquin Basin. The studies by these geologists serve to shed light on the granitic rocks of the basin as a whole.

On his map of the foothills zone between the San Joaquin and Kings Rivers, Macdonald (1941, p. 217, 251-257, 271-273) distinguishes an earlier group of hornblende gabbros and hornblende diorites from a later group of intrusive rocks which includes hornblende biotite quartz diorite, pyroxene quartz diorite, and muscovite granite. Of these rocks, the quartz diorite occupies by far the greatest area. It is described as being quite uniform in composition throughout the area mapped but variable in appearance because of differences in grain size, structure, and texture.

In the southeastern part of the Mount Lyell quadrangle, Erwin (1934, p. 7-78; 1937, p. 391-413) found that the composite Sierra Nevada batholith includes intrusive igneous bodies of five types: andesine diabase, diorite porphyry, diorite, quartz monzonite-diorite, and micropegmatitic granite. These rocks, intruded in an order of increasing silica content, are thought to have resulted from one general period of igneous intrusion. The quartz monzonite-diorite composes the main mass of the batholith.

Mayo (1937, map p. 172; 1941, map facing p. 1000), in making a northeasterly geologic section through the San Joaquin Basin, found that the granodiorite-granite series extends uninterruptedly from the vicinity of Black Mountain (southwest corner of Kaiser quadrangle) almost to the crest of the range, a distance of about 45 miles. He has differentiated on his map a long narrow intrusion of porphyritic quartz monzonite which extends southeastward from the south end of the Ritter Range. This intrusion, distinguished by large phenocrysts of potassium feldspar, he designated as the Cathedral Peak granite, using the name previously given by Calkins (1930, p. 126-127) to the rock of this type in the Yosemite region.

[4] This border area is marginal to the region with which the present report primarily deals, and has been studied in detail, chiefly from the stratigraphic and petrographic standpoints, by Gordon A. Macdonald (1941).

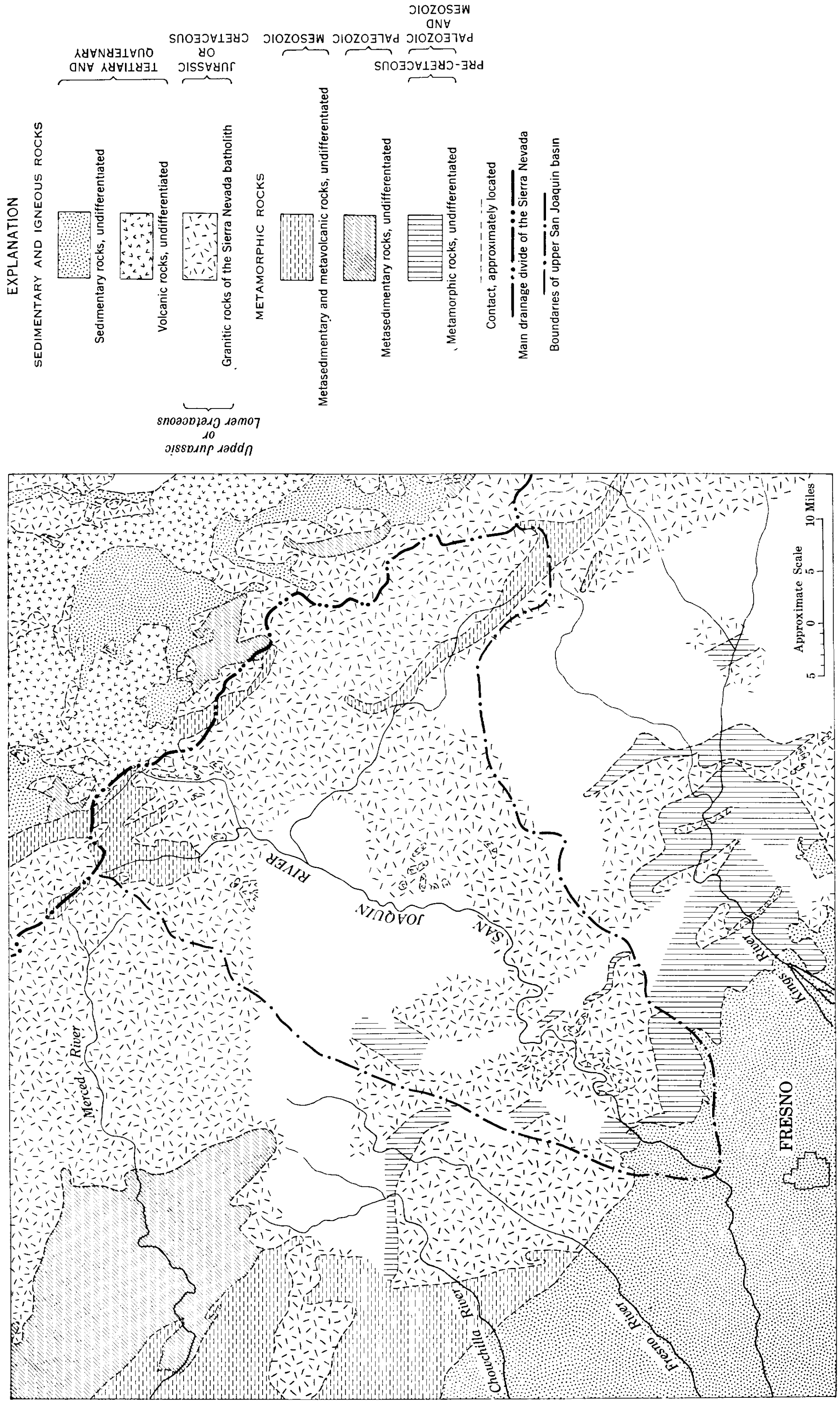


FIGURE 5.—Geologic map of San Joaquin Basin and surrounding region.

### JOINTING AND EXFOLIATION

In the San Joaquin Basin, as in the Yosemite region (Matthes, 1930a, p. 39), the granitic rocks are sparsely jointed, in many places the intervals between fractures measuring tens, hundreds, or even thousands of feet. However, in some places the granitic rocks are closely jointed (that is, have joints spaced one to several feet apart). As in the case of the Yosemite region, the character of the jointing has played a dominant role in governing the manner and rate of weathering processes, and of erosion by streams and glaciers, as well as in determining the character of the resultant landforms. In fact, the concepts of these processes and the analyses of the distinctive forms produced, as set forth in the author's report on the Yosemite Valley, were based on broad regional studies made in many parts of the Sierra Nevada, including the San Joaquin Basin. These concepts and analyses need not be restated here, but the illustrations in the present report include a number of views depicting representative landforms developed in the granitic rocks of the San Joaquin Basin.

In the Geographical Sketch, reference was made to the plateaulike uplands (p. 8) which are a distinctive feature of the central part of the San Joaquin Basin, and also to the broad shallow valleys which hang with respect to the San Joaquin Canyon and its principal branches. The exceptional preservation of the uplands and their hanging valleys is accounted for by the durability of the massive granite which underlies them. Some geologists would account for the relatively abrupt drop from the plateau to the foothills, south and southwest of Shaver Lake, by faulting, but no clear evidence of faults was discovered, and the same topographic effect could readily have been produced by differential erosion in well-fractured bodies of granite in juxtaposition to massive granite. The edge of the plateau south of Shaver Lake, which is scalloped by the heads of branches of Blue Canyon at the head of Big Creek, can hardly be delimited by a fault or zone of faults, but appears to indicate approximately the boundary between the massive rocks to the north and the fractured rocks to the south, in which a normal erosion topography, with dendritic drainage pattern and forking spurs and spurlets, has been developed.

The large-scale exfoliation of massive granitic rocks, so remarkably illustrated in the Sierra Nevada, is evident in many places in the San Joaquin Basin. The cause of this exfoliation is still obscure. Some geologists consider the most probable primary cause to be the liberation of expansive stresses within the granite, as the result of the progressive removal of superincumbent loads of rock by erosion; probably auxiliary causes are diurnal insolation and secular warming (Gilbert, 1905a, 1905b; Matthes, 1930a, p. 114–115; Matthes, 1937b). Exfoliation along plane or convex surfaces is illustrated at various places on the sides of the San Joaquin gorge, for example below the mouth of Big Creek, and on benches around the head of Evolution Creek, and elsewhere. Domes, the striking rounded forms evolved from giant monoliths by long-continued exfoliation, are neither numerous nor, generally, as spectacular in this basin as in the Merced Basin, but nevertheless examples are found.

Balloon Dome (altitude 6,900 feet) is the outstanding dome in the region (figs. 6, 15). It is situated between the Middle and South Forks of the San Joaquin River, immediately above the junction of the two streams. This dome is referred to in J. D. Whitney's report (1865, p. 401) as "a most remarkable dome, more perfect in its form than any before seen in the state," and it is described as having "exactly the appearance of the upper part of a sphere; or, as Professor Brewer says, 'of the top of a gigantic balloon struggling to get up through the rocks.'" As a matter of fact, it is not as regularly shaped as many of the domes of the Yosemite region, but because of its strange form, unique situation, and bare figure—all the more conspicuous because the surrounding uplands are forested—it is an imposing landmark.

Two miles to the northwest of Balloon Dome is Squaw Dome (altitude 7,806 feet), also a conspicuous topographic feature (fig. 7); and in the vicinity are Cattle Mountain (fig. 6), the Balls, and several other relatively small subdued domes. Near Cascada station, providing a background for the Big Creek Falls, is Kerckhoff Dome (fig. 19, not shown on topographic map); and on the north boundary of Kings Canyon National Park, occupying a position within the fork formed by Piute Canyon and the valley of the South Fork of the San Joaquin River, a situation very similar to that of Balloon Dome, is Pavilion Dome (altitude 11,721 feet). On Chiquito Ridge, exfoliation is prevalent but not regular and continuous, owing to steepness of the slopes and the presence of interfering master joints. Peaks and spurs of the ridge are imperfect domes, and on the exfoliation surfaces, rainwash flutings are common (fig. 8).

### MODES OF WEATHERING

Exfoliation is not a universal phenomenon of the massive granitic rocks. In places, for example on Bald Mountain, east-southeast of Shaver Lake, one may see immense exposures of massive granitic rock that are not exfoliating in the manner so characteristic of the

FIGURE 6.—View northwestward across the canyon of the South Fork of the San Joaquin River, toward Squaw Dome (left background), Balloon Dome (center of picture), and part of Cattle Mountain (in background at extreme right). The canyon of the Middle Fork extends across the view immediately back of Balloon Dome.

domes of the Yosemite region. The rock on Bald Mountain disintegrates into granules, which are washed away by rainwater and accumulate farther down the slope in large quantities. Exfoliation partings appear here and there, but are not conspicuous.

A striking feature in fresh road cuts on the steep grade above Tollhouse and on other roads leading to Shaver Lake is the massive granite, breaking down by mechanical processes, and without significant chemical decomposition. On the middle and upper parts of the San Joaquin Basin, accumulations of loose granular sand resulting from disintegration of the granitic rocks is one of the most widespread phenomena. The sand covers the lower slopes of bare rocky hills and ridges, and deeply cloaks the interfluves on the uplands. On the moraines of the later glaciation, the sand accumulates in the swales and on the upslope sides, so that the crests become flattened. The moraines of the earlier glaciation are in many places so mantled with sand derived from the disintegration of the glacial boulders that the materials of the moraine itself are exposed only here and there, generally where the uprooting of trees has revealed boulders and cobbles.

FIGURE 7.—Squaw Dome, situated about 3 miles north of the junction of the Middle and South Forks of the San Joaquin River. The view is from the east. Exfoliating granite forms the bare slopes of Squaw Dome and a lesser dome to the right.

As was explained in the author's report on the Yosemite Valley (1930a, p. 107–108), the disintegration of the granitic rock in these situations appears to be in the main a phenomenon of mechanical weathering, due largely to the disruptive effect of solar heat. Frost presumably plays a part in this disruption, but if so, only a very subordinate part, for typical frost cracks are absent in the rock masses wherein it occurs. The loose grains show scarcely any effects of chemical decomposition, even when examined under the microscope. The crystals of feldspar are but slightly cloudy at the edges, and the flakes of biotite and rods of hornblende as a rule show no alteration. However, this crumbling of the granite into undecomposed grains takes place only on the domes, cliffs, and other conspicuously bare rock masses that are subjected to intense insolation. In the densely forested areas on the uplands, where the heat of the sun is partly excluded by the foliage of the trees, and where the granitic rocks are covered by a layer of moisture-conserving, acid-producing humus, the chemical processes reduce the granite in much the same way as in a humid region.

FIGURE 8.—Imperfect development of domes in sparsely jointed granite on Shuteye Peak (altitude 8,358 feet), principal summit of Chiquito Ridge. The flutings are produced by rainwater, guided, in part, by minor joints.

The massive granitic rocks also disintegrate by flaking off in thin scales, the thickness of these as a rule being only ¼ inch but ranging from ⅛ inch to 1 inch. The scales vary in size but commonly break off in patches a few inches in diameter. Evidences of decomposition under the flakes, promoted by moisture and by the presence of green algae and lichens, are found in some places.

### METAMORPHIC ROCKS

The granitic rocks are interrupted at many places by small to moderately large masses of metamorphic rocks of Paleozoic and Mesozoic age. The largest of these masses are found in the foothills region, in the Mount Ritter region at the northern end of the basin, and in the Goddard Canyon region in the southeastern part of the basin.

The metamorphic rocks in the foothills region are a part of the broad belt of such rocks extending along the lower west slope of the Sierra Nevada. The belt is traversed, farther north, by the gold-bearing quartz veins of the Mother Lode system (Jenkins, 1938). Remarkably continuous as far southeast as the Merced Basin, this belt narrows notably near Mariposa, but tongues continue across the Chowchilla Basin and into the Fresno Basin (fig. 5). In the San Joaquin Basin the metamorphic rocks are represented by a series of relatively small disconnected bodies. Still farther to the southeast, in the basins of the Kings, Kaweah, and Kern Rivers, they again occur in larger masses along the lower west slope. Accordingly it would appear that the San Joaquin Basin, of all the drainage basins in the central and south-central part of the Sierra Nevada, is the one in which—so far as the lower west slope is concerned—the metamorphic rocks comprise the least, and the batholithic rocks the greatest proportion of the area.

In the foothills section between the San Joaquin and the Kings Rivers, the metamorphic rocks of Paleozoic and Mesozoic age occur in tightly folded anticlines and synclines which strike northwestward (Macdonald, 1941, p. 217, 270–2 2). The oldest division of the metamorphic sequence is a metasedimentary series between 20,000 and 30,000 feet thick, consisting chiefly of mica schist. Above this is a metavolcanic series at least 10,000 feet thick containing minor amounts of interbedded metasediments. The volcanic rocks, which are intermediate to basic, have been converted into plagioclase amphibolite and amphibole schist. The youngest division of the metamorphic sequence is another metasedimentary series close to 10,000 feet thick, consisting mainly of mica schist. Sills of serpentine and a few bodies of olivine gabbro have been metamorphosed to a degree comparable with the surrounding rocks.

The body of metamorphic rocks in the Mount Ritter region is the largest in the basin. This body, in its broader relations, is the expanded southern part of the narrow belt of metamorphic rocks, of Mesozoic age, which extends for about 40 miles along the crest of the range, at the heads of the Tuolumne, Merced, and San Joaquin Basins (Jenkins, 1938). The body is irregular and measures about 12 miles across in its larger dimensions. It forms the bulk of the Ritter Range, and extends across both the Middle Fork and the North Fork Canyons. At the northeast it passes beneath Tertiary lavas capping the main divide.

The rocks of the Mount Ritter region have been described by Erwin (1934, 1937) and also considered in the regional studies by Mayo (1935, 1937, and 1941). They consist mainly of intensely folded metavolcanic rocks which form an almost isoclinal series striking in general N. 30° – 40° W. The metavolcanic rocks, predominantly pyroclastic rocks, include diverse rock types altered into schists and, particularly, mylonites. There are minor intercalations of metasediments, and Erwin has mapped these separately in the upper Middle Fork basin.

In the Middle Fork basin, the metavolcanic rocks, being of various hues, give the landscape a distinctively banded appearance which contrasts with the uniformly dark or light aspect of nearby areas. The Ritter Range looms almost black above the light-colored granitic rocks to the south and southwest. Its rocks, mostly metatuffs and breccias, are generally more massive than those in the Middle Fork basin, and apparently less severely metamorphosed. In the North Fork basin and to the west of it, the metamorphic rocks again are more completely altered and more schistose than in the Ritter Range.

Between Mono and Bear Creeks, metavolcanic rocks of Mesozoic age reappear in a long narrow belt which extends southeastward along Goddard Canyon (Jenkins, 1938). This belt reaches far beyond the limits of the San Joaquin Basin, continuing, with some interruptions, across the Kings River Basin to the headwater area of the South Fork of that river.

The rocks of this belt, presumably Mesozoic in age, have not been fully mapped or studied in detail. They crop out along Goddard Canyon and make up a considerable part of both the Goddard Divide and the LeConte Divide. Where observed in the course of this reconnaissance they consist predominantly of intricately folded, nearly vertical metavolcanic schists striking northwestward.

Other smaller masses of metamorphic rock lie widely scattered within the San Joaquin Basin, some in belts, others without apparent system. The mountains of Kaiser Ridge, west and northwest of Nellie Lake, are composed largely of quartzite which disintegrates into angular blocks less than 2 feet across, contrasting with the much larger and more rounded granite boulders of nearby areas. The peak (altitude 9,622 feet) north of the lake is composed partly of quartzite, partly of granite; the extreme summit is granite. Farther east, Kaiser Peak itself is composed of thinly bedded quartzite and schist. On the north side of the peak these rocks are cut by thick sills of granite and aplite. The quartzite on the east spur of Kaiser Peak breaks down into distinctive small fragments. The Twin Lakes are bordered on the north by a belt of crystalline limestone forming an arc-shaped outcrop more than 1 mile long, the concave side of which is toward the northeast. The peak east of Potter Pass is composed, in its eastern part, of closely plicated grayish-green schist.

Small bodies of metamorphic rock, mostly schist, were also observed on the east side of Silver Creek, ¾ mile above its junction with Fish Creek; at the east end of Junction Bluffs; ½ mile northwest of Clover Meadow Ranger Station; on Green Mountain, 1½ miles north of Soldier Meadow; and in Shakeflat Creek basin, as well as on the ridge to the southwest of it, where the local rock is largely schist and quartzite. Similar small bodies of metamorphic rock undoubtedly occur at many other places in the San Joaquin Basin.

## VOLCANIC ROCKS

The volcanic rocks, scattered from the Sierra crest to the western foothills, occur in many small patches whose aggregate area is only a minor part of the San Joaquin Basin. In age they range from Miocene to late Pleistocene or perhaps even to Recent. Unlike the extensive flows in the northern half of the range, they have interfered but little, and only locally, with the orderly development of the valleys and canyons.

The principal areas of volcanic rocks lie on the main divide adjacent to the Middle Fork Canyon, and farther south within the canyon. This region, included in the southeastern part of the Mount Lyell quadrangle, has been mapped by Erwin (1934) who distinguished 5 volcanic units, 2 of late Miocene age and 3 of Pleistocene age.

The older Miocene unit, consisting of basalt flows, includes a relatively large occurrence east of the Middle Fork Canyon (southeast of Agnew Pass); also remnants south of Iron Mountain between the North and Middle Forks of the San Joaquin River, in the upper East Fork of the Granite Creek basin, in the vicinity of Clover Meadows, and elsewhere. At the Middle Canyon locality the basalt rocks are exposed in cross section, giving a bold, steplike profile to the east side of the canyon. The flows vary in number from place to place; in the thicker sections they "do not exceed 36" (Erwin, 1934, p. 46). North of Agnew Pass their aggregate thickness is estimated to be more than 1,500 feet. The flows, which have columnar or blocky jointing, permit surface water to seep through to the underlying metamorphic rocks, whose surface is followed to Middle Fork Canyon. Here, emerging from beneath the lavas, the water gives origin to most of the streams on the east side of the canyon. The other lava caps in the region are of similar character but smaller.

FIGURE 9.—Ice-truncated columns of basalt on the Devils Postpile. Some of the facets are rounded and polished by the ice.

The younger Miocene unit includes andesitic flows, with a maximum thickness of about 1,000 feet, which overlie the basalt on the Sierra crest, east of Middle Fork Canyon. A few miles farther southeast, andesites also make up the bulk of Mammoth Mountain, an isolated and deeply eroded preglacial volcano which Mayo (1941, p. 1068) has termed "the most impressive volcanic edifice in the region."

The three Pleistocene units are basalt flows, tuffs, and pumice. There are several occurrences of the basalt, the most important being a Y-shaped mass immediately west of the Sierra crest. The converging arms of the Y, each about 3 miles long, extend southward from the head of Pumice Flat and westward from Mammoth Pass, and unite just below Reds Meadow to form the upright, which extends south-southwestward about 4 miles farther. This mass includes the Devils Postpile (Matthes, 1930b) (fig. 9). A short distance below the Postpile a cliff of the basalt gives rise to Rainbow Falls, 150 feet high, the most notable waterfall in the San Joaquin Basin (fig. 10). The basalt appears to have descended from the vents at Red Cones and Pumice Butte, and from a fissure near Mammoth Pass.[5] It issued after the El Portal glacial stage onto the glaciated surfaces of Middle

[5] Location of these and other volcanic vents is shown on Erwin's map, also on pl. 3 and fig. 6 of Mayo's report, Deformation in the interval Mount Lyell–Mount Whitney, California (1941).

FIGURE 10.—Rainbow Falls, a short distance below the Devils Postpile on the Middle Fork of the San Joaquin River. The falls, 150 feet high and the most spectacular in the region are produced where the river leaps over the edge of a basalt cliff.

Fork Canyon, accumulating to depths of 100 to 700 feet. When the Middle Fork glacier readvanced in the Wisconsin stage, it removed all but the more obdurate parts of the lava (Matthes, 1930b, p. 5).

The other Pleistocene volcanic units consist of an area of crystallithic tuff in the vicinity of Satcher Lake and Reds Meadow, and a scattering of pumice pellets, as much as 1 inch in diameter, widely distributed throughout the region and particularly abundant between Agnew Meadows and Pumice Butte. Erwin considers the pumice to be "younger than older glacial material."

In this reconnaissance several volcanic cones and many small patches of volcanic rock were noted. Black Point, 1½ miles west of Huntington Lake, is a small volcanic cone. Another cone, Brown Cone, lies to the north of Kaiser Creek; still another is situated in nearby Cow Meadow. The latter is the remnant of an andesitic eruption crater, the west and north sides of which are best preserved. About 3 miles farther southeast is another small andesitic volcano which is probably interglacial, because granite erratics left by the Wisconsin stage rest on its lava. The volcano stands about 100 feet above the surrounding country, and contains a shallow lake in what appears to be a compound crater.

Of the many scattered patches of volcanic rock observed, mention may be made of several in the lower South Fork Canyon; also those in the vicinity of Pincushion Peak, particularly west of the summit; those at the northwest end of Mono Ridge, one of them giving rise to the eminence called Volcanic Knob; several extending from Onion Spring Meadow southwestward almost to the South Fork of the San Joaquin River; the patches in upper Big Creek Basin which form Chinese Peak, Red Mountain, and Black Peak (fig. 47); an occurrence in Chiquito Creek basin, 1 mile northwest of Placer Ranger Station; and the patches which partly cap the summit of Squaw Dome. In the case of Chinese Peak, three large dikes radiate from the central summit.

Though none of the occurrences mentioned has been studied in detail, most of them apparently are andesitic. However, patches of olivine basalt (Miocene or Pliocene) which cap Table Mountain and a few other foothills in the Friant and Academy quadrangles are described by Macdonald (1941, p. 266 and folded map).

## GEOMORPHOLOGY

The west slope of the Sierra Nevada, of which the San Joaquin Basin forms a part, is a region of exceptional interest to the geomorphologist, both in its broader aspects and in its details. Although furrowed by many deep canyons, it nevertheless retains on its undissected intercanyon uplands considerable remnants of ancient erosion surfaces, as well as lofty monadnock ridges with occasional tabular summits. These features, together with the evidences of Pleistocene glaciation in the higher portions, present a decipherable, if partly obscured, record of the geomorphologic history of the range. Moreover, as the rise of the Sierra Nevada was intimately related to the earth movements that affected the Great Basin, to the east, and as, furthermore, the growing height of the range brought upon that province the stark aridity that has so profoundly influenced its erosional development, it will be apparent that the story to be read in the features of the west slope of the Sierra Nevada has bearings that extend far beyond the confines of the range.

The precipitous east front of the Sierra Nevada, though extremely impressive, is to the geomorphologist less instructive than the gently declining west slope. The product of essentially one episode in the life history of the range, and that a relatively recent one, the east front tells a rather short and simple story. The west slope, on the other hand, recounts a long history reaching back into the beginning of the Tertiary period; and it even retains sculptural and drainage elements which were inherited from an ancient mountain system of Appalachian type, that occupied the site of the present Sierra Nevada during the Cretaceous period.

The west slope of the Sierra Nevada is the only large area of elevated land in the United States west of the Rocky Mountains that presents such a comprehensive geomorphic record in fairly readable form. Primarily because of its great areal extent it has escaped thorough dissection in spite of strong uplift and consequent vigorous erosional attack. By comparison with the Sierra Nevada, the back slopes of the Basin Ranges are of very limited extent, measuring, as a rule, only 4 to 6 miles from crest to base. The Sierra back slope, however, measures 40 to 60 miles from crest to base, and—in the distance of 430 miles through which it maintains this breadth—is traversed by rivers as long as 100 miles. Even if the northernmost and southernmost portions, which are complicated by lines of dislocation, are subtracted, the west slope remains by far the largest sharply delimited unit area of uplifted and tilted earth surface in the western United States. The Cascade Range, it is true, covers a greater area than the Sierra Nevada, but most of its elevation is due to irregular upwarping. Its surface configuration in addition reflects the vagaries of volcanic action and scarcely offers an advantageous field for geomorphologic studies of a broad regional nature.

Three factors besides areal extent have retarded the dissection of the west slope of the Sierra Nevada: first, the resistance to erosion of the harder metamorphic rocks and the sparsely jointed, massive granitic rocks that prevail over large areas; second, the general absence, except in the northernmost and southernmost parts of the range, of lines of dislocation that facilitate localized trenching; and third, the protection against gullying erosion which its soil and its vegetation afford, and which probably always have afforded, except in the crestal parts which were severely glaciated during Pleistocene time and have since remained barren because of their altitude. In the latter respect the Sierra Nevada stands in marked contrast to the naked, craggy flanks of the Basin Ranges, which are fully exposed to the processes of denudation.

## COMPARISON OF SECTIONS OF THE SIERRA WEST SLOPE

Before narrowing consideration to the San Joaquin Basin, it will be profitable to consider the various sections of the west slope of the Sierra Nevada as a whole, both to the north and to the south of the basin, in regard to the problems they present with reference to geomorphologic analysis.

The northern two-fifths of the Sierra Nevada, extending approximately as far south as the northwestern boundary of Yosemite National Park, is in large part mantled with volcanic agglomerate and lava, with the result that its earlier erosion surfaces are almost completely obliterated. The buried valleys and ridges can be glimpsed here and there in the sides of the newer canyons that trench through the volcanic cover, but the glimpses thus afforded hardly suffice to permit reconstruction of the ancient landscapes with any degree of confidence. Moreover, several northwestward-diverging faults of considerable throw disrupt the unity of the west slope at the northern end of the range, thereby complicating the geomorphologic record.

The southern one-fifth of the range, from the Kern Canyon south to the Tehachapi Pass, is traversed by several lines of faulting which, though not seriously affecting its unity, nevertheless control some of the principal drainage lines and have influenced erosion. Furthermore, this part of the range does not slope gently toward the western foothill belt, but has the aspect of a profoundly dissected horst that breaks off abruptly at its western as well as its eastern margin.

The upper Kern Basin is probably unsurpassed for simplicity of sculpture; probably no other part of the range retains erosion surfaces which so clearly exhibit the effects of incomplete cycles of erosion as does this basin, in which Lawson (1904, 1906) made his classic morphologic analysis. But the precise correlation of these erosion surfaces with those in the central part of the range presents difficulties, for in several respects the Kern River is anomalous among the master streams of the Sierra Nevada. Its course appears to have been determined largely by structural factors, rather than by tilting of the Sierra block; for it flows southward along a zone of faulting, in a course that trends parallel to the crestline of the range instead of normal to it, as in the case of the other master streams. Furthermore, the Kern River traverses that part of the range wherein a transition takes place from tilted block structure at the north to horst structure at the south; and in the lowermost part of the Kern Basin there are other structural irregularities. The tributaries of the Kern River trend in various directions, without apparent system, rather than in patterns decipherable in terms of the early geomorphologic history of the basin. It appears, therefore, that the Kern River Basin is hardly typical for the range as a whole, but presents a rather special case, complicated by several local factors.

It is in the central and south-central parts of the range that the geomorphologist finds the conditions most favorable for his purpose. More specifically this area extends from the northwestern boundary of the Yosemite National Park southeastward to that spur ridge in Sequoia National Park known as the Great Western Divide, and it comprises the drainage basins of the Tuolumne, Merced, San Joaquin, Kings, and Kaweah Rivers. This part of the Sierra Nevada, 150 miles long in the direction of its axis and averaging 60 miles in breadth, appears to have been essentially a single massive rigid block, and has remained relatively free from deformation or fracturing except locally, as at its western margin. The drainage system of the west slope of this portion of the range, so far as known, has not been dislocated or rearranged in consequence of either faulting or warping, except in a minor way as in certain parts of the foothill belt. Neither have any of its streams been eliminated or significantly diverted by extensive volcanic outpourings such as prevailed in the northern parts of the range. Local extrusions have not been wanting in various places and at different times, but the drainage changes caused by them have been inconsequential.

One drainage basin, that of the Merced River, has remained free from volcanic outpourings, containing only one diminutive crater. As a consequence, within its confines, the processes of stream erosion have worked without interference, except by the glaciers of the Pleistocene epoch, ever since the earliest recognized cycle. Nevertheless, the Merced Basin is not the simplest field for geomorphologic study on the west slope, for its central feature, the Yosemite Valley, is of a peculiarly enigmatic sort (Matthes, 1930a). It is a chasm of aberrant type in whose interpretation the geomorphologist can hardly hope to succeed without having first gained an insight into the history of the more normally shaped canyons of the west slope. Furthermore, the lower half of the Merced Basin, being composed of upturned strata of thin-bedded metamorphic rocks that differ sharply in resistance to erosion, is dissected by a maze of valleys and gulches, and retains on its skeleton ridges few recognizable remnants of the more ancient erosion surfaces. The profiles of the Merced River for each of two earlier erosion cycles can be reconstructed with some confidence throughout the upper half of the basin, which is composed almost wholly of granitic rocks. However, these profiles cannot be extended for any great distance down through the lower half, for lack of reliable diagnostic features in its greatly dissected topography. It was because of these baffling circumstances that the author deferred publication of his conclusions regarding the history and mode of development of the Yosemite Valley until he had had opportunity to test their validity by comparative studies of other major canyons in the range, not only of those that possess Yosemite-like widenings but also those that are normally shaped throughout.

Reconnaissance for this purpose in the Tuolumne Basin (1916, 1917, and 1919), which adjoins the Yosemite region on the north and northwest, afforded an opportunity to examine the Hetch Hetchy Valley, which is most closely analogous to the Yosemite Valley. The outstanding lesson of Hetch Hetchy was that the geomorphic history is by no means recorded with equal clearness in all parts of the Sierra Nevada, for in some parts it may be extremely obscure in spite of the grand scale on which the features of the landscape are modeled. The Tuolumne Basin, though rich in glacial features, did not prove especially helpful in defining successive landscapes produced by successive cyles of erosion, for it contains few well-preserved remnants of ancient surfaces of erosion, and is poor in clean-cut hanging valleys whose discordance is demonstrably due to preglacial canyon cutting. Over considerable parts of the Tuolumne Basin the granitic rocks have the same unusual structure as in the Yosemite region, and have given rise to similar aberrant sculptural forms. The Hetch Hetchy Valley is another yosemite, although of smaller dimensions than its prototype.

The Table Mountain region (fig. 1), visited in 1921, on the divide between the lower Tuolumne and lower Stanislaus canyons, proved to be an unexpectedly fruitful field because the gravels in some of its lava-entombed stream channels yielded well-preserved fossils that afford a means for determining the age of one of the older erosion surfaces. (See p. 23.) Farther north, however, the older topographic features are largely buried under the mantle of volcanic rocks.

Just south of the San Joaquin Basin, the writer's investigations have indicated that in the basins of the Kings and Kaweah Rivers, likewise, there are conditions which interfere with geomorphologic analyses of a broadly regional character, notably that these basins exhibit relatively few of the well-preserved hanging valleys which are of critical importance in deciphering the successive events of the history of the range.

## SUITABILITY OF THE SAN JOAQUIN BASIN FOR GEOMORPHOLOGIC ANALYSIS

The broad San Joaquin Basin appears in some ways to be the most revealing drainage basin of the west slope in regard to features that aid in the interpretation of regional geomorphologic problems. Briefly stated, its importance in this respect stems from the following combination of circumstances:

The erosional features of the basin are unobscured by volcanic flows except in relatively small areas.

The granitic rocks, exceptionally extensive in this basin, are prevailingly massive and exert profound influence on the topography. The San Joaquin Canyon is, therefore, consistently narrow, and exhibits neither anomalous Yosemite-like widenings nor, for the most part, the unusual sculpturing characteristic of the yosemites. Furthermore, the resistant nature of the massive granitic rocks accounts for the preservation of an exceptionally fine record of the successive cycles of erosion, and an extraordinary wealth of clean-cut hanging side valleys.

The granitic rocks are practically continuous to the foot of the range. Consequently, the ancient erosion surfaces and the array of hanging valleys likewise extend not merely throughout the manifestly glaciated upper course of the San Joaquin Canyon but also through the unglaciated lower course—in fact to within a few miles of the foothills.

The San Joaquin River has an essentially normal southwestward course. Thus flowing down the slope of the Sierra block, the river must have received the entire effect of the rejuvenation caused by each tilting movement. In contrast, the tributaries of the San Joaquin River for the most part have northwesterly or southeasterly courses, substantially at right angles to the master stream as well as to the direction of tilting of the block. The flow of the tributaries, therefore, must have been only mildly accelerated by the tilting of the Sierra block. In this contrasting relationship of master stream to tributaries, the drainage pattern of the San Joaquin Basin is typical for most of the basins in the central and southern part of the Sierra Nevada, but probably in no other basin is the relationship so well shown.

Finally, it may be noted that in the San Joaquin Basin the erosion surfaces form broad uplands which bear lofty monadnock ranges. The erosion surfaces of the uplands have remained essentially undisturbed because of the resistant nature of the bodies of massive granitic rock which underlie them. The monadnock ranges, by their position and prevailingly northwestward trends, are representative for the Sierra Nevada as a whole, and significant in the interpretation of its early geomorphic history. Moreover, by their great height above the erosion surfaces which surround them, they testify, more clearly than does the evidence which the author has observed in other parts of the range, to the relatively great antiquity of that most ancient erosion surface which is still identifiable from small but sharply defined remnants preserved on a few of the summits.

## SUMMARY OF CONCLUSIONS CONCERNING THE YOSEMITE REGION

A primary purpose in undertaking studies in the San Joaquin Basin was to test the soundness of conclusions reached in the Yosemite region regarding the geomorphologic development and the glaciation of that region, and to determine the bearing of these conclusions on the history of the Sierra Nevada in general. It is appropriate, therefore, to summarize the results of the author's study of the Yosemite Valley (Matthes, 1930a). (See fig. 11.)

The most significant conclusions relate to the origin and significance of the hanging side valleys of the Yosemite chasm. Detailed mapping of the morainal system of the ancient Yosemite Glacier indicated that that glacier never extended more than a mile beyond the site of El Portal. The hanging side valleys of the Merced Canyon below El Portal do not hang, therefore, because of any glacial deepening which that canyon has undergone. The explanation was offered that they hang because their streamlets have been unable to trench as rapidly as the Merced River since the re-

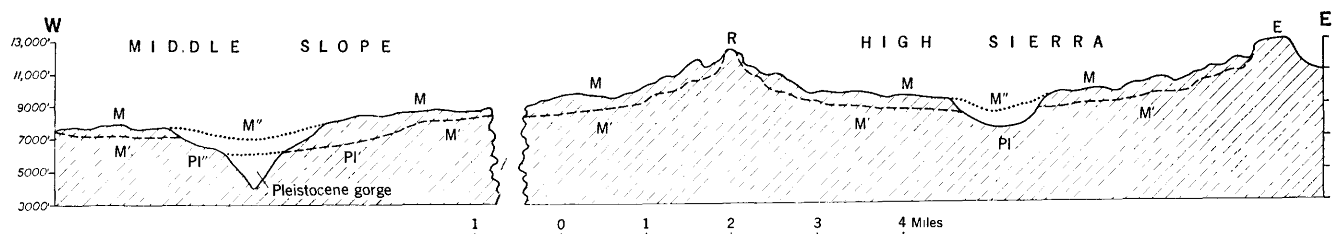


FIGURE 11.—Idealized profile showing features produced by successive cycles of erosion in the Yosemite region. *E*, tabular remnant of Eocene surface on high residual peak; *R*, residual peak no longer bearing remnants of Eocene surface; *M*, Miocene surface preserved on intercanyon uplands; *M'*, longitudinal profiles of hanging valleys of Miocene cycle (glaciated in the High Sierra); *M''*, reconstructed cross profiles of main valleys of Miocene cycle; *Pl*, main valley of Pliocene cycle (glaciated); *Pl'*, longitudinal profile of hanging valley of Pliocene cycle; *Pl''*, reconstructed cross profile of main valley of Pliocene cycle; Pleistocene gorge of Pleistocene cycle (unglaciated). Vertical scale same as horizontal scale. From 16th International Geological Congress, Guidebook 16, p. 35, 1933.

juvenation of the Merced by the last uptilting of the Sierra Nevada. The streamlets were handicapped not only by their comparatively small volume but also by the fact that their courses trend northwestward and southeastward, substantially at right angles to the direction of the tilting, and therefore have remained essentially unsteepened, whereas the Merced's course trends southwestward, directly down the slope of the Sierra block, and therefore has been appreciably steepened.

Projection of the longitudinal profiles of these hanging valleys forward to the axis of the Merced Canyon shows that they are closely accordant in height. Their profiles indicate a series of points on a former profile of the Merced with respect to which the side streams had graded their courses prior to the last uplift. This old profile can be extended upward into the glaciated part of the Merced Canyon above El Portal and even into the profoundly glaciated Yosemite Valley, accordant points being furnished by a number of hanging side valleys (due allowance being made for the effects of glacial erosion on those valleys).

However, not all hanging valleys of the Yosemite region are accordant with this set. Several constitute a separate set indicating another old profile of the Merced at a level 600 to 1,000 feet higher than the first. Others point to an old profile of the Merced about 1,200 feet lower than the first. There are thus three distinct sets of hanging valleys produced in three cycles of erosion. Those of the upper set, like those of the middle set, were left hanging as a result of rapid trenching by the Merced induced by an uplift of the range, there having been two such uplifts. Only the valleys of the lower set hang because of glacial deepening and widening of the Yosemite Valley, the cycle in which they were cut having been interrupted by the advent of the Pleistocene glaciers.

During the remote cycle of which the hanging valleys of the upper set and the undulating Yosemite upland are representative, the Yosemite Valley itself was broad and shallow, postmature in form. That early stage in its development, accordingly, is called the broad-valley stage. The deeper hanging valleys of the middle set were graded with respect to a deeper Yosemite Valley of submature form which must have had the aspect of a mountain valley. That stage in its development is therefore called the mountain-valley stage. The short, steep hanging valleys of the lower set and certain topographic features associated with them show that during the third cycle of erosion the Yosemite Valley was a roughly V-shaped canyon with a narrow inner gorge. This stage, which immediately preceded the glacial epoch, is therefore called the canyon stage.

In the Yosemite region, paleontological evidence for the age of the upland erosion surface is lacking, but farther north, in the Table Mountain district between the Tuolumne and the Stanislaus Rivers (figs. 1, 12), lava-entombed stream channels correlative with the upland have yielded well-preserved impressions of leaves and a few mammalian remains. These fossils, according to determinations by Ralph W. Chaney and Chester Stock, date back to the later part of the Miocene epoch (Matthes, 1930a, p. 1, 28; 1933a, p. 35, 70). Accordingly, the upland erosion surface in the Yosemite region is thought to be of late Miocene age. Uplift of the Sierra Nevada at the end of the Miocene epoch initiated the next cycle, during which the mountain-valley stage was evolved. That cycle lasted presumably through most, if not all of, the Pliocene epoch. The canyon stage was produced in all probability during the Quaternary period.

The excellent preservation of the hanging valleys of the upper set, in spite of their great age, is explained by the exceedingly resistant nature of the massive granite that underlies them. The valleys of the middle set were carved in prevailing jointed rocks that were less resistant to stream erosion, and the gulches of the lower set were carved in closely fractured rocks in which the streams eroded with relative ease.

The gradients of the two higher profiles of the Merced furnish data from which the amplitude of each of the two great uplifts of the Sierra Nevada can be roughly calculated. The uplift at the end of the Miocene epoch added about 3,000 feet to the height of the range; the uplift at the end of the Pliocene epoch added 6,000 feet more. These determinations rest on deductions made after the reconnaissance of the San Joaquin Basin was completed, and which took into consideration the Tertiary profiles of the San Joaquin River and the rivers of the northern Sierra Nevada as well as those of the Merced River (Matthes, 1930a, p. 44).

Of the earlier geomorphologic history of the Yosemite region a glimpse is afforded in the explanation of the origin of the southwesterly course of the Merced River and the arrangement of the lesser tributaries at right angles to it. The Merced River established its course conformably to the southwesterly slant of the Sierra region, presumably early in the Tertiary period, when there still existed remnants of a system of northwestward-trending mountain ridges of Appalachian type, which had been formed at the end of the Jurassic period by the folding of sedimentary and volcanic strata of Paleozoic and Mesozoic age. As it grew headward, the Merced River probably captured the drainage from the longitudinal valley troughs between these ridges. Below El Portal, on the lower slope of the Sierra Nevada, where the folded strata still remain in a broad belt, the lesser tributaries of the Merced are for the most part adjusted to the northwesterly strike of the beds. In the Yosemite region and the adjoining parts of the High Sierra, from which the folded strata are now stripped away, broadly exposing the granitic rocks, the northwesterly and southeasterly trends of many of the streams are largely an inheritance by superposition from the drainage system of the now vanished older mountain system. The northwesterly trend of the Clark Range, the Cathedral Range, and certain stretches of the main crest of the Sierra Nevada are probably likewise inherited from that ancient mountain system. Though the majority of these monadnock ranges have sharp or splintered crests, a few retain tabular summits, the isolated remnants of an erosion surface which is clearly far more ancient than the Miocene uplands and therefore probably Eocene in age.

## GEOMORPHOLOGY OF THE SAN JOAQUIN BASIN

### DESCRIPTION OF GEOMORPHOLOGIC FEATURES

#### FOOTHILL BELT

In the foothill belt, the mountainous surface of the Sierra Nevada declines to the level of the Great Valley of California and becomes covered by overlapping sediments. The relief diminishes in the first place through the progressive decrease in the eroded depth of the main canyon and secondly through the burial of the canyon floor and the tributary valleys to greater and greater depths. The mountains accordingly stand out with less and less height, until only their tops emerge from the engulfing sediments at varying distances from the range foot, like rocky islands fringing a mountainous coast indented as a result of recent submergence. A typical example of such an outlying mountain top is Round Mountain (altitude 870 feet) which rises about 450 feet above the plain. (See Round Mountain quadrangle.) Smaller knobs of this type occur to the south and southeast of it.

A third cause for diminishing relief in the foothill belt seems to be in the diminishing height of the mountains above the hard-rock valleys. Black Mountain (altitude 3,621 feet), at the inner margin of the foothill belt, stands 2,500 feet above the valley of nearby Dry Creek; but the hills to the southwest rise only about 1,200 feet above the same valley, and still farther to the southwest most of the hills are only 300 to 700 feet high. Owens Mountain, southeast of

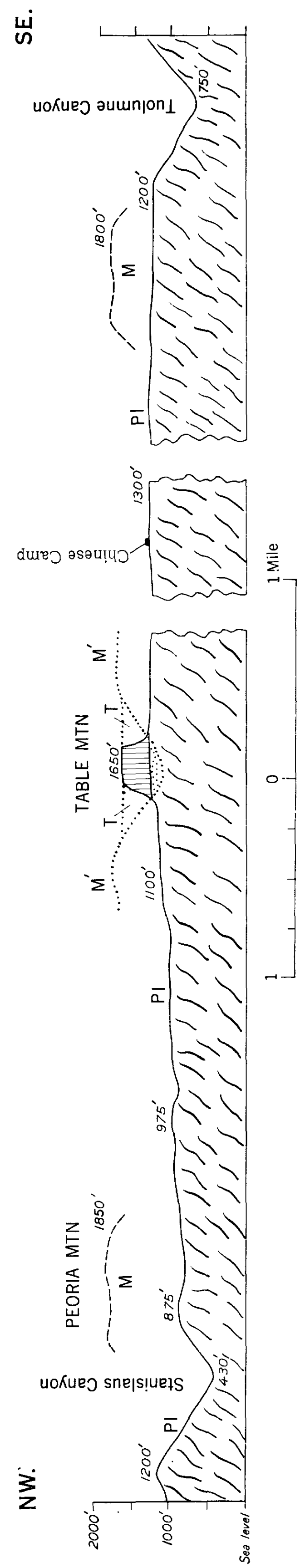


FIGURE 12.—Section through Table Mountain region, Sierra Nevada. *Pl*, Pliocene surface of erosion developed on unresistant slates and volcanic rocks of the Mariposa formation; *M*, residual mountains bearing remnants of Miocene surface; *M'*, reconstructed hills on Miocene surface flanking the ancient valley through which the latite of Table Mountain flowed; *T*, reconstructed portions of Table Mountain flow. Beneath the columnar latite of Table Mountain is the gravel of the buried river channel, which has been mined for gold. The Stanislaus and Tuolumne Canyons were cut during the Pleistocene cycle. Vertical scale is twice the horizontal scale. From 16th International Geological Congress, Guidebook 16, p. 36, 1933.

Friant (see Friant quadrangle), dominates the foothills roundabout with an altitude of 1,611 feet and stands 1,180 feet above the neighboring valleys, but its height is exceptional. Immediately south of it, the country drops off to levels of 600 and 500 feet, and only small rocky knobs, a few tens of feet high, rise above the level of the plain, which here is about 450 feet above sea level.

A conspicuous feature of the foothill belt is the series of flat-topped hills, or mesas, capped by volcanic rock, that extends in a southerly direction athwart the southwesterly course of the San Joaquin River. Like other volcanic mesas of this type farther north in the foothill belt of the Sierra Nevada, these are collectively known as Table Mountain. (See Millerton Lake and Academy quadrangles.) The partly disconnected mesas have an aggregate length of 16 miles, of which somewhat more than 6 miles lies on the northwest side of the river and the balance on the southeast side. Where the San Joaquin River transects the series of mesas, the river bed is fully 1,700 feet below the surface of the ancient lava flow. West of the river near the outer fringe of the foothills, is another lower and less well preserved series of flat-topped hills known as Little Table Mountain. (See Lanes Bridge quadrangle.) This series is only 5 miles long and extends in a south-southeasterly direction, ending about 4 miles below Friant in a bluff overlooking the river.

The plain immediately in front of the debouchure of the San Joaquin River consists of a great alluvial fan built by the river. This fan extends westward and southwestward for about 30 miles out from the foothills. At Friant, near the apex of the fan, the surface is 460 feet above sea level. Thence it slopes down to an altitude of about 200 feet at its outer margin. So gentle is this slope that to the traveler's eye the surface appears utterly flat. The city of Fresno stands near the middle of the fan, about 17 miles below the apex and 6 miles south of the river.

A number of radiating and usually double-crested ridges on the surface of the fan indicate natural levees along old channels which the river, or branches of it, have occupied at different times. Although the eye hardly detects these features, they stand clearly revealed on the detailed topographic maps, on which the contour lines are drawn at intervals of 5 feet. (See Friant, Lanes Bridge, Clovis, Bullard, Herndon, Biola, Gravelly Ford, Kerman, Kerney Park, Fresno, and Malaga quadrangles.)

These ridges are of the type which Kirk Bryan (1923, p. 29) noted in the Sacramento Valley and has called "channel ridges." Most of the old stream channels are now dry, but some have been improved and are being used as irrigation ditches.

In geologically Recent time the San Joaquin River has cut a trench in its great fan. This trench is 155 feet deep at Friant; thence downstream its depth diminishes progressively to only a few feet at the margin of the fan. The trench varies in width from ½ to 2 miles and contains several terraces marking successive stages in its cutting.

#### SAN JOAQUIN CANYON AND ITS MAIN BRANCHES

The canyon of the San Joaquin River (figs. 13–15) is neither among the deepest nor shallowest of the canyons in the west slope of the Sierra Nevada, but is in an intermediate class. It is not to be compared with the canyon of the Kings River, which attains the prodigious depth of 8,000 feet, nor with the canyons of the Tuolumne and Kern Rivers, which are between 4,000 and 5,000 feet deep. On the other hand, the San Joaquin Canyon is not to be classed with the trenches of the Feather, Yuba, American, Mokelumne, and Stanislaus Rivers, in the northern half of the range, which scarcely exceed 3,000 feet in depth. It falls, rather, in that middle class to which the Merced Canyon also belongs. The latter, though less than 3,000 feet deep in its lower course, reaches depths of 4,000 feet and locally, of 4,800 feet, in the Yosemite region.

The San Joaquin Canyon ranges for the most part between 3,000 and 4,000 feet in depth below the flanking uplands, but it exceeds 5,000 feet in depth, on the east side at least, for several miles in its middle course above and below the mouth of Big Creek. Its depth increases to 5,800 feet opposite the platform west of Huntington Lake, and a few miles farther up it reaches a maximum of 6,800 feet opposite the westernmost summit of Kaiser Ridge. On the west side, the nearest summit of the Chiquito Ridge rises 5,100 feet above the river, but the canyon side there is broken at a height of 2,200 feet above the river by a broad upland bench. Immediately above this deep portal between the Chiquito Ridge and the Kaiser Ridge the depth of the canyon again diminishes to an average of 3,000 feet, and that depth is maintained as far as the junction of the Middle and South Forks.

Of special geomorphologic significance is the fact that the San Joaquin Canyon has a distinct 2-story form throughout the greater part of its length (fig. 13). It has the appearance of a deep mountain valley of mature form with moderately steep, forested sides, in whose broad floor a narrow, sheer-walled inner gorge of approximately equal depth is cut. This 2-story aspect begins a short distance above the foothills, about

FIGURE 13.—View down San Joaquin Canyon from B.M. 4112 on road to Hogue Ranch. The railroad, barely discernable on the far side of the canyon (see arrow), follows a sloping bench (Pliocene surface) above the gorge (Pleistocene canyon), and a corresponding bench on the near side of the gorge appears in the lower part of the photograph.

FIGURE 14.—View in San Joaquin Canyon below mouth of Stevenson Creek, looking downstream. A few exfoliation shells cling to the massive granite walls. The white streak on the left is a streamlet that glides down the smoothly curving surface of the rock.

a mile above Auberry. There, a well-defined gently sloping bench, representing a strip of floor of the mountain valley, appears at a height of 1,200 feet above the river. This bench extends 15 miles along the east side of the canyon to the tributary canyon of Big Creek. It varies in width from a hundred yards to a mile, the average being well over a half mile. Uninterrupted by any deep-cut side gorges, it afforded an excellent location for the San Joaquin and Eastern narrow gage railroad which formerly led to Cascada Station (Big Creek Post Office).

The height of this bench above the canyon bottom increases progressively upvalley to 1,800 feet in the Jose Basin and to 2,200 feet just below the side canyon of Big Creek. The upland in turn rises fully 2,000 feet above the bench. Some of the mountains on the upland surface rise higher yet. Music Peak stands 2,800 feet above the bench; Mount Stevenson 3,000 feet.

On the west side of the canyon a similar bench begins near Oat Mountain, and thence extends up 16 miles to the hanging valley of Shakeflat Creek. It is more irregular than the bench on the east side, its surface being diversified by alternating spurs and shallow transecting valleys, yet its average height above the canyon bottom corresponds to that of the eastern bench and, like the latter, increases gradually upvalley. To the west, wooded slopes of moderate declivity rise 1,500 to 2,500 feet to the uneven surface of the upland. Neither of the two benches persists clearly defined all the way up to the junction of the Middle and South Forks. The eastern bench is but feebly developed above Big Creek, and the western bench is scarcely traceable above Shakeflat Creek. Nevertheless, most of the inner part of the canyon beyond these points is steeper sided and more gorgelike than the outer part.

The inner gorge [6] is narrowest and most conspicuously sheer walled in that part of the San Joaquin Canyon where the flanking benches are most prominent. Indeed, in the 5-mile stretch from Mill Creek to a point below the mouth of Big Creek (fig. 14) it is so constricted that in its natural state, before the road was built, the gorge was utterly impassable. Even the engineers who surveyed the course and profile of the San Joaquin River for the U. S. Geological Survey, although experienced in making their way up the rough, bouldery beds of mountain torrents, were balked by this exceedingly narrow portion of the San Joaquin's gorge, and were obliged to carry their line over the flanking benches. In several places, the walls of bare massive granite descend to the rock channel of the brawling stream with marvelously smooth convexly curved profiles that are steepest at the bottom.

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[6] In his field notes Matthes describes features that suggest that the inner gorge of the lower San Joaquin Canyon is a two-storied affair, but he does not incorporate this suggestion in the rough draft which formed the basis for this report. To put his observations on record, they are herewith quoted:

"Below the mouth of Big Creek, [San Joaquin Canyon is] narrow, V-shaped. River runs in rock cut channel. Granite prevailingly massive, exfoliating on large scale. Well-defined shoulders about 500-600 feet up. Apparently indicative of an old valley floor. These shoulders, however, are themselves about 1,000 feet below mouths of late-Pliocene hanging valleys. Lowermost part of shoulders prominent on west side of canyon, north of Italian Bar (2,100 feet). Also on south side, east of mouth of Mill Creek. Road built on this shoulder. Shoulders of corresponding height (about 400 feet above river) north of mouth of Big Creek. Would seem to indicate renewed tilting of Sierra late in Pleistocene. Farther down river these shoulders are not marked or [are] entirely absent for long stretches, for instance in stretch below Italian Bar, as far as mouth of North Fork. Still even in this stretch the slopes immediately adjacent to river bed are much steeper than higher up."

Equally impassable is the inner gorge for a stretch of 1½ miles above Ross Creek, and again for a distance of 4 miles below the junction of the Middle and South Forks. In the last named stretch (fig. 15) the walls, though relatively low, are exceptionally sheer and close together. They grow rapidly higher toward the junction, where they measure 1,400 feet and are continued in the still higher walls of the gorges of the Middle and South Forks, which gorges are of essentially the same, sheer-walled type. Viewed from any of the high surrounding mountains, these gorges all seem like great mysterious moats dug by cyclopean hands deep in the granite floors of the broad mountain valleys. The extraordinary aspect of the junction is further enhanced by Balloon Dome, the solitary monumental dome of smooth, bare granite 600 feet in height, which rises from the upland spur between the two tributary gorges.

Although impressive as a scenic feature, the inner gorge of the San Joaquin River is far surpassed in depth and grandeur by the gorge of the Middle Fork. That gorge, with its smooth walls of exfoliating granite 3,000 to 3,500 feet in height, streaked with silvery ribbon cascades that glide down from lofty hanging valleys, affords an unusually fine example of the massive type of cliff sculpture that finds its noblest expression in the Yosemite region. The gorge maintains its great depth and rugged grandeur for 15 miles, a distance of more than twice that of Yosemite Valley. As far as the vicinity of Fish Creek, it makes many turns that correspond to the crooked course of the river. Two to three miles broad from rim to rim, the gorge occupies practically the entire width of the canyon, there being little left of the outer mountain valley beyond its rims. Into it empty two great tributary gorges 2,000 to 2,500 feet in depth, the gorges of the North Fork and Fish Creek, with the result that a climax of imposing canyon topography is seen that is surpassed in but few other parts of the Sierra Nevada.

FIGURE 15.—View up gorge of the San Joaquin River toward Balloon Dome (altitude 6,900 feet), the great monolith which stands between the canyons of the Middle Fork and the South Fork at their juncture. The massive granitic rocks which here form the walls of the gorge are exfoliating in many places.

Above the mouth of Fish Creek, the canyon of the Middle Fork makes a right angle turn, and immediately beyond, it undergoes a radical change in form and aspect. Its walls flare apart, and a longitudinally ridged rock floor, a mile wide, spreads out between them. There is still an inner gorge cut in this rock floor, but it is a relatively small, subordinate feature. Northward this gorge becomes shallow rapidly, and in about 4 miles it comes to a head, one half of a mile below Rainbow Falls. Thence upward the canyon assumes the form, essentially, of a simple glacier trough with broad level floor and parallel spurless sides. It maintains depths, below the flanking uplands, which decrease from 1,500 feet to 1,000 feet a short distance from its head. The latter divides, the east branch leading steeply up to the Agnew Pass, the west branch to the outlet of Thousand Island Lake.

In the midst of this broadly open part of the canyon, which with its charming meadows and stately pine groves is the very antithesis of the constricted, forbidding gorge below, is situated the Devils Postpile. This mass of columnar basalt forms a solitary hump in the canyon, about 300 feet high and elongated along the axis of the valley of Middle Fork. This hump is the first of several such obstructions. For several miles above Pumice Flat, the broad trough shape of the canyon is hardly evident to one traveling through its depths because of the succession of rock ridges, 300 to 500 feet high, that occupy its floor. These ridges are composed not of basalt, but of metamorphic and granitic rocks. Between them are timbered flats and lush meadows, among which the Agnew Meadows are by far the largest.

In its upper course the canyon contracts to a V-shape, but otherwise it retains the aspect of a glacial canyon. Its sides are notably smooth, spurless, and parallel, and on the west side a series of hanging valleys containing rock-rimmed lakes and lakelets overlook the canyon at heights varying from 500 to 1,400 feet. This upper stretch of the canyon, which trends southeastward, parallel to the main divide of the Sierra Nevada, and the broadly trough-shaped stretch below, which has a southward trend, are both remarkable for their nearly straight courses. The river follows a sinuous path through the bottom, but the sides of the canyon in both of these stretches have but faint curvature, in contrast to the walls of the gorge below the elbow-bend at Lion Point.

Two tributaries of the Middle Fork of the San Joaquin River—the North Fork and Fish Creek—likewise have notable canyons. North Fork Canyon heads on the southeast face of Mount Lyell (13,090), at the extreme north end of the San Joaquin Basin, and between Electra Peak (12,462 feet) on the west and Mount Davis (12,308 feet) on the east. It extends southward along the west base of the great Ritter Range, though gradually diverging westward from it. North Fork Canyon is troughlike throughout, its west walls rising 1,500 to 2,500 feet to irregular, glaciated uplands, and its east walls, which are continuous with the slopes of the Ritter Range, rising to impressive heights of 5,000 feet or more in the Minarets and neighboring summits. The southerly course of the North Fork Canyon is zigzag, rather than direct, reflecting similar irregularities in its river, whose course has short southwestward sections alternating with longer southeastward ones. Glacial modification of North Fork Canyon is evident not only in its cross section, which is typically U-shaped, but also in the rounding of its many bends. The canyon is, therefore, better described as sinuous than as sharply angular. On the east, many short, straight tributaries descend steeply from the west slope of the Ritter Range; and on the west longer tributaries, with less steep gradients, enter the North Fork through prevailing southeastward courses.

Fish Creek Canyon, which trends northwestward for the most part, parallel to the adjacent main crest of the range, differs from the North Fork Canyon in being remarkably straight and spurless. Its floor lies 2,500 to 3,000 feet below the glacially scoured uplands to the west, and 4,000 feet below high points on Mammoth Crest, to the east. The 3½-mile section above its junction with Middle Fork is a steep-walled, narrow gorge; farther upstream, the canyon opens and becomes broad-floored, particularly beginning at the 7,800 foot level. In its upper part the valley has the aspect of a troughlike glaciated canyon, and its many small tributaries have scores of alpine lakes in their upper reaches and cirques.

The South Fork of the San Joaquin approaches its junction with the Middle Fork through a sheer-walled gorge that is even narrower than that of the Middle Fork and impassable so far as is known to the author. It attains a maximum depth of 2,200 feet opposite Balloon Dome and thence it shallows headward very rapidly, so that in a distance of about 10 miles it is reduced to an insignificant trench a few hundred feet in depth (fig. 16). As a consequence, the gorge of the South Fork is not comparable in scenic grandeur to the gorge of the Middle Fork. It has instead the aspect of a mysterious cleft or abyss in whose depths the river is all but hidden from view.

The South Fork makes an extremely rapid descent in this gorge. It falls 2,300 feet in 12 miles—that is, nearly 200 feet to the mile on an average. Actually the descent is largely concentrated in the lower third of the gorge, the fall there being 1,250 feet in 4 miles. The steepest stretch is but a short distance above the junction; the stream there descends about 400 feet in 1 mile.

The head of the gorge is ill defined. About 14 miles above the junction, near the mouth of Rattlesnake Creek, the gorge is still 500 feet deep, and for several miles farther upstream it continues as a shallow furrow in the floor of the broad mountain valley of the South Fork. That mountain valley is, in comparison even with the deeper and wider parts of the gorge, of immense size. Throughout the first 12 miles above the junction it is 4 to 5 miles wide, measured from the base of the mountains on one side to the base of the mountains on the other. It is not level floored, however. The bases of the mountains just referred to are 1,000 feet above the edges of the central gorge. The flanking peaks on the south side rise 4,000 feet above the valley, those on the north side from 4,500 to 5,000 feet.

FIGURE 16.—View southeastward from end of ridge north of Hoffman Meadow, looking up the shallowing, upper section of the Pleistocene canyon of the South Fork of the San Joaquin River. On either side of the canyon are remnants of the broad Pliocene valley.

The conditions along the South Fork are exactly the reverse from those along the Middle Fork. On the latter the inner gorge widens at the expense of the outer valley and attains imposing dimensions; on the South Fork the inner gorge dwindles to a mere furrow and the outer valley is the dominant feature.

Headward the great mountain valley of the South Fork contracts by degrees, at the same time assuming more and more the form of a simple U-shaped glacial trough with parallel, spurless sides. However, its floor is level only in places, being obstructed at intervals, like the floor of the upper Middle Fork Canyon, by knobs and ridges of resistant rock. Such is the case notably above the junction of Mono Creek, where a ridge 600 feet high and a multitude of lesser ridges and knobs, all of granite, make a curiously broken topography, extremely rugged on a small scale and correspondingly difficult to traverse. The most conspicuous obstruction is a ridge of granite 1,000 feet high that separates Poison Meadow from Jackass Meadow. It is known as the Jackass Dike although it is not a dike at all in the geologic sense. This ridge stands directly in the axis of the valley, forcing the river to make an eastward detour. Of unusual interest is the ridge of smooth, almost flawless massive granite between 100 and 200 feet high that projects squarely across the valley floor just below Florence Lake, leaving a small gateway through which the river can pass.

In the vicinity of Florence Lake the U-shape and the glacial aspect of the valley become pronounced and unmistakable. Upland shoulders develop on both sides, thereby delimiting the U-shape more sharply; and associated with these shoulders are many small hanging valleys nearly all of which contain typical glacial tarns. At the Blaney Meadows the U-shaped trough is still further accentuated by the presence of lateral moraines that extend like continuous embankments along the upland shoulders. These shoulders stand about 2,300 feet above the valley floor, and the adjoining peaks rise 3,500 to 4,600 feet about it.

Above the Blaney Meadows the trough narrows, so that there is room for only a few strips of bottom land along the stream, making the term canyon more appropriate than the term valley. Each of the three head branches of the South Fork Canyon—Goddard Canyon, Evolution Valley, and Piute Canyon—is of the same general type. All are narrow troughs with smooth, spurless, parallel sides; and all have, like the upper course of the Middle Fork Canyon, nearly straight or at best gently curving courses. Sharp bends and strong windings such as characterize the main canyon of the San Joaquin River are conspicuously absent from them.

Goddard Canyon, which is the pathway of the main headwater branch of the South Fork, is the most nearly straight of the three. It maintains a depth of about 2,000 feet below the upland shoulders to within a mile of its head, where the floor rises abruptly to the level of the upland and terminates in a beautiful amphitheater containing Martha Lake, a nearly circular lake three quarters of a mile in diameter. Throughout its extent, Goddard Canyon is flanked by peaks that rise from 3,000 to 3,500 feet above its floor.

Evolution Valley, which hangs 600 feet above the main valley (fig. 17), is correspondingly less deep below its upland shoulders. These shoulders, moreover, are much broader than those of Goddard Canyon —so broad that they constitute platforms from which the flanking peaks rise as separate entities, far removed from the central trough (fig. 20). As a result the valley as a whole has a widely open aspect which, together with the breadth of its floor and the presence of several natural meadows, justifies the appellation of "valley" rather than of "canyon," although the total depth below the flanking peaks is fully as great as that of Goddard Canyon.

Evolution Valley comes to a head abruptly in a small cirque to the east of the majestic peak named The Hermit; but this valley head does not mark the extreme limit of the hydrographic basin of Evolution Creek. The basin extends 5 miles farther to the southeast at a higher level, the true head being at Muir Pass, beyond which are the sources of the Middle Fork of the Kings River. Evolution Creek drops into the head of Evolution Valley by a spectacular cascade 1,000 feet in height. It spills from the lip of an upland valley of rare scenic beauty that contains a series of vividly colored, gemlike lakes, and is guarded by a group of imposing alpine peaks—the Evolution group, which is dominated by Mount Darwin, 13,841 feet in altitude. This remarkable upland valley has come to be known as Evolution Basin (fig. 23). It is a noteworthy fact that, although it forms an upper story, so to speak, to Evolution Valley, and has its lip at an altitude of 10,990 feet, it still lies 2,850 feet below the flat summit of Mount Darwin.

Piute Canyon differs from the two canyons just described mainly in that it splits into two forks extending almost at right angles to each other. Both forks, however, consist of typical smooth-sided and nearly straight troughs, flanked by broad upland shoulders. The northeast fork, known as French Canyon, heads in a shallow amphitheater below Pine Creek Pass; the southeast fork similarly heads in a shallow amphitheater below Piute Pass. These passes have altitudes of 11,000 and 11,400 feet respectively.

FIGURE 17.—View from valley of the South Fork of the San Joaquin River looking eastward at the mouth of Evolution Valley, which hangs 600 feet above the floor of the main valley. Photograph by G. K. Gilbert.

The uplands flanking these troughs attain remarkable breadth in some places and are covered by many lakes and tarns. No less than 9 good-sized lakes and 12 small tarns lie on the upland to the east of French Canyon; 5 lakes and several tarns lie on the upland to the west of it, and 1 lake and several tarns lie at its head. The upland to the north of the southeast fork, which is known as Humphreys Basin, comprises 10 square miles of area and contains a dozen lakes and many tarns. Its central feature is a lake over 1 mile in length, well named Desolation Lake.

Two other canyons are tributary to the South Fork, namely, the canyons of Bear Creek and Mono Creek. Both are essentially of the trough type and have distinctly U-shaped cross sections; both have upland shoulders in their lower courses, but are almost devoid of such features in their upper courses. Both are 3,000 to 4,000 feet deep below the flanking peaks.

#### HANGING VALLEYS

In describing the San Joaquin Canyon and its main branches, cursory mention has been made of hanging valleys that debouch into the canyons. These hanging valleys are a characteristic feature of the basin, and, compared to the other basins of the west slope of the Sierra Nevada, they are unusually numerous. Indeed, so few of the lesser tributary valleys of the San Joaquin River and its main branches are continuously graded down to the level of the master stream throughout their length, that it may be said that hanging valleys are the rule rather than the exception. Though the basin lacks the many spectacular waterfalls that distinguish the Yosemite region, it does possess an array of cascades that pour from the mouths of the hanging valleys (figs. 18, 19).

Of special note is the fact that the hanging valleys are found not only in the glaciated upper course of the canyon but also throughout the unglaciated lower course—in fact, into the foothills zone, within a few miles of the mouth of the canyon. Indeed, the hanging valleys are most numerous in this lower section, and here also are found some of the best preserved examples.

The hanging valleys are as a rule, of moderate depth, broad, and of gentle gradient—that is, they are mature or even postmature in form. Several terminate abruptly at the brinks of the canyons, with lips as yet

FIGURE 18.—Falls of Stevenson Creek on east side of San Joaquin Canyon. Exfoliation shells are evident in the massive granitic rock which holds up this hanging tributary valley.

FIGURE 19.—Big Creek Cascade, viewed from vicinity of Cascada Station below Huntington Lake. Kerckhoff Dome (not labeled on topographic map) in background. Photograph by R. A. Parker.

scarcely notched, so that their waters tumble from them in spectacular cascades; others are trenched by incipient gulches for short distances from their mouths; still others are so trenched for distances of several miles, but even these have untrenched upper courses long enough to show unmistakably that they belong to a family of mature valleys graded to a former higher level of the master stream.

As became clear in the field, and is evident also from the topographic map, most of the hanging valleys appear to fall into two distinct sets, or tiers. Those of the lower set are associated with the benches and shoulders which flank the San Joaquin Canyon. Those of the upper set form part of the billowy topography of the upland surface.

The hanging valleys of the lower set are more numerous, and, generally speaking, are better preserved. Some are remarkably clean-cut, being as yet almost unnotched, and the waters that issue from them cascade and glide down the walls of the inner gorge still unrecessed. This is notably the case in the 6-mile section of the San Joaquin Canyon above the mouth of Italian Creek, wherein the shoulders and benches are most strongly developed and the inner gorge is narrow and steep sided.

Though the hanging valleys of the lower set terminate above the canyon floors at different heights, they nevertheless vary within certain limits and according to a significant pattern. Their heights are least in the foothills and increase upstream, as the following examples show. The valley of Fine Gold Creek has a profile showing a discordance, with reference to the floor of San Joaquin Canyon, of about 400 feet; Big Sandy Creek, 7 miles farther upstream, has a somewhat greater discordance. About 15 miles above the mouth of Big Sandy Creek, Backbone Creek and Bald Mill Creek hang about 1,100 and 1,200 feet respectively. Still farther upstream are several valleys, mostly on the west side, clearly related to the flanking benches and shoulders of the canyon, which hang above the canyon floor at closely accordant heights ranging, for the most part, from 1,400 to 1,700 feet, generally close to 1,600 feet. Representative of this group are the hanging valleys of Saginaw Creek, Italian Creek, Hookers Creek, Clearwater Creek, Ross Creek, Fish Creek, and Shakeflat Creek. Shakeflat Creek is just within the glaciated area.

Big Creek, in leaving the upland at Huntington Lake at close to 7,000 feet, descends steeply about 4,850 feet through narrow Big Creek Canyon to reach the San Joaquin River (fig. 19). Its branch, Pitman Creek-Tamarack Creek, similarly leaves a broad open valley on the uplands south of Chinese Peak at about 7,000 feet, and descends about 4,900 feet to the San Joaquin River. These hanging valleys are representative of the upper tier.

In the lower, unglaciated section of the San Joaquin Canyon a few streams are noteworthy in that they first cascade from lofty upland valleys into the outer canyon of the San Joaquin River, and then, some 2,000 feet lower, they plunge abruptly from a well-defined bench into the narrow inner gorge. These streams are hanging with reference to both the upland and the flanking benches. The most conspicuous example is Stevenson Creek, which descends in a brawling cascade from a broad, shallow upland valley lying at about 5,100 feet, now partly drowned by Shaver Lake; and then, from a bench at about 3,400 feet, it makes a second descent, with a steep drop of about 1,600 feet, into the inner gorge of the San Joaquin River (fig. 18). The situation in the case of Jose Creek is somewhat similar. Four branches of this stream (the longest ones heading about a mile above Ockenden) cascade from shallow vales on the gently undulating plateau known locally as Pine Ridge, leaving its edge at an altitude of about 5,400 feet; and then, after uniting into a single stream and flowing several miles on a relatively gentle gradient, at an altitude of 2,900 feet the waters again cascade wildly from the lip of the Jose Basin, making a descent of about 1,500 feet to the bottom of the inner gorge.

Farther up the San Joaquin Canyon, within the outermost glaciated section, where flanking benches and shoulders are feebly represented or lacking, most of the hanging valleys are part of the upland surface and therefore are referable to the upper set. Such is the case with the valleys of both Rock Creek and Jackass Creek. The latter, for example, leaves a mature valley on the uplands and descends steeply about 2,900 feet to join the San Joaquin River.

Along the Middle Fork are numerous hanging valleys, most of which also belong to the upper set. Granite Creek tumbles into the Middle Fork from the fairly clean-cut lip of a hanging valley about 2,400 feet high. Stairway Creek, like Stevenson and Jose Creeks, has headwaters that descend steeply from upland valleys, and in its lower course it leaps from the unnotched lip of a hanging valley about 1,900 feet high. Directly opposite Stairway Creek, a streamlet cascades down about 2,300 feet from the brow of Junction Bluffs; and east of Lion Point another streamlet makes a precipitous descent of 2,600 feet from the edge of the upland. Crater Creek leaves its shallow upland valley at 8,600 feet and makes a steep descent of 2,600 feet to join the Middle Fork; the last 700 feet of this descent is made as it drops into the head of the inner gorge. Farther up the Middle Fork, the height of the hanging valleys decreases by degrees, as the upper valley becomes shallower. Shadow Creek makes a descent of only 500 feet, and the streamlet that issues from Garnet Lake drops only 600 feet.

In the lower South Fork one finds only a few hanging valleys of notable height. The streamlet which drains Cow Meadow hangs over 2,000 feet; Hoffman Creek falls about 1,800 feet from its upland vale; and Rube Creek makes a plunge of 1,500 feet. Farther up, the discordances diminish rapidly as the South Fork gorge shallows headward. Four Forks Creek and Rock Creek first cascade from upland valleys, and then in their lower courses they descend steeply about 1,000 feet to join the South Fork. A few miles farther upstream, Rattlesnake Creek cascades from a valley only 500 feet high. Beyond this point new forms of topography appear; the broad upper valley of the South Fork, as it gradually contracts to a U-shaped glacial trough, possesses a set of lofty hanging side valleys.

#### INTERCANYON UPLANDS

The great canyons of the San Joaquin River and its main branches are deeply trenched in the plateau-like uplands distinctive of the basin. These uplands are extensive in the central part of the basin, which in this respect is typical of the middle slope of the Sierra farther north. The uplands that flank the Yosemite Valley on both sides are of this general type, and so are the uplands on both sides of the Hetch Hetchy Valley and adjoining stretches of the Tuolumne Canyon. Lindgren (1911, p. 37–38) has noted the prevailingly plateaulike character of the middle slope still farther north in the range. In the southern Sierra Nevada, also, in the drainage basins of the Kings, Kaweah, and Kern Rivers, there are similar areas on the middle slope.

In the San Joaquin Basin, the uplands form extensive plateaulike areas, commonly several miles wide, mostly at altitudes of 7,000 to 8,000 feet and having an aggregate area of about 100 square miles. They are readily traced westward and decline in altitude to 5,000 or even 4,000 feet at their western margins within a few miles of the foothills, where they break off in declivities of 2,000 feet or more. Traced eastward, the uplands become higher and, for the most part, smaller and less continuous. Nevertheless they are recognizable as distinctive benches, shoulders, and other areas of undulatory surface which extend to the base of the High Sierra crests, at altitudes of 9,000 feet or higher.

Where most typical, as on the middle and lower slopes of the Sierra, the uplands are not strictly flat, but undulating, with a relief generally less than 500 feet and only exceptionally 1,000 feet. The valleys on the upland, where transected by the canyons of the San Joaquin River and its branches, are abruptly cut off and left hanging, or descend with greatly steepened gradient, as described in the foregoing section. The uplands bear many broad, grassy meadows (figs. 47, 48), which from their topographic situation and considerable extent obviously belong in a different category from the generally more restricted meadows which in places occupy the canyon floors (fig. 44).

The somewhat monotonous aspect of the uplands, resulting from the approximate concordance of their billowy timbered ridges, is relieved by scattered eminences that stand above their general level. These include isolated knobs and mountain groups, a few hundred feet high, common in the central part of the basin, and lofty ridges—actually mountain ranges several thousand feet high—especially characteristic of the upper part of the basin.

Some representative upland areas will be described its main branches are deeply trenched in the plateau-of the San Joaquin Basin. Uplands slope southward and southeastward from the Chiquito Ridge and Kaiser Ridge and have hills and scattered knobs which range from a few hundred feet to as much as 1,000 feet in height. These eminences have no definite trend, but many of the shallow upland valleys parallel the crests of the High Sierra. The uplands in this section, as well as elsewhere in the basin, have many bright green meadows in some of the broadly open valleys, interrupting the somber green mantle of coniferous forests that otherwise extends uniformly over the entire area. It is noteworthy that most of the uplands in this area were never overridden and modified by ice, even in the more extensive earlier glacial stage. (See glacial map, pl. 1.)

The lower San Joaquin Canyon, which bisects this area from northeast to southwest, separates the uplands adjoining Chiquito Ridge from those adjoining Kaiser Ridge. The uplands west of the canyon begin, at the base of Chiquito Ridge, at about 7,000 feet, and extend southwestward 5 to 10 miles; then, at 5,500 feet, they terminate in an abrupt escarpment 1,500 to over 2,500 feet high. This escarpment, named South Fork Bluffs at the north, runs south-southeastward in a remarkably straight line as far as the San Joaquin River.

The uplands east of the canyon slope southwestward from altitudes of more than 9,000 feet at the head of Big Creek, to 4,500 feet on Bald Mountain, northeast of Big Sandy Valley. They thus decline 4,500 feet in a distance of 25 miles, or at a mean rate of 180 feet to the mile. Southward and southeastward the plateau country extends without significant break into the drainage basin of the Kings River.

Particularly noteworthy is the fact that the upland on Bald Mountain reaches within a few miles of the foothills, where it breaks off first in slopes of moderate declivity, then in a precipitous escarpment known as the Big Sandy Bluffs, the total drop being between 2,000 and 2,500 feet. It is up through a recess in this escarpment that the celebrated "tollhouse grade" of the road from Tollhouse to Shaver Lake reaches the upland. To the southeast of the tollhouse grade the escarpment is continued by the steep front of the flat-topped ridge known as Burro (Burrough) Mountain. The general trend of the escarpment is southeastward, and associated with it is a linear ridge, named Backbone Mountain, that trends in approximately the same direction.

North and northeast of Chiquito Ridge are other upland areas of essentially similar configuration, lying, for the most part, at altitudes of 6,000 to more than

7,000 feet. Such are the Beasore and Mugler Meadows, in the headwaters of Chiquito Creek; and the various meadows in the area drained by the middle courses of Jackass Creek and Granite Creek. In the basin of Jackass Creek, where the many natural meadows afford summer pasturage for large herds of cattle, resistant rocks form residual knobs such as Jackass Rock, Squaw Dome, and Cattle Mountain, which stand 600 to 900 feet above the undulatory upland (fig. 6).

Another upland tract occupies the triangle isolated by Kaiser Ridge on the south, the San Joaquin Canyon on the northwest, and the South Fork Canyon on the northeast. It slopes from a maximum altitude of 7,500 feet along the northeast edge to about 6,000 feet at the southwest corner. This tract includes Cow Meadow and Hoffman Meadow, and from it rises Mount Tom, almost 2,000 feet high.

Farther to the north and northeast, upland tracts border the North Fork Canyon and, especially, the Middle Fork Canyon. For example, on the southeast side of Middle Fork Canyon a billowy tract at 7,500 to 9,000 feet extends southward from Junction Bluffs. Across the canyon, a similar tract slopes southward from 9,000 feet at the Granite Stairway to 8,500 feet at Lion Point. Also, there is a significant upland stretching, with undulatory surface, from 8,700 feet at the north edge of Fish Valley to more than 9,000 feet at the base of Mammoth Crest and Mammoth Mountain. Both Mammoth Pass, altitude 9,300 feet, and Minaret Pass, altitude 9,200 feet, are at the general level of this upland surface and form part of it.

Other upland tracts are found in the areas drained by the South Fork and its tributaries. Those within the arc formed by the South Fork and Mono Creek include Onion Spring Meadow, Warm Creek Meadow, and other meadows lying, for the most part, at 7,000 to 8,000 feet. Along the principal valleys tributary to the South Fork, remnants of the upland surface form marginal benches and shoulders. In some places, as along Mono Creek Canyon and Evolution Valley, these features are remarkably regular and continuous (figs. 20, 21). In most places they undoubtedly have been more or less modified by glacial erosion. At the headwaters of Big Creek, in the Black Mountains-Hot Springs Pass area, upland tracts give rise to a number of extensive meadows, such as Long Meadow (figs. 47, 48) and Rock Meadow.

Finally it should be noted that many of the valley heads at 9,000 feet or higher that indent the mountain ridges of the High Sierra are probably the erosional equivalents of the upland surfaces so extensively and well preserved at lower altitudes. This is indicated by their appropriate situation, altitude, and configuration,

FIGURE 20.—View down Evolution Valley from high rock sill west of Evolution Lake. Upland benches, remnants of the Miocene erosion surface, extend almost continuously along both sides of the U-shaped trough, which is a Pliocene valley modified by glaciation.

and is evident despite the fact that they have been resculptured in varying degrees into capacious, flat-floored cirques through intense and repeated glacial erosion. In this category may be placed the cirque basin of Thousand Island Lake (altitude 9,850 feet) at the head of the South Fork (fig. 38), the uppermost reaches of Fish Valley (the 5-mile section lying above 9,000 feet), and Evolution Basin (the 6-mile stretch above 11,000 feet, leading to Muir Pass), and probably many other cirques such as the Pioneer Basin at the head of Mono Creek and the expansive Humphreys Basin between the forks of Piute Creek.

#### LONGITUDINAL AND TRANSVERSE CRESTS

It might be anticipated that on the back slope of a tilted block range like the Sierra Nevada, furrowed as it is by deep transverse canyons, one would find a preponderance of transverse crests. Yet in the higher parts of the San Joaquin Basin, as also in those of the Tuolumne and Merced basins and many other sections of the Sierra Nevada, subsidiary crests trending northwest-southeast, parallel to the axis of the range, greatly predominate. Indeed, such longitudinal crests are characteristic features of the upper part of the range, adding greatly, by their bold sculpture, to the scenic beauty of that alpine region, which has come to be known as the High Sierra. But nowhere in the range are longitudinal crests more numerous, more continuous, and more closely spaced than in the upper part of the San Joaquin Basin. Rising 2,000 to 3,000 feet above the plateaulike uplands, and 4,000 to 5,000 feet above the floors of adjacent canyons, they stand high enough to be considered mountain ranges. A number of the crests, as will be noted below, do not lie entirely within the San Joaquin Basin, but extend far

FIGURE 21.—Well-preserved bench, a remnant of the Miocene erosion surface, on the south side of Evolution Valley. The cascade descends from the mouth of a hanging valley.

FIGURE 22.—View southeastward along Glacier Divide, showing marked asymmetry of crestline resulting from more intense glaciation on the northerly slopes of this ridge. The northerly slopes bear a number of small glaciers, two of which show in this view.

beyond its limits. The presence of the longitudinal crests accounts also for the preponderance of longitudinal stream courses among the tributaries of the San Joaquin River.

One of the most noteworthy of the longitudinal crests is the Ritter Range in the northern part of the San Joaquin Basin. Its summits range from 11,000 to over 13,000 feet in altitude, including Mount Lyell (13,090 feet), Banner Peak (12,957 feet), Mount Ritter (13,156 feet), and the Minarets, that imposing group of summits which Californian mountaineers have aptly styled "the king and queen of the Sierras [7] and their retinue." The Ritter Range, exceptional in that it greatly overtops the drainage divide of the Sierra Nevada, about 6 miles to the east (see fig. 4), extends from Mount Lyell on the northwest to Iron Mountain on the southeast, a distance of 12 miles; but as will be clear from the topographic map, it is continuous northwestward with the Cathedral Range, which divides the upper Merced and Tuolumne Basins and which is also 12 miles in length. The two ranges, therefore, form a continuous crest whose aggregate length is 24 miles.

The Glacier Divide (fig. 22), in the southeast part of the San Joaquin Basin, is appropriately named for the many small ice bodies that cling to its shady and precipitous northeast flank. It is only 6 miles long, but as will be evident from the topographic map, it forms a northwestward extension of the sinuous crest that constitutes the main divide of the Sierra Nevada at the head of Evolution Creek (fig. 23). This crest continues southeastward far beyond the limits of the San Joaquin Basin and, as may be seen on the Bishop and Mount Whitney quadrangles, extends without significant break around the heads of the Kings and Kern Rivers. It has a total length, including the Glacier Divide, of 76 miles, and bears no less than 90 peaks ranging from 12,000 to over 14,000 feet in altitude, including Mount Whitney (14,496 feet), the culminating summit of the Sierra Nevada.

Noteworthy also is a series of alined crests farther to the west, whose principal units within the San Joaquin Basin are Chiquito Ridge, Kaiser Ridge, and the LeConte Divide.

Chiquito Ridge (fig. 8) is the crest lying west of the San Joaquin Canyon. It controls the southeastward courses of Chiquito Creek and its West Fork. This ridge, more than 10 miles in length, trends northwestward to the border of the San Joaquin Basin and continues within the Merced Basin as far as Mount Raymond, on whose west spur stands the Mariposa Grove of Big Trees. Its total length, thus measured, is 14 miles. Its summits rise a little above 8,000 feet in altitude, yet they stand 3,000 to 4,000 feet above the valleys of Chiquito Creek and its West Fork.

South of the San Joaquin Canyon is Kaiser Ridge, the great crest that controls the course of the South Fork of the San Joaquin River and walls off the High Sierra portion of the basin. A western segment of Kaiser Ridge (termed Kaiser Crest on some maps) rises to the north of Huntington Lake (fig. 24). Another segment continues the crest to the east of Kaiser Pass. Together the two segments form an arcuate ridge 19 miles long, bearing first toward the east, then east-southeast, and finally south toward the Hot Spring Pass. The principal summits on this divide

[7] The popular use of the plural form Sierras, though it may seem inconsistent with the singular form of the name Sierra Nevada and High Sierra, is nevertheless fully justified by the multiplicity of serrate crests in the higher parts of the range. The term Sierra Nevada Mountains, on the other hand, is not tolerated in California, it being manifestly tautological.

FIGURE 23.—Panorama looking southward from granite hill near outlet of Evolution Lake (altitude 10,990 feet). At the left is the flank of the sharp-crested ridge bearing Mount Darwin and Mount Wallace. The conical peak in the center is Mount Spenser. At the right is a glaciated ridge that separates Evolution Basin from the head of Evolution Valley below.

exceed 10,000 feet in altitude and stand 4,000 feet above the valley of the South Fork.

From Hot Spring Pass, a sinuous mountain rampart runs eastward with increasing elevations to Mount Henry (altitude 12,197 feet), where it joins the LeConte Divide. The latter, a spectacular crest bearing a row of 12,000-foot peaks, extends in a straight line 9 miles southeastward to Mount Reinstein (altitude 12,595 feet), at the extreme southeastern corner of the basin. The crest continues southeastward 8 miles farther, into the Kings River Basin, where it is known as the White Divide.

This succession of crests, from Mount Raymond at the north to the south end of the White Divide, has an overall length of more than 60 miles, and two-thirds of this length lies athwart the San Joaquin Basin. Though the line of crests shows many irregularities of trend, as might be expected in view of its great length, the northwestern direction nevertheless predominates.

FIGURE 24.—View southeast across Twin Lakes. The cirque wall in the background is cut into Kaiser Ridge, only the north side of which was effectively eroded by the ice in the later glaciation. The near shore and the low cliffs on the right are composed of white crystalline limestone; the island and the far shore are composed of granite.

There are other northwestward-trending crests in the San Joaquin Basin, but none are comparable in length and continuity to those described. A nameless crest between the South Fork of Bear Creek and the South Fork of the San Joaquin River, bearing Mount Senger and Mount Hooper, is 9 miles long. Another nameless crest between Goddard Canyon and Evolution Creek, bearing Mount McGee (fig. 25) and Emerald Peak, is only 6 miles long, but if its continuation in the Kings River Basin, here called the Black Divide, be added to this length the entire length is 15 miles. About 10 miles southwest of the Ritter Range is a crest bearing Madera, Gale, and Sing Peaks; and northwestward from Triple Divide Peak, where it enters the Merced Basin, this crest is continued in the much more impressive Clark Range. The over-all length of this crest is also about 15 miles.

FIGURE 25.—Section of a High Sierra crest: the Mount McGee group of summits and the cirques at the head of McGee Creek, viewed from a point south of Evolution Valley.

As compared with the prominent and persistent longitudinal ridges which have been described, the transverse crests are not only fewer but of subordinate importance in the configuration of the San Joaquin Basin. One of these, the Goddard Divide (fig. 26), follows part of the southeast edge of the basin, where it separates the headwaters of the South Fork of the San Joaquin River from those of the Middle Fork of the Kings River. From Mount Wallace on the main Sierra crest, this divide trends southwestward to Mount Reinstein on the LeConte Divide, linking the two crests, which here are only 7 miles apart. Noteworthy features of the Goddard Divide are Mount Goddard (altitude 13,555 feet) and Muir Pass, by which the John Muir Trail enters the basin of the Middle Fork

FIGURE 26.—View from base of Red Mountain, looking up Goddard Canyon to Goddard Divide and, at left, Mount Goddard (altitude 13,555 feet). Photograph by G. K. Gilbert.

of the Kings River. At the north edge of the San Joaquin Basin, a nameless transverse crest straggles along the 11-mile interval between Mount Lyell and Triple Divide Peak, separating the headwaters of the North Fork of the San Joaquin Basin from those of the Merced Basin.

A few minor crests form curves or hooks. The most prominent examples are the Silver Divide, about 10 miles long, and the Mono Divide, 7 miles long, both in the High Sierra region between the South and Middle Forks. Both branch off from the main Sierra crest in southwestern directions but gradually curve around to the northwest.

### TABULAR SUMMITS

Most ridges in the High Sierra part of the San Joaquin Basin have splintered crests or sharp summits due to the widening of adjacent valleys and the enlargement of cirques by glacial action. However, there are at least two summits in this basin which, like a number of other peaks in parts of the Sierra Nevada (Matthes, 1933a, p. 34–35; 1933c; 1937a, p. 8–9) have tabular summits. These peaks, Mount Darwin and Mount Wallace (fig. 27), are both on the main crest of the range, near the southeast corner of the basin. Mount Darwin has two detached summit platforms, 13,841 feet and 13,701 feet in altitude, respectively, which stand nearly 3,000 feet above the level of the adjacent Evolution Basin. Mount Wallace has a summit platform at an altitude of 13,328 feet.

These tabular summits were preserved because the preglacial Mount Darwin and Mount Wallace were full-bodied mountains, broad enough so that—though trimmed back by the erosional effects of glaciers heading on their slopes—they nevertheless were not reduced to attenuated points, like the neighboring peaks. The flat summits that remain, appear to have escaped glaciation altogether and exhibit only the smoothing effect of long-continued nivation and concomitant solifluction.[8]

FIGURE 27.—View from John Muir Trail in Evolution Basin: Mount Darwin at left, Mount Wallace at right. These two mountains have nearly level summits that are remnants of an ancient erosion surface. The level to which the ice rose in Evolution Basin is indicated by the upper limit of corrasion. Above this level the cliffs are deeply riven by frost and gullied by snow avalanches.

### MAIN DRAINAGE DIVIDE

The main drainage divide of the Sierra Nevada at the head of the San Joaquin Basin is of unusual interest. It does not follow the same northwestern crest throughout its length, but is in places offset abruptly from one crest to another. Thus at the Piute Pass the divide is offset sharply northeastward to the crest which bears Mount Humphreys. Six miles farther, at the northwestern end of that crest, the divide again is sharply offset to the southwest, across the Pine Creek Pass. Thence the divide pursues a winding course along alternate northwestern and northeastern crests, as far as Mount Stanford, at the head of Mono Creek. There it turns abruptly southwestward along the crest which, farther to the southwest, bears the name Silver Divide. At Red and White Mountain, it finally resumes a northwestward course, and this it maintains for a distance of 27 miles to Agnew Pass at the northern corner of the San Joaquin Basin. The divide makes many minor turns and windings, especially in the stretch southeast of the Mammoth Pass, but these are due largely to deeply inset glacial cirques.

Throughout the greater part of its extent, the divide at the head of the San Joaquin Basin has a strongly serrate skyline marked by a long succession of jagged peaks. Even the Piute and Pine Creek Passes are scarcely deep enough to mar the general sawtooth effect. But at the Mammoth Pass, the divide abruptly loses its spectacular aspect and, dipping from altitudes of over 11,000 feet to a level of 9,300 feet, assumes a subdued and relatively monotonous appearance. Mammoth Mountain, it is true, again lifts the divide for a space above the 11,000-foot level, but beyond that mountain the divide again sags to about 9,200 feet in the low Minaret Pass. From this long sag it ascends by gentle slopes to the crest of the relatively smooth ridge that culminates in San Joaquin Mountain and terminates at the Agnew Pass.

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[8] These summits apparently were not visited by Matthes. They are probably very similar to the summit of Mount Whitney, which Matthes has described in detail (1937a, p. 16–18; 1950b, p. 83–89).

Just outside the San Joaquin Basin is another summit which may belong to the same category as Mount Wallace and Mount Darwin. This summit, not labeled on the topographic map, has been designated "Mono Mesa" by J. T. Howell, and is a granitic tableland with an altitude of 12,240 feet, located at the head of Mono Creek, 1 mile east of the intersection of Fresno, Mono, and Inyo Counties. Howell suggests that "it represents what is probably California's oldest land surface that is unaltered by erosion."

Opposite the low sag at the Minaret Pass the valley lands to the east of the Sierra Nevada attain an unusually high level—about 8,000 feet above the sea—and as a consequence the eastern escarpment, which at Mount Humphreys stands 9,500 feet high, here dwindles to a mere 1,200 feet. The escarpment, in this its lowest stretch, is masked by great accumulations of pumice derived from nearby volcanoes, and so presents only an unimpressive slope of moderate declivity. As if to dwarf it completely into insignificance, the sky piercing summits of the Ritter Range (fig. 4) rise a few miles to the west.

#### RELATION OF MAIN DRAINAGE DIVIDE TO ESCARPMENT ON EAST SIDE OF RANGE

It is commonly stated, in brief generalized sketches of the Sierra Nevada, that the range consists essentially of one great crustal block tilted toward the southwest, with its northeastern edge elevated so as to form the crestline. That statement, which implies that the crestline, or main drainage divide, coincides with the top of the great east escarpment, is literally true for some parts of the range, but it does not hold good for many other parts, notably the part here under consideration.

To any one who traces in detail on the topographic map the course of the main drainage divide, or crestline, of the range around the headwaters of the San Joaquin River, it must be evident that as a geomorphic feature it is distinct and essentially independent from the escarpment. In some places the main divide lies many miles to the southwest of the escarpment. Indeed, throughout its total length of 70 miles at the head of the San Joaquin Basin the divide coincides with the top of the escarpment only in two short stretches: in the 3-mile section between Mount Humphreys and Mount Emerson, and on the top of Mammoth Mountain.

From the crest between Mount Humphreys and Mount Emerson the escarpment falls off steeply 5,000 feet to what is known as the Buttermilk Country. The Buttermilk Country is still between 3,000 and 4,500 feet above Owens Valley and separated from the latter by several miles of the jumbled Tungsten Hills; but these hills are only details of the much-faulted and fractured front of the range, and the fact remains that the main escarpment of undisturbed rock rises directly from the Buttermilk Country. Near Mount Emerson southward, the escarpment is abruptly offset 12 miles northeastward, and as a consequence to the southeast of Bishop Creek, a large triangular area of upland country intervenes between escarpment and main divide. It is thus evident that in this section the main drainage divide of the range is in no wise determined by the top of the escarpment, but is an ancient erosional divide that antedates the creation of the escarpment by tectonic movements.

Northward from Mount Humphreys, the main divide and the escarpment diverge. Basin Mountain and Mount Tom, which presumably indicate approximately the original brink of the escarpment, stand 1½ and 3 miles respectively to the northeast of the divide, attached to it by spurs that bear remnants of an unbroken surface corresponding in general altitude with the upland to the west of the divide. North of the canyon of Pine Creek, moreover, the distance between divide and escarpment increases abruptly, and another large upland area intervenes between them. This upland area attains a maximum breadth of 6 miles at the point where the escarpment makes a right-angle turn, from north-northeast to west-northwest. The configuration of the upland area is, like that of the upland to the southeast of Bishop Creek, essentially analogous to that of the High Sierra portion of the San Joaquin Basin, except that it drains northeastward instead of southwestward. The upland area just mentioned narrows westward and tapers to a point on Mammoth Mountain. Thence to the Agnew Pass the divide remains close to the top of the escarpment but it nevertheless does not coincide with the latter, being separated from it throughout by a narrow strip of gently sloping upland.

At Agnew Pass, the main divide finally deviates widely from the generally northwestward course of the main escarpment. It swings westward and southwestward to the Ritter Range, follows that range from Mount Davis to Mount Lyell, and returns to the escarpment by a northeasterly course, thus making a detour around the head of the Rush Creek Basin, which drains into Mono Lake. The maximum departure of the main divide from the escarpment, on Mount Lyell, is 8 miles. The Rush Creek Basin is not merely a canyon with branching headwater gulches cut into the escarpment, but an upland area of High Sierra aspect, and its central valley, though cut to considerable depth, hangs 1,800 feet above the foot of the escarpment at Reversed Creek.

From these facts it is clear that at the head of the San Joaquin Basin the main drainage divide of the Sierra Nevada bears no constant relation to the east escarpment of the range, but is, except at two points, an independent feature and one of wholly different origin.

#### INTERPRETATION OF GEOMORPHOLOGIC FEATURES

The geomorphologic features of the San Joaquin Basin closely resemble in their broad relationships those of the neighboring Yosemite region. However, as previously noted, they are distinguished by relative simplicity, being singularly free of those conditions which make Yosemite a special case and which complicate the records of other basins.

Briefly, the salient features may be summarized as follows: The San Joaquin Canyon is essentially a narrow, youthful gorge cut into the floor of a relatively broad, mature valley. This in turn is flanked by extensive undulating uplands surmounted by knobs and mountainous crests. At least one crest has peaks that bear distinctively tabular summits.

It is evident that these features are the products of four partial cycles of stream erosion, each initiated by a major uplift. At higher levels, erosional records have been obscured, as a result of repeated glaciation. The erosional records will be analyzed first, and in the next chapter the superimposed effects of glacial action will be considered. In general, it will be found advantageous in the present analysis, to work from the youngest to the oldest features of the landscape, and so far as possible to begin with the unglaciated lower part of the range, thence discussing the glacially modified higher parts to the east.

#### EROSION SURFACES

Expressive of the latest partial cycle of stream erosion are the narrow, V-shaped gorge or "inner canyon" of the San Joaquin River and its branches. These features are regarded as being entirely of Pleistocene origin. The youthfulness of the gorge, as shown by its narrow -shape and the steepness of its cliffy sides, is evident, and the fact that it is still being deepened and extended headward clearly shows that enough time has not elapsed since the last uplift took place to enable the stream to intrench itself deeply all the way to its sources. At the same time there are ample indications that most of the gorge cutting was done prior to the great extension of the El Portal glaciers. On the basis of these relationships, the Pleistocene gorge of the San Joaquin Canyon may be correlated with the "canyon stage" of the Yosemite region.

The benches and shoulders which flank the Pleistocene gorge in the lower and middle reaches of the basin, giving the San Joaquin Canyon a "two storied" aspect by reason of the "outer valley" which they produce, are remnants of a mature valley developed in a partial cycle of erosion that preceded the canyon stage. These remnants are best preserved in the 6-mile section between the mouth of Italian Creek and the mouth of Big Creek; farther upstream they are less continuous and distinct but nevertheless traceable; and in the main branches of the San Joaquin, above the heads of the gorges, they are continued by the actual upper valleys themselves,—here untrenched by streams but glacially deepened and remodeled to a greater or less extent into U-shaped troughs. The maturity of these valleys is indicated by their broadly flaring cross sections and their low, smooth gradients (deduced, in the case of the San Joaquin Canyon itself, from the extended gradients of the lateral valleys that were left hanging in the latest cycle of erosion). Evidently in this partial cycle of erosion the San Joaquin River extended its main branch valleys much farther headward than it has in the present (canyon) cycle—in fact almost to the crest of the range. The head of Middle Fork valley, for example, probably was then about 3 miles above Agnew Meadows; that of the South Fork at about the position of the present head of Evolution Valley. The maximum depth of the San Joaquin valley at this stage was in the vicinity of the mouth of Stevenson Creek, where it was cut about 1,800 feet below the uplands.

To have attained its mature character the valley must have required, considering the durable character of the rocks in which it was produced, a period several times—and probably not less than five times—as long as that which was required for the carving of the Pleistocene gorge. It may be inferred that the partial cycle of erosion in which the valley was developed embraced all, or nearly all, of the Pliocene epoch. Accordingly, the Pliocene valley of the San Joaquin River may be assigned to the "mountain valley stage" of the Yosemite region.

The undulating uplands into which the Pliocene valleys have been cut are erosion surfaces referable to a still earlier cycle. Remnants of this surface are extensive and well preserved, in spite of their antiquity, because they are developed on the prevailingly massive, and therefore obdurate, granitic rocks which underlie a great part of the basin. The remnants clearly indicate that the landscape produced in this cycle was one of late mature aspect, with a relief over wide areas of less than 1,000 feet. Locally, however, monadnocks—not only scattered hills and mountain groups but even ranges a dozen to a score of miles long, most of them trending in a northwestern direction—give it much greater relief, for example 1,500 feet in the vicinity of Shaver Lake and over 2,500 feet at the present crest of the Sierra Nevada.

In the High Sierra region, the uplands reached to the base of the monadnock ranges and occupied the intervals between them. The head of Middle Fork valley lay essentially where it now does, in the position of Thousand Island Lake; that of the South Fork valley, in Evolution Basin; and other principal valleys headed in comparable situations.

The forms of the uplands are so much more mature than those of the Pliocene valleys that there is good reason to assign for their development a correspondingly greater span of time. Furthermore, they are clearly correlative with the uplands of the Yosemite region—indeed, they are traceable across the divide and continuous with the uplands of that region. From evidence already set forth (see p. 23) it appears that the Yosemite uplands, representing the "broad valley stage," are of late Miocene age. Accordingly, the uplands of the San Joaquin Basin are also thought to have been produced in a cycle of erosion which began some time back in the Miocene and continued until the latter part of that epoch.

Finally, the tabular summits of Mount Darwin and Mount Wallace are, from the evidence of the great height to which these summits rise, much older than the Miocene uplands. These small but significant platforms are undoubtedly the remnants of a once extensive erosion surface, and they are clearly referable to that most ancient erosion surface recognizable in the region, of which traces survive on certain summits in the Yosemite region and elsewhere in the Sierra Nevada. This erosion surface is thought to be Eocene in age.

#### HANGING VALLEYS

The hanging lateral valleys of the San Joaquin Canyon and its main branches present one of the striking features of the basin. In the glaciated area, especially in Middle Fork Canyon, the question arises as to how much of the discordance of the hanging side valleys is due to glacial erosion and how much of it is due to stream erosion; but in the lower canyon where, below the limits of glaciation, the landforms are essentially all stream-sculptured, obviously glacial erosion may be ruled out as a complicating factor. It is here, in the 40-mile stretch of canyon beginning a few miles below the mouth of Chiquito Creek and extending to within a few miles of the foot of the range, that the hanging valleys are especially well developed and numerous.

The explanation is offered that the lateral valleys of the lower San Joaquin Canyon are hanging because their streams have been unable to keep pace with the accelerated trenching of the San Joaquin River following its rejuvenation by uptiltings of the Sierra Nevada. The disadvantage of the side streams may be attributed not only to their smaller volume but also, and more particularly, to the fact that their courses—trending southeastward or northwestward, at right angles to the direction of tilting—were essentially unsteepened, whereas the course of the San Joaquin River—trending southwestward, parallel to the direction of tilting—was appreciably steepened.[9]

Most of the hanging lateral valleys are in two tiers or sets, the one much higher than the other. Valleys of the upper set are features of the plateaulike uplands, that is they hang with reference to the mature Miocene erosion surface. Valleys of the lower set are associated with the flanking benches and shoulders of the San Joaquin Canyon, that is, they hang with reference to the Pliocene erosion surface. These two sets of hanging valleys are quite distinct; those of each set are remarkably accordant in level, but no amount of adjusting enables one to bring the two sets into accord.

The hanging valleys, no less than the associated erosional surfaces, are clearly indicative of two separate and distinct stages in the erosional history of the region. They attest to two rejuvenations of the master stream induced by two uptiltings of the Sierra Nevada. Valleys of the upper set were left hanging as a result of the uplift which initiated the Pliocene or "mountain valley" stage of erosion; those of the lower set, as a result of the uplift which initiated the Pleistocene or "canyon" stage of erosion. Valleys of the upper set, being developed on massive granitic rock of an exceedingly resistant nature, have been preserved in spite of their great age. Valleys of the lower set, being developed on rock which is less massive and therefore less resistant to stream erosion, during the Pliocene stage became graded to the new base level of the master stream, but in the latest or Pleistocene stage have become hanging again through the cutting of the canyon. The two sets of hanging valleys are analogous to the two upper tiers of hanging valleys in the Yosemite region.

#### RESTORED MIOCENE AND PLIOCENE PROFILES

The hanging valleys of the San Joaquin Basin provide data from which it is possible to reconstruct the longitudinal profiles of the San Joaquin River and its two main branches for each of the two stages of erosion indicated. Similar stream profiles were reconstructed for the Merced River and were useful in analyzing the erosional features of the Yosemite region (Matthes, 1930a, p. 33–45; pl. 27). In the San Joaquin Basin the reconstruction of profiles is particularly successful because hanging valleys are exceptionally numerous, and they occur throughout a longer section and farther

[9] Erwin (1934, p. 59) observes, for the Minaret District, that the relative cutting power of the streams, as a factor in the production of hanging valleys, has depended upon the volume of the streams, the resistiveness of the bedrock, and the relation of the stream courses to the tilt of the range. He analyzes the hanging valleys of the district with these factors in mind. For most hanging valleys at high altitudes, glacial erosion must also be taken into consideration.

down toward the foothills than in the case of the Merced River.

The method used is essentially as follows (Matthes, 1930a, p. 35–36): The longitudinal profile of a hanging tributary valley may be projected with a fair degree of accuracy to the axis of the master valley, thereby restoring the destroyed lower part of the profile of the hanging valley and determining the approximate point at which the tributary stream formerly joined the master stream. The method assumes, of course, that there was originally no break in the profile of the tributary valley, but this assumption is justified in view of the mature form of the hanging valley and the smoothly concave character of its profile as far down as it is preserved. These two characteristics, which all the hanging valleys have in common, show that they were developed in a protracted cycle of erosion during which side streams evolved courses smoothly graded down to the level of the master stream.

If this method is applied to those hanging valleys of the San Joaquin River which careful study indicates will yield reliable data, two series of points are obtained, indicative of the former level of the San Joaquin River at the end of the "broad valley" or Miocene stage of development and the "mountain valley" or Pliocene stage of development. These two series of points may be plotted on the longitudinal profile of the present San Joaquin River, and when connected they give the restored profiles of the river, as shown on pl. 2.

The Miocene and Pliocene profiles cannot be reconstructed empirically from the topographic map alone, by one unacquainted with the ground. On the contrary, judgment based on close field observation is required, as well as sufficient understanding of topographic methods to enable one to appraise the accuracy of features shown on the map. The writer has had sufficient experience in the topographic mapping of difficult mountain country to realize that much has to be sketched in from plane table stations with only such control as is afforded by intersecting points. Traversing along stream courses is as a rule precluded because it is too time consuming, and the topographer, if at all experienced in this work, will make the most of such views as his planetable stations afford to sketch the areas of relatively simple configuration such as uplands, especially those that are only sparingly timbered. Any data relating to hanging valleys based on the topographic map must, therefore, be critically evaluated before being used. This is illustrated, in following paragraphs, by analysis of some of the hanging valleys considered in reconstructing the Miocene profile of the Middle Fork of the San Joaquin River.

Granite Creek, the first tributary of the Middle Fork above the junction with the South Fork, affords a particularly reliable altitude point for the restoration of the Miocene profile of the Middle Fork. A careful plot of its profile shows that in spite of local modifications due to glacial action, including the development of a glacial stairway in its upper course, the general curve of the preglacial profile is readily reconstructed. Differences in the personal judgment of several individuals attempting to make such a reconstruction probably would not prevent their obtaining closely accordant results. The extension of the curve forward to the axis of the main canyon involves but little extrapolation. The total length of the upland course of Granite Creek (following the West Fork and Post Creek, which is really the main headwater branch) is 12.5 miles; the extension of the profile from the edge of the upland to the axis of the main canyon measures 1.85 miles.

The hanging valley of Granite Creek has been well preserved, despite its great age, because of the great resistance the stream has had in trenching the massive granite that underlies its lower course. The granite that extends from Soldier Meadow down to the edge of the upland and over a considerable area to the southwest is so sparsely fractured that vegetation still is very scant in places. Luxuriant meadows, it is true, occur on alluvial ground in the shallow valleys, and groves of forest trees stand on the gentle slopes where granite sand offers at least a thin soil for their roots, but the hills and ridges from which the granite sand is being stripped are still largely bare. The massive structure of the granite, further, is conspicuous in the sides of the canyon of the Middle Fork, where it gives rise to smooth, unscalable cliffs.

The East Fork of Granite Creek does not afford data that can be used for restoration of the Miocene profile of the Middle Fork. As will be clear from the map, the East Fork of Granite Creek was originally a tributary to the North Fork of the San Joaquin, its course being southeastward either through the depression now occupied by the Cora Lakes or, farther south, through the deeply incised channel north of Green Mountain. Its old valley has been so thoroughly remodeled by recurrent glacial action that very probably the stream has followed different channels at different times during the Pleistocene. Its present course southward through the notch west of Green Mountain is undoubtedly due to a diversion brought about by the glacier that filled its old valley. The notch itself was in all probability produced by an ice lobe that spilled southward over a low divide west of Green Mountain.

The point on the Miocene profile of the Middle Fork indicated by Granite Creek has an altitude of 6,600 feet or more; and a very closely accordant point is indicated by the profile of the small unnamed tributary of Granite Creek that flows past the north end of Squaw Dome.

Although the gently sloping upland back of the Junction Bluffs, on the southeast side of the Middle Fork, and the similar upland back of Lion Point, on the northeast side, are almost certainly good-sized remnants of the Miocene surface, they afford no data that can legitimately be used in the restoration of the Miocene profile of Middle Fork. Only short streamlets traverse these wooded uplands, and as the contouring must necessarily have been sketched by eye from planetable stations on distant summits, it can hardly be relied upon to give trustworthy results.

The upland course of Crater Creek presumably has a fairly reliable profile curve which may be extended to the axis of the Middle Fork. The detail with which its crooked, wandering course is mapped affords some guarantee of accuracy in altitudes. The fact that the streamlet reaches the edge of the upland between the two Red Cones, which must have been located by planetable intersections and doubtless have well-determined elevations is, further, some guarantee of the accuracy of the altitude of the stream to the edge of the plateau. Due allowance must be made for glacial erosion at the head of the valley, but this cannot have been extensive. As the contour lines on the topographic map plainly show, the lower part of the upland course of Crater Creek is incised below the original profile of the Miocene cycle, and is therefore disregarded.

Fish Valley may be considered, as a final example. This valley has been so profoundly altered by glaciation that its earlier profiles cannot be determined with confidence. But several of the lower tributaries of Fish Creek, notably Silver Creek, the west fork of Silver Creek, the unnamed streamlet to the west of the west fork, and the streamlet that descends from the upland to the north, into the head of Fish Valley, furnish mutually accordant points that define probably with a fair degree of accuracy a stretch of 3 miles of the Miocene profile of Fish Creek. The curve of this profile, extended downstreamward, accords well with the profile of the Middle Fork of the San Joaquin as determined by the two nearest tributaries, Stairway Creek below, and Crater Creek above.

The Pliocene profile of the San Joaquin River, as is shown on plate 2, has been reconstructed, from altitude points provided by the lower tier of hanging valleys, for a distance of about 60 miles below the junction of the Middle and South Forks. This profile extends, therefore, to within a few miles of the mouth of the San Joaquin Canyon. From its lowest point, at Fine Gold Creek, upstream to the junction of the Middle and South Forks, the profile steepens gradually and quite regularly.

The Pliocene profile has been reconstructed for a distance of about 12 miles up the Middle Fork to a point provided by the hanging valley of Stairway Creek. If the profile be extended beyond this point, through the glacially remodeled and deepened upper valley of the Middle Fork, it reaches to a point about 3 miles above Agnew Meadows, which is believed to be the approximate position of the head of the Pliocene valley.

The Pliocene profile has been reconstructed up the South Fork for a distance of about 14 miles, from points provided by the hanging valleys of Four Forks Creek and Rattlesnake Creek. If the profile be extended on up the South Fork, through the glacially remodeled and deepened upper valley, it meets the floor of Evolution Valley at an accordant level. This valley, which now hangs about 600 feet above the floor of the main valley (fig. 17), appears to be the glacially modified head of the Pliocene valley (Matthes, 1925, p. 41).

Similarly, the Miocene profile of the San Joaquin River has been reconstructed, from altitude points provided by the upper tier of hanging valleys, for a distance of about 27 miles below the junction of the Middle and South Forks. The lowest point on this profile, at Jose Creek, is about 40 miles from the mouth of the canyon. Throughout this section, the slope of the profile is quite uniform.

Above the junction, the Miocene profiles of both the Middle Fork and the South Fork are better documented than the corresponding Pliocene profiles, as there are more altitude points, some even within the upper valleys.

The Miocene profile has been reconstructed for a distance of 30½ miles, up the Middle Fork to a point provided by the hanging valley of Garnet Lake. There is a marked steepening of the gradient as far as Crater Creek, but above this point the profile flattens, as far as the uppermost point, at Garnet Lake. If the profile is extended a short distance beyond this point, it reaches the basin of Thousand Island Lake at an accordant level. This basin, which lies about 1,650 feet higher than Agnew Meadows, is apparently the glacially modified head of the Miocene valley.

The Miocene profile has been reconstructed 34 miles up the South Fork to a point provided by the hanging valley in which Heart Lake is situated. Throughout this distance, the profile steepens progressively. If the profile is extended on up through Evolution Valley, with a gradient that continues to steepen, it joins the floor of Evolution Basin at an accordant level. This basin, which hangs more than a thousand feet above the head of Evolution Valley, appears to be the glacially modified head of the Miocene valley (Matthes, 1925, p. 41).

It is to be noted that if the reconstructed Middle Fork and South Fork profiles of either the Miocene or the Pliocene set are compared for the sections above the junction wherein both sets are represented, those of the Middle Fork are steeper than those of the South Fork. In these sections, the two branches of the San Joaquin River are oriented at right angles to each other, the Middle Fork flowing southwestward, directly down the west slope of the range, and the South Fork flowing northwestward, along the slope and parallel to the crest of the range. As a result of this difference in orientation, the ancient profiles of the Middle Fork have been steepened by the uptiltings of the Sierra Nevada, whereas the corresponding profiles of the South Fork have remained unsteepened or have been steepened to a negligible amount. The decrease in slope of the Miocene profile of the Middle Fork, between Crater Creek and Deadman's Pass, probably reflects the change in trend of the river, which in this section has a southerly course; and the further flattening of this profile above Deadman's Pass probably reflects the southeastward course of the river in this section.

These relationships in the San Joaquin Basin are consistent with those which have been found farther north in the Sierra Nevada, where the reconstructed Tertiary profiles of other rivers similarly show steepening in those sections of their courses that trend parallel to the direction of tilting, and lack of steepening in those sections where their courses are at right angles to that direction (Lindgren, 1911, p. 46–48; Matthes, 1930a, p. 43–44).

#### SIGNIFICANCE OF PATTERN OF RIDGES AND VALLEYS

The hills, mountain groups, and long mountain ranges standing above remnants of the Miocene erosion surface are monadnocks and, in all probability, are features inherited from the system of northwestward trending ridges that occupied the place of the present Sierra Nevada in Late Jurassic and Cretaceous time. The folded sedimentary and volcanic beds have been largely worn away from most of these ranges, as at Kaiser Ridge, and only the cores of granitic rock remain; but in a few instances, notably the Ritter Range and the LeConte Divide, the metamorphic beds still remain in large volume.

Recognition of the mountain crests as features inherited from the older mountain systems carries with it, by implication, the recognition of the northwestward-trending valley troughs between them as similarly inherited features. It would appear, therefore, that the South Fork of the San Joaquin River follows a valley that dates far back into Cretaceous time, and that the same is true of the other northwestward-trending valleys, such as those of Chiquito Creek, Granite Creek, the North Fork, and the upper course of the Middle Fork.

In the case of the South Fork, the headward part of the river still flows over the metamorphic rocks, to whose structure it long ago became adjusted and in which Goddard Canyon has been excavated. Throughout the rest of its course, however, the South Fork flows over granite. The South Fork in this section, and also the other longitudinal streams in the basin which similarly are now cutting in granite, are believed to have acquired their northwesterly or southeasterly courses largely by superposition from the metamorphic rocks. Their trends over the areas of granitic rock still reflect the pattern of the ancient drainage which had become extensively adjusted to the structure of the Appalachian-type mountains (Matthes, 1930a, p. 2).

The canyons of the North Fork and the upper part of the Middle Fork also are cut in metamorphic rocks, and their courses conform in large part to the structures of these rocks (Erwin, 1934, p. 55). The southeasterly trend of the canyon of the Middle Fork, from the vicinity of Agnew Pass to a point about a mile below Agnew Meadows, accords with the strike of the upturned beds and the parallel system of strike faults. The course of the river coincides approximately with the trace of one of these faults for a distance of several miles. Several small tributary streams on the east side of the canyon likewise follow the strike throughout the major part of their courses. The canyon of the North Fork, taken as a whole, has a more southerly trend than the strike of the beds, but when examined in detail its course is found to consist of four long southeastward-trending segments that have southwesterly trends, across the strike. Most of the tributary streams on the west side of the North Fork flow southeastward.

Similar structural control is evident in the Ritter Range, whose major landforms, and also certain of its minor ones, trend parallel to the strike of the metamorphic rocks (Erwin, 1934, p. 9). The great height of the range doubtless is due to the superior resistance to erosion of the rocks which make up its bulk. The LeConte Divide probably illustrates the same relationships.[10]

Over wide areas, however, correspondence of this kind between landforms and the constituent rocks, or their structures, is not evident. Presumably in these places the lithologic dissimilarities either were not such as to cause noteworthy topographic contrasts, due to differential weathering and erosion, or else the contrasts were obliterated during the long Tertiary cycles of erosion. Thus in the northern part of the basin, none of the projecting tongues of metamorphic rock, whether in the western, southern, or southeastern margins of the metamorphic area, finds expression in the primary or even in the secondary features of the topography. One cannot infer the windings of the contact between metamorphic and granitic rocks from the positions and forms of ridges or valleys. The latter features appear to have been carved indifferently across both kinds of rock, and the trace of the contact wanders among and over them without attendant changes in style or topography, except perhaps in the minutely sculptured details.

In connection with the course of the San Joaquin River, the broad sag in the crest of the range at Mammoth Mountain appears to be of critical significance. Mayo (1941, p. 1068, 1081, pl. 3) points out that this sag lies at the southwestern corner of the "Mammoth reentrant" in the eastern front of the Sierra Nevada. The reentrant coincides with a complex of intersecting faults. The latter probably played an important part in determining not only the reentrant but also the development of the sag and the localization of the intrusive rocks in it. This sag is thought to be the mouth of a Tertiary valley which extends far to the eastward and whose stream joined the Middle Fork when the waters from the country to the east still drained westward across the Sierra region. The Middle Fork flowed in a relatively shallow valley slightly below the level of the sag and below the shoulders that now flank the canyon. It seems probable, in view of the depth and breadth of the sag, that the valley indicated by it was then occupied by a large river—the San Joaquin—and that that part of the present South Fork, which pursues a general southeasterly course from Thousand Island Lake to the Devils Postpile, was merely a tributary of the master stream. The San Joaquin River, therefore, appears to be a "beheaded" stream, its original upper course having been cut off as a result of the faulting which produced the Sierra escarpment. Several other Sierra streams besides the San Joaquin, that now begin in gaps in the crest of the range, doubtless were similarly decapitated.[11]

#### RELATION OF MAIN DRAINAGE DIVIDE TO ESCARPMENT ON EAST SIDE OF RANGE

At the head of the San Joaquin Basin the main drainage divide, or crestline, does not coincide with the top of the great east escarpment of the Sierra Nevada except at two very short stretches. Throughout the rest of its 70-mile course, the main drainage divide bears no constant relation to the escarpment, but is separated from it, in places by intervals of many miles, and is a wholly independent feature in regard to altitude and trend.

It is evident that the main drainage divide is an erosional feature, and is of much greater antiquity than

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[10] The investigations of Erwin (1934) and Mayo (1937, 1941) made subsequent to this reconnaissance, indicate that joint patterns also have been highly influential in determining drainage and topographic patterns in the central and southern parts of the Sierra Nevada. Mayo (1941, p. 1053) has found that the steep, primary joints are features inherited from the oldest structural patterns of the range.

By mapping the joints that dip more than 60°, Mayo (1941, p. 1050–1053, pl. 2) has shown that throughout a considerable part of the Sierra Nevada, including a portion of the San Joaquin Basin, there are four principal joint sets. These trend, respectively, west-northwest, northwest, north-south, and northeast.

The northwest joints are especially well developed and important as a topographic influence. For example, according to Mayo (1941, p. 1052) "in the Mt. Goddard quadrangle, many canyons, such as First and Second Recesses, and Goddard Canyon, trend northwestward . . . Throughout the area the sculpturing of many a bold peak and sharp ridge has been partly controlled by the orientations and spacings of northwest joints."

Adjustment to north-south joints may explain the course of the Middle Fork in the section south of Pumice Flat (Mayo, 1937, p. 181).

In the metamorphic rocks of the Ritter Range, Erwin (1934, p. 56) noted that the northeast set of joints is best developed, and it is reflected in topographic features of the sharp and rugged Minarets.

Mayo (1941, p. 1052) states that the northeast joints "are followed by many of the master streams that drain the western slope of the Sierra Nevada and by most of the canyons that furrow its eastern scarp. Along the crest of the range . . . swarms of northeast joints are responsible for jagged irregularities in the skyline of the northwest-trending ridges."

[11] The interpretation of the San Joaquin River set forth above is the one which Matthes published (1930b). In unpublished and undated notes he has also given the following interpretation, which assumes that the San Joaquin River has had much the same history as that of the Merced River (Matthes, 1930a, p. 30–31). According to this interpretation, the San Joaquin River established its course conformably to the southwestern slant of the region, presumably early in the Tertiary period, when the first upwarpings or tiltings occurred that determined the southwestward direction of nearly all the master streams of the Sierra Nevada. As it grew headward it did so at the expense of the streams of the older drainage system, which were successively captured. The dividing ridges probably did not stand in the way of this capturing as much as might be supposed, for they were discontinuous, with many gaps. Among the captures made by the San Joaquin were those of the South Fork and the upper part of the Middle Fork. The sag in the crest of the range may simply mark a low divide; it may indicate an ancient valley through which the upper course of Middle Fork flowed northeastward, before it was captured; or it may record the valley of a former tributary to the Middle Fork.

Recent stream capture, of the type postulated by this interpretation, is illustrated on a small scale by Stevenson Creek. The former head of this creek flowed northwestward into the Shaver Lake Basin, but it was captured by the small stream of Blue Canyon, which flows south-southeast, into the Kings River.

the escarpment: an ancient divide which parted northeastward-flowing waters from southwestward-flowing waters long before tectonic movements gave rise to the escarpment. The forms and gradients of the upland valleys to the northeast of the divide are closely similar to the corresponding features of the upland valleys on the southwest side, showing that prior to the formation of the escarpment, the Sierra region fell off rather symmetrically in both directions. Ancient erosional features like those referred to above, of Miocene and Pliocene age, are found only at high levels of the eastern slope.

The east escarpment is probably largely of early Pleistocene origin, and is a feature produced as a result of the downfaulting of the Owens Valley graben. There is reason to believe that it did not assume its imposing height until after the Sierra Nevada had undergone its first period of glaciation. For, whereas the moraines of the Sherwin, Tahoe, and Tioga stages of Blackwelder (1931) lie at the mouths of the deep canyons that gash the east mountain front, certain moraines of Blackwelder's earliest, the McGee stage, are situated on a high shoulder overlooking the escarpment, where they could have been deposited only before the canyons were cut to their present depth. (Matthes, 1933a, p. 35–39; 1950b, p. 42–50.)

## GLACIATION

During the Pleistocene epoch, the higher parts of the San Joaquin Basin, like those of the other basins on the west slope of the Sierra Nevada, were mantled repeatedly with glaciers.[12] Practically all of the glacial sculpturing that gives the High Sierra its distinctive scenic aspect, has been superimposed on a landscape inherited from Miocene and Pliocene times (Matthes, 1933a, p. 37). While the San Joaquin River was cutting its sharply V-shaped gorge in the lower slope of the Sierra, the untrenched Pliocene valleys of the upper slope were being vigorously glaciated and transformed into broadly U-shaped troughs. The little side valleys on the Miocene uplands, which already were hanging above the Pliocene main valleys, were occupied by tributary glaciers and as the side valleys underwent less excavation than the main valleys, the discordance between the two was generally increased. The heads of the little Miocene valleys carved in the flanks of the High Sierra crests were resculptured into amphitheaterlike cirques. The latter were cut deeply into the tabular remnants of the Eocene surface that persisted on the higher peaks, but on Mount Darwin and Mount Wallace, the remnants were not wholly consumed. These summits escaped glaciation and were subject only to nivation.

In the San Joaquin Basin the same method was employed for tracing and mapping the courses of the ancient glaciers and for determining the farthest limits which they had reached that had proved effective, previously, in the Merced and Tuolumne basins. That method relies on the testimony of glacial deposits rather than on that of sculptured features, and consists primarily of a systematic survey of the moraines which were built by the individual glaciers.

In open country, such a survey can be executed readily with sufficient accuracy for a reconnaissance map on the scale of 1:125,000 by locating the moraines by eye with respect to identifiable landmarks; but in the forested tracts, the more important moraines must be actually followed out and, in some places, even located by traverse—a laborious and time-consuming process. Fortunately, the forested areas in the San Joaquin Basin, though of considerable extent, are so amply diversified by topographic drainage features, as well as by occasional meadows, that no traversing was needed, and a large share of the work could be done by following the moraines, or the swales between moraines, on horseback. In the rougher areas, of course, the mapping had to be done on foot.

In spite of the rapidity with which the survey was carried out in a rugged mountain region largely devoid of roads, and only scantily traversed by trails, the resulting map (pl. 1) is probably of more than reconnaissance accuracy, for it shows not merely the areas that were formerly ice covered but also, by rows of dots, the crestlines of the individual moraines of the later glaciation. These crestlines, it is evident, tell the story of the glacial invasions, and the minor fluctuations of the glaciers, more precisely and more graphically than can mere words.

In the central part of the basin, which contains the outer fringes of the glaciated territory, special pains were taken in the mapping of the glacial deposits, as a definite knowledge of the extreme limits of glaciation is of paramount importance in the correct analysis of the landscape. It was necessary to do this work with more care as the outermost glacial deposits in most places are older than the Wisconsin and generally consist of small, obscure patches no longer identifiable

[12] Distribution of the Pleistocene glaciers for the entire Sierra Nevada is shown on the Glacial Map of North America (scale 1:4,555,000), published by the Geological Society of America, New York, 1945. This map distinguishes between the Wisconsin and the pre-Wisconsin (undifferentiated) glaciations.

Distribution of the late Pleistocene (Wisconsin) glaciers for the entire Sierra Nevada is shown on an inset map printed on Sheet No. V of the Geologic Map of California (scale 1:500,000), published by the Division of Mines, California Department of Natural Resources, San Francisco, 1938. The north half of this glacial map is by Eliot Blackwelder (1932), the south half by F. E. Matthes (1937).

by their topographic forms. It is due largely to that circumstance that the true extent of the former glacial mantle of the Sierra Nevada long remained in doubt and a subject of misconceptions.

Reliance was not placed on topographic forms as possible indicators of changes wrought by glacial erosion because, as had been learned in the Yosemite region and in the Tuolumne Basin (Matthes, 1930a, p. 89–91), the extraordinarily varied joint systems in the granitic rocks of the Sierra Nevada in large measure controlled the eroding action of the ice. The joints more than any other factor determined whether a V-shaped river canyon would or would not be transformed into a typical U-shaped trough. Where the granite is thoroughly divided by joints (figs. 28, 29), glacial plucking, or quarrying, was particularly effective and typical glacial forms were actually produced; but where the joint features are spaced far apart, or are wholly absent over distances of hundreds and even thousands of feet, glacial action was reduced largely to abrasion, and only minor changes were effected in the valley form. Even the Tuolumne Glacier, which attained a length of 60 miles and a depth of 4,000 feet, failed to give its canyon a typical U-shaped form throughout, because the walls, for mile after mile, are composed of prevailingly massive granite.

It was discovered also, in the Yosemite region, that hanging valleys, on the western slope of the Sierra Nevada, are not necessarily indicative of profound glacial erosion, many of them having gained their hanging aspect long before the glaciers appeared upon the scene, simply as a result of rejuvenation of the master stream induced by the tilting of the Sierra block. Many hanging side valleys occur in the lower, unglaciated courses of the main canyons as well as in the intensely glaciated upper courses.

FIGURE 28.—Hackly surface produced by glacial plucking of jointed bedrock. On crest of ridge west of Evolution Basin, looking eastward. Mount Huxley in distance. Photograph by G. K. Gilbert.

FIGURE 29.—Valley floor modified by glacial plucking in jointed bedrock. Ice movement from left to right. Upper Evolution Valley. Photograph by G. K. Gilbert.

In the San Joaquin Basin, therefore, it likewise was deemed best to regard the varying forms of the canyons and, indeed, of all the features of the glaciated landscape, as things to be explained rather than as features diagnostic of past events.

In the morainal deposits of the San Joaquin Basin, as in the Yosemite region, abundant and unmistakable evidence was found of two distinct stages of glaciation separated by a lengthy time interval; also meager indications of a third, very early stage (Matthes, 1929). Many examinations of the morainal deposits of the two easily recognizable glacial stages in this basin confirm the interpretations of the moraine systems of the Yosemite and Tuolumne regions and help establish the succession of events making up the glacial history of the west slope of the Sierra.

It should be added that in later years much corroborative evidence has been found in the Kings River, Kaweah, and Kern Basins. Throughout the south-central Sierra Nevada, therefore, the morainic systems of the great trunk glaciers and their numerous branches spell out the same story of three distinct stages of extensive and long-continued glaciation during the Pleistocene epoch.

## DIFFERENTIATION OF MORAINES AND CORRELATION OF GLACIAL STAGES

For discriminating between moraines belonging to the different stages of glaciation it was found best, in the San Joaquin Basin, to apply the criteria which the writer had developed in the course of his detailed studies of the Yosemite region, because the general nature of the country in the two areas, the character of their rocks, the climatic conditions, the vegetal cover, and the soils are closely similar.

On the glacial map (pl. 1) distinction is made only between the Wisconsin and pre-Wisconsin stages. Although at some localities (see pages 56, 57–58) the field data appear to warrant subdivision of the Wisconsin moraines into those of early Wisconsin time and those of late Wisconsin time, corresponding to the Tahoe and Tioga stages of Blackwelder (1932), such division could not, in the time available for the reconnaissance surveys, be carried consistently over the entire area. In many places the moraines of early and late Wisconsin time are so closely alike that their separate mapping would have required detailed and prolonged study. All the moraines of the Wisconsin stage are therefore shown on the map provisionally as a single unit. The data, nevertheless, are sufficiently detailed to permit individual moraine crests to be indicated by rows of dots.[13]

The moraines of the Wisconsin stage as a rule are well preserved, sharp-crested, and studded with fresh-looking unweathered boulders. A few weathered and even thoroughly decomposed boulders occur, but it is evident from their sparse occurrence in deposits composed almost wholly of fresh, unweathered rocks that ring under the hammer, that the weathered boulders represent an admixture of material that already was considerably weathered when the glacier picked it up, perhaps from moraines of earlier glacial stages. It is significant, moreover, that in these younger moraines not only the boulders of siliceous granite but even those of much weaker diorite and gabbro are essentially unweathered and unstained.

The pre-Wisconsin moraines in the San Joaquin Basin are in all respects closely similar to those in the Yosemite region, and are therefore referred to the El Portal stage. Compared to the moraines of the later stage, they are poorly preserved, and generally are cloaked with granite sand derived from their own disintegrating boulders. In places, the bouldery character of the ancient moraines is shown mainly in exposures made by uprooted trees. The boulders in the interior of the moraines are, as a rule, encased in ferruginous rinds; many are entirely decomposed, so that they may be cut with a shovel. Although originally of much greater bulk than the moraines of the Wisconsin stage, the older moraines have long since lost their crests, and their form has become subdued and flattened. Over considerable distances they have not only lost their ridgelike aspect but have become inconspicuous in the landscape. The accumulation of sand on the upslope sides of morainal ridges in some places has largely concealed them.

Terminal moraines of the El Portal stage appear to be generally absent in the main canyons on the west slope of the Sierra Nevada. At least, methodical search has failed to reveal any remnants of such moraines in the principal canyons of the Stanislaus, Tuolumne, Merced, San Joaquin, Kings, Kaweah, and

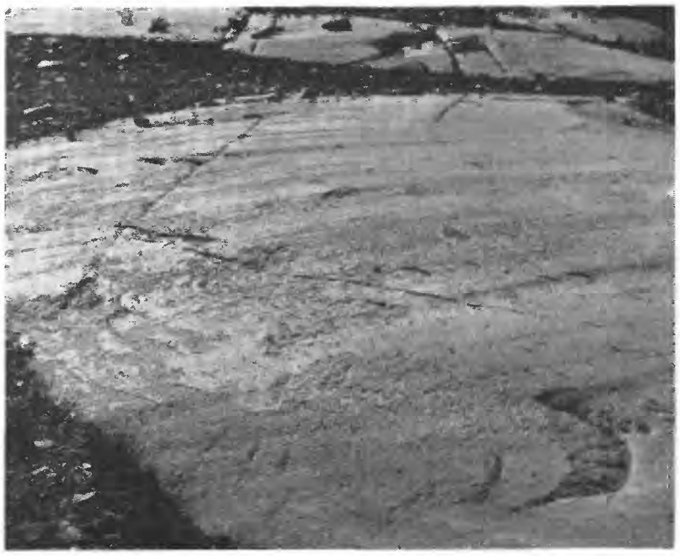

FIGURE 30.—Details of ice-scoured rock floor of Evolution Basin, near Sapphire Lake. In lower right-hand corner are two crescentric gouges. In left center are curved tension cracks in parallel overlapping series. The ice came from the left.

[13] Detailed study of the glacial record along the South Fork of the San Joaquin River and its tributary, Mono Creek, has recently been made by Birman (1954). In this region, Birman reports the occurrence of seven moraine sets, which he has divided into three groups. "Group I, the oldest, contains highly weathered erratics and till. Original morphology has been largely destroyed. Group II contains three sets of well-formed moraines, each with distinctive weathering characteristics. End moraines are virtually absent in the earliest set, scarce in the intermediate set, and present at about 7,000-feet elevation in the latest set. Group III contains three moraine sets mostly above 8,500 feet. Distinct reversal of weathering ratio in the oldest set suggests minor short-lived glaciation long after withdrawal of Group II ice. The youngest set includes bare, unstable rock glaciers and moraines at cirque headwalls. The intermediate moraines occur as much as a mile from cirque headwalls. Abundant lichens and tree-ring counts indicate a minimum age of 250 years.

"Work in upper Rock Creek and visits to other Eastern Slope canyons tentatively suggest that: (1) Group I deposits are largely Sherwin in age; (2) in Group II, the earliest and latest sets closely resemble respectively Tahoe and Tioga moraines; (3) the intermediate set of Group II occurs in Eastern Slope canyons as moraines apparently distinguishable both from Tioga and from Tahoe deposits; (4) Group III moraine sets record minor advances, probably since Climatic Optimum."

FIGURE 31.—Crescentric gouges near base of Mount Huxley. The rock face is inclined toward the foreground at 45°. The ice motion was from right to left. A pocket knife inserted in one of the central gouges of the lower tier gives the scale. Photograph by G. K. Gilbert.

Kern basins. Their total absence can hardly be explained as the result of post-El Portal stream erosion and collateral slope-wash, slumping, and other degrading processes; for in some of the canyons, notably in the San Joaquin Canyon, the local conditions are distinctly favorable for the preservation of at least the wings of terminal moraines and recessional moraines, but no vestiges of such remain. It seems probable, therefore, that the glaciers of the El Portal stage did not maintain their maximum extension long enough to build bulky terminal moraines.

The El Portal stage is believed to correspond to Blackwelder's Sherwin stage at the east base of the range (Blackwelder, 1932), and is thought to be not younger than the Illinoian stage of the continental glaciation (Matthes, 1933b, p. 72, 76; 1935). In the San Joaquin Basin as in the Yosemite region, however, these older moraines differ considerably among themselves in degree of preservation and in the decomposition of their granitic boulders, and it therefore seems entirely possible that they include remnants of two or more as yet unseparated stages that differ considerably in age, including perhaps both the Kansan and the Illinoian (Matthes, 1933a, p. 33). Only intensive studies in selected areas are likely to settle that question. The correlation of the older glacial deposits of the Sierra Nevada must necessarily remain tentative until the glacial field of the Pacific ranges has been more closely connected with the glacial fields of the Rocky Mountains and the Great Plains.

No morainal deposits belonging to the Glacier Point stage, the earliest stage of glaciation that was recognized in the Yosemite region, are shown on the map; but it is not to be inferred from this that no deposits whatever of that early glaciation remain preserved in the San Joaquin Basin. A few small, isolated patches of an ancient moraine were discovered in the central portion of the basin, on a mountain summit at a high level above the surrounding canyons, and these may well be representative of the Glacier Point stage, in view of their elevated positions.[14] The deposits of the Glacier Point stage thus far discovered, notably those in the type locality in the Yosemite region, on the divide to the east of Mount Starr King (Matthes, 1930a, p. 73–74), are situated at a great height above the neighboring canyons, which would seem to imply either that the Sierra Neavda at one time was fairly overwhelmed with ice, or that a great deal of canyon cutting has taken place since these ancient moraines were laid down. As the latter hypothesis seems the more probable of the two and finds support in a variety of circumstantial evidence, there is good reason for assigning the Glacier Point stage, together with Blackwelder's McGee stage, to the early Pleistocene—presumably corresponding to the Nebraskan stage (Matthes, 1933a, p. 33). In the San Joaquin Basin, meanwhile, until more conclusive proof is forthcoming that the isolated patches of morainal material mentioned are of decidedly greater antiquity than the deposits of El Portal age, it seems best not to differentiate them from the latter on the map.

### GLACIERS OF THE PRE-WISCONSIN STAGES

The San Joaquin glacier system of the pre-Wisconsin stages was by far the largest system of confluent glaciers in the Sierra Nevada, measuring more than 50 miles in length along the crest of the range and 30 to 35 miles wide. Of the 1,760 square miles comprised in the San Joaquin Basin, almost 1,100 square miles were covered by glaciers. This ice mass, together with the ice masses in the basins of Dinkey Creek and the North Fork of the Kings River, formed a mer de glace 1,500 square miles in extent. Yet it was not an icecap, strictly speaking, for its surface was broadly concave rather than dome shaped. It consisted of a large number of confluent glaciers that had descended from the surrounding peaks and crests, filled the canyons, and overflowed onto the intermediate uplands (Matthes, 1947, p. 208; 1950b, p. 62).

The San Joaquin glacier system was essentially bilobate, in that it comprised two great primary branches

[14] No references to the exact location of these deposits, or descriptions of them, were found in any of Matthes' field or office notes, and the only information available is that given above, which is taken from a brief published paper (Matthes, 1935).

that descended Middle Fork and South Fork canyons. The branches united below the junction of the two forks, to form a very broad trunk glacier that overflowed the main San Joaquin Canyon and spread widely over the central part of the basin, northeast of Chiquito and Kaiser Ridges. The glacier ended in a rather blunt tongue, only a few miles long, which lay in that part of the main canyon which separates Chiquito and Kaiser Ridges. The length of the San Joaquin glacier system, measured from Muir Pass at the head of the South Fork branch to the terminus of the trunk glacier, 1¼ miles below the mouth of Rock Creek, was nearly 60 miles. The length measured along the Middle Fork branch was almost 45 miles. The shortness of the trunk glacier, which descended to a point about 14 miles below the junction of the Middle and South Forks, is explained by the fact that the ice which spread over the vast expanse of rolling uplands bordering the canyon was dissipated by ablation much more rapidly than it would have been if it had been concentrated in a deep cliff-shaded trench.

Ice was contributed not only from areas along the crest of the range but also from all sides of the various ridges on the west slope, except in the case of Chiquito Ridge, which, because of its low altitude (maximum 8,358 feet), developed glaciers only on its north side. The glaciers of the south side of Kaiser Ridge were tributary not to the main San Joaquin glacier system but to a separate and much smaller system in the basin of Big Creek.

#### MIDDLE FORK GLACIER

Middle Fork glacier, in conforming to the course of the canyon which it occupied, flowed successively northeast, southeast, south, and finally southwest, to its junction with the South Fork glacier. Its length, from its source on Mount Davis to its junction with the South Fork glacier, 1 mile southwest of Balloon Dome, which was overridden by the ice, was 31 miles.

In its upper course, the sources of this glacier lay at altitudes of 10,000 to over 13,000 feet on the northeast slope of the Ritter Range, mainly in the basins of Thousand Island Lake, Garnet Lake, Shadow Creek, Minaret Creek, and King Creek. As these sources were situated to the west of the main trunk, the upper part of Middle Fork glacier was highly asymmetrical.

Farther downstream, Middle Fork glacier was augmented by large tributary glaciers, notably those in the valleys of Fish Creek, North Fork, and Granite Creek. These glaciers filled their valleys and, overflowing the intervening divides, became confluent in most places.

Fish Creek glacier, which was 17½ miles long, measured from Red and White Mountain to its junction with the Middle Fork glacier, originated, for the most part, in cirques at altitudes of 10,000 to 12,000 feet on the main crest of the Sierra and on the north side of the Silver Divide. North Fork glacier, which was 16½ miles long, measured from Rodgers Peak to its junction with the Middle Fork glacier, was fed principally from areas on the southwest and south sides of the Ritter Range, and from basins at altitudes of 10,000 to 12,000 feet on the southeast side of the nameless crest trending southwest from Mount Lyell. Granite Creek glacier, which was 14 miles long, measured along its west branch, had its main sources at altitudes of 9,500 to 11,000 feet on the crests which bear Black, Sing, Gale, and Triple Divide Peaks.

#### SOUTH FORK GLACIER

South Fork glacier, measured from the head of Evolution Creek at Muir Pass to its junction with Middle Fork glacier 1 mile southwest of Balloon Dome, was 46 miles long. Throughout most of its course it flowed northwestward, its consistent trend being in marked contrast to the course of the Middle Fork glacier. South Fork glacier received much of its ice from cirques on adjacent mountains and from its many tributary glaciers, most of which joined it from the east and northeast. The most important tributaries were Goddard Canyon glacier, Piute Creek glacier, Bear Creek glacier, and Mono Creek glacier.

The upper part of the South Fork glacier, which occupied Evolution Valley and Evolution Basin and therefore may be called the Evolution glacier, was 11 miles long, measured from Muir Pass to its junction with Goddard Canyon glacier. It was fed from cirques at altitudes of 11.500 to over 13,500 feet, located at its head along the main crest of the range, and from others on the high confining ridges, such as Glacier Divide and the nameless ridge which bears Mount McGee.

Goddard Canyon glacier was 8½ miles long, measured from the divide south of Martha Lake to its junction with the Evolution glacier. Its sources lay in cirques at altitudes of 11,500 to 12,500 feet on the bordering ridges, especially on the LeConte Divide; but much ice was also contributed from the cirques at its head whose walls rose to the lofty summits of Mount Goddard and Mount Reinstein.

Piute Creek glacier, a branching ice body 11 miles long measured to its head on Mount Emerson, was fed mainly from several enormous compound cirques that ranged along the crest of the range at altitudes of 11,000 to over 13,000 feet, the largest of these, Humphrey's Basin, being more than 3 miles across. However, throughout the course of this glacier the lateral cirques along both sides contributed notably to its volume—for example those at 11,500 to 13,000 feet on the north slopes of Glacier Divide.

Bear Creek glacier and Mono Creek glacier were tributaries of even greater length and complexity. Bear Creek glacier was 15 miles long, measured up Hilgard Branch, and headed at altitudes of 10,000 to over 13,500 feet mainly in cirques on the south side of Mono Divide, and on the northwest side of a long curving nameless crest which bears Mount Senger and Mount Hooper. Mono Creek glacier was 20 miles long, measured to Mount Mills, and accordingly was the longest tributary of the South Fork glacier, and longer than any tributary of the Middle Fork glacier. Its most important sources lay on the main crest of the range, between Mount Abbott and Red and White Mountain, at altitudes of 10,000 to over 13,500 feet; others were located to the north on the Silver Divide, and to the south on the Mono Divide.

### CENTRAL ICEFIELD

The union of the Middle Fork and South Fork glaciers produced an enormous volume of ice which overflowed the canyons and spread broadly across the plateaulike uplands, forming a practically continuous icefield.

At the northwest this icefield was augmented by several confluent glaciers which descended the valleys of Jackass Creek, Chiquito Creek, and other smaller southeastward flowing streams. The sources of these glaciers lay at altitudes of 8,000 to 10,000 feet on the northeast slope of Chiquito Ridge and on the southeast slope of the crest just north of Beasore and Mugler Meadows. The Chiquito Creek glacier, the largest of the group, was about 16 miles long, measured from Redtop Mountain to the San Joaquin Canyon at San Joaquin Bridge.

West of the junction of the Middle and South Fork glaciers, the ice was sufficiently deep to overtop the knobs and hills which rise 200 to over 800 feet above the uplands—Jackass Butte, Jackass Rock, Squaw Dome, Cattle Mountain, and others—as shown by the scattering of erratics all the way to the summits of these eminences.

On the rolling country south of Jackass Meadows, erratics are in evidence almost everywhere, but there are no heavy concentrations of drift. Between the Placer Ranger Station and the San Joaquin Bridge, the gentle, smoothly rounded slopes of the lower Chiquito Creek basin are not visibly affected by the presence or absence of the drift (figs. 34, 35). Most

FIGURE 32.—Perched erratic boulder of the earlier ice invasion on sloping platform south of Junction Bluffs along the Middle Fork of the San Joaquin River, opposite the mouth of Stairway Creek. The pedestal is nearly 12 feet high.

of the interfluves are deeply cloaked with loose sand derived from disintegrating rock—much of it, apparently from boulders in the older drift. Only here and there are patches of the drift exposed. Most of it consists of rounded, evidently water-worn pebbles and small cobbles, which are mixed with more irregularly shaped and typically glacial cobbles and boulders. Quartzite, schist, dark-colored porphyry, and lava are common, and in places are more abundant than granitic rocks.

Northeast of Mugler Meadow, where a wagon road crosses Chiquito Creek, glacially striated cobbles are present in profusion. There is, northeast of the crossing, what appears to be a terracelike deposit of gravel and boulders. In this area the schists are particularly well striated, but the granite cobbles are either unstriated or so slightly striated as not to serve as diagonistic glacial material. Quartzite and schist are plentiful, and are probably derived from the south slope of Black Peak, but no trace was found of lava such as occurs in the Jackass country, a few miles to the east. This drift may be younger than that of the earlier glaciation in the Jackass region—perhaps in-

FIGURE 33.—Remarkable imitation of a perched erratic boulder of granite, produced wholly by weathering in place. Most of the weathering has taken place since the passage over this spot of the earlier ice. Upper valley of Chiquito Creek, on west side of trail to Chiquito Pass.

termediate in age between that drift and the Wisconsin drift to the north. In any event it is not Wisconsin, since in most places it underlies smooth slopes covered with granite sand.

Important contributions to the central icefield were also made by glaciers that originated at altitudes of 9,000 to 10,500 feet on the north slope of Kaiser Ridge, and that filled the valleys of Kaiser Creek and neighboring streams on the upland. Older drift forms a more or less continuous veneer covering the slopes on both sides of Kaiser Creek, and it is present in large quantities in the neighborhood of Kaiser Creek Diggings, where it forms terraces or terracelike benches with very steep slopes facing the creek bed. Farther north, in the vicinity of Cow Meadow, the scattered erratics which are evidence of the earlier ice, are very sparse. Mount Tom was a nunatak, its summit rising 1,000 feet above the level of the surrounding ice.

### LOWER SAN JOAQUIN GLACIER

Although the central icefield was restrained on the southwest and south by Chiquito Ridge and Kaiser Ridge, nevertheless it was not wholly confined by these barriers, but discharged southward through the gap between the two ridges, by way of the lower San Joaquin Canyon. The extent of this lobe must be inferred from remnants of its lateral moraines, since here, as in the other principal canyons of the west slope of the Sierra Nevada, there are no traces of El Portal terminal or recessional moraines. It appears that a blunt lobe about 2 miles wide pushed a little more than 3 miles, down the canyon to an altitude of about 2,600 feet, the lowest point reached by the ice in the San Joaquin Basin. Measured from the junction of the Middle and South Fork glaciers to its terminus, the San Joaquin trunk glacier was about 14 miles long.

### GLACIERS IN BIG CREEK BASIN [15]

The Big Creek glacier system was distinct from the great San Joaquin glacier system. It attained a length of about 20 miles and an areal extent of about 105 square miles. The ice was derived in part from cirques at 9,000 to 10,500 feet on the south side of Kaiser Ridge, but principally from the broad shallow cirques situated at about the same altitudes on the uplands at the head of Big Creek basin. The ice streams converging from these sources coalesced into a small trunk glacier which pushed several miles down Big Creek Canyon, to an altitude of 3,100 feet—a point almost as low as that reached by the neighboring San Joaquin trunk glacier. Thus the terminals of the two glacier systems approached each other but never united.

North and south of Huntington Lake, older drift is plastered against the slopes to heights of several hundred feet, except on those steeper places from which it has been removed. On the ridge northwest and north of Boneyard Meadow, older drift is present to within a few feet of the summit, that is, to altitudes over 7,700 feet. Crags on the summit (like those shown in figures 36 and 37) clearly show that in places rock has been stripped to a depth of 10 feet since the passage of the earlier ice; hence the absence of drift on some intermediate summits does not necessarily indicate that the ice did not overtop them.

On the trail to Potter Pass, older drift extends up to 7,500 feet, and at this altitude the trail crosses a distinct morainal ridge which is probably the crest of the highest lateral moraine on the north side of the lake. Northwest of Huntington Lake, on the small volcano called Black Point, granite boulders are within about 400 feet of the top, an altitude probably corresponding to the upper limit of the ice. The earlier glaciers did not overtop the ridge connecting Black Point and Kaiser Ridge. Farther east, the lower course of Bear Creek is entrenched in massive terraces of the older drift. Still farther east, in the

[15] On the glacial map (plate 1), Matthes shows no areas in the southeastern part of the Kaiser quadrangle, south of Big Creek Basin, as having been covered by ice during the earlier glacial stages, though it is reasonable to suppose that older drift probably occurs here, as in the upper valley of Dinkey Creek beyond the limits of the Wisconsin glaciation. The omission may be due to the fact that this region lies mainly outside the San Joaquin Basin, but it may also reflect the author's failure to find evidence of pre-Wisconsin glaciation, or his inability to carry out the requisite field investigations for lack of time.

FIGURE 34.—Chiquito Creek basin, north of Placer Ranger Station. Typical view of forested slopes covered with drift of the earlier glaciation. Smoothly rounded spurs alternate with shallow ravines, and no topographic evidences of glaciation remain.

lower valley of the North Fork of Big Creek, a large volume of morainal material forms broad terraces on both sides of the creek. These terraces slope westward toward Huntington Lake, and diminish in height from nearly 100 feet to about 50 feet.

Near the mouth of the North Fork, the tunnel of the Southern California Edison Company enters the mountain at a slight angle to the valley side, and for 900 feet traverses older moraine, being heavily timbered in this treacherous material. The thickness of the moraine against the valley side is estimated at close to 100 feet.

Southwest of Huntington Lake, older drift is scattered over the narrow, nearly level spur on which the town of Big Creek (altitude 4,500 to 5,000 feet) is built. Boulders and cobbles derived from it are used extensively to line garden walks. The moraine can be traced from Shaver Crossing down the road to Power House No. 2.

### DEPTH OF CANYON CUTTING SINCE EARLIER GLACIATION

In a few places, there is evidence that throws light on the question of how much canyon cutting has occurred since the earlier glaciers withdrew. One of these places is in the basin of Kaiser Creek, north of Kaiser Ridge, where older drift forms a discontinuous veneer over the undulating slopes on both sides of the creek. In this region the stream lies in a small rock gorge apparently cut since the earlier glaciation. The gorge ranges in depth from about 20 feet, south of Mount Tom, to over 50 feet at the place where the trail from Potter Pass to Daulton Ranger Station crosses the creek.

In the lower part of Chiquito Creek basin, the older drift mantles smoothly rounded, gentle slopes and flat benches on either side of the stream (page 48). Chiquito Creek itself flows through a gorge cut in this mature topography. The gorge is about 10 feet deep, just above Placer Ranger Station, and over 100 feet deep near the mouth of the creek. The gorge is interrupted at Logan Meadow, where, for a section, the creek has been prevented from deepening its channel due to the massiveness of the granite. Relationships typical of those found along the Chiquito Creek gorge are shown in figure 35.

With reference to the San Joaquin River, similar evidence was found in the vicinity of the mouth of Chiquito Creek. The lowest occurrence of older drift, in place, was found on the north side of the San Joaquin channel, at an altitude of 3,250 feet, that is, 300 feet above the river level. It would appear that at this point the maximum depth by which the river could have deepened its channel since the earlier ice withdrew is 300 feet.

### GLACIERS OF THE WISCONSIN STAGE

In the San Joaquin Basin, as elsewhere in the Sierra Nevada during the Wisconsin stage of glaciation, the volume of ice was considerably smaller than in the earlier stage, and the ice-covered area was, therefore, much less extensive. The San Joaquin glacier system had, of course, the same general pattern as in the earlier stage, for it reoccupied most of the cirques and followed the same valleys and canyons, but it took the form of numerous discrete glaciers which became confluent only in part. Accordingly, large upland areas which were ice covered in the earlier glaciation re-

FIGURE 35.—Gorge of Chiquito Creek, cut into gently sloping valley floor cloaked with drift of the earlier glaciation.

mained bare throughout the Wisconsin stage (figs. 36, 37).

By far the greater part of the ice which formed in the San Joaquin Basin was again part of a bilobate system, and this character was the more pronounced because the ice was largely confined within the canyons or broad valleys. The trunk glacier in the main canyon, formed through union of the Middle Fork and South Fork glaciers, was only a feeble tongue reaching but 2 miles below the junction. The altitude at the terminus, the lowest point reached by the Wisconsin ice in this basin, was 3,400 feet. The maximum length of the San Joaquin glacier system, measured from Muir Pass at the head of the South Fork, was 47 miles; the length, measured along the Middle Fork, was 32 miles.

FIGURE 36.—Residual shafts of type found on Cattle Mountain, between junction of Granite Creek and Middle Fork of the San Joaquin River, and on other summits (for example around Huntington Lake). These summits were overridden by the earlier ice but ever since have been subject to disintegration. The shafts are of solid granite which has survived the destruction of the jointed granite roundabout.

FIGURE 37.—Other examples of residual granite shafts of type found between Granite Creek and Middle Fork of the San Joaquin River (see fig. 36).

Some glaciers, which in the pre-Wisconsin stages were tributary to the San Joaquin glacier system, in the Wisconsin stage fell short of joining that system, and throughout their existence remained separate ice bodies or became confluent only with adjacent glaciers. This was the situation with the Granite Creek glacier, the Big Creek glacier system, and many smaller glaciers on Chiquito Ridge, Kaiser Ridge, and other ridges.

### MIDDLE FORK GLACIER

Middle Fork glacier was a complexly branching body. The main ice stream, in Middle Fork Canyon, received tributaries from all of the important branch valleys occupied in the earlier glaciation, excepting Granite Creek. In their upper reaches (fig. 38), the branch glaciers were largely separated by long ridges of the cleaver type, many of them nunataks. Conspicuous among these ridges was the narrow crest of the Ritter Range, between the upper North Fork and the Middle Fork glaciers. At the south, the rather similar Silver Divide parted the sources of Fish Creek glacier from glaciers of the South Fork system. Downstream, the branch glaciers were channelized

FIGURE 38.—Lower end of Thousand Island Lake, in cirque at head of the Middle Fork of the San Joaquin River; Banner Peak in the background. The ice-smoothed ledges of quartzite are breaking up by opening of joint cracks.

within the gorges into relatively narrow but deep ice streams. The lower courses of the North Fork, South Fork, and Fish Creek glaciers swept around and isolated several broad upland tracts which the earlier ice had overridden, for example that platform extending from the Granite Stairway to Lions Point. The ice reached a depth of more than 2,500 feet at the junction of the North and Middle Forks. Balloon Dome was a nunatak, the ice of this stage rising to a level of 1,500 feet above its base but never overwhelming the summit.

The North Fork glacier received a large branch from the valley of what is now the East Fork of Granite Creek. The East Fork glacier bifurcated, one very small lobe extending southward across a low divide into the Granite Creek basin, where, at Soldier Meadow, it just reached but failed to join the glacier of that basin. During deglaciation, the disappearance of this small lobe permitted the rearrangement of drainage whereby a stream previously tributary to the North Fork of the San Joaquin River was diverted across the low divide and became the present East Fork of Granite Creek.

### SOUTH FORK GLACIER

The glacier system in the basin of South Fork was larger and more complex than that in the basin of Middle Fork. Its maze of ramifying sources was incompletely defined by the winding, branching crests of Mono Divide, Glacier Divide, Goddard Divide, Le Conte Divide, the Silver Divide, and other ridges (fig. 39). Some of the small glaciers on the south side of the Silver Divide and on the north side of the Kaiser Ridge joined the South Fork system.

FIGURE 39.—Cirque northwest of Selden Pass showing fine development of a "sapline," with spintered cliff above and corraded slope below. The moraine loop (double-crested) in the foreground, traversed by the trail from the South Fork of Bear Creek to the South Fork of the San Joaquin River, probably was formed in historic time.

FIGURE 40.—Typical roches moutonnées, upper end of the Blaney Meadows, in the valley of the South Fork of the San Joaquin River. The ice movement was from left to right. Photograph by G. K. Gilbert.

The trunk glacier, although the product of many large, convergent ice streams, was relatively unimpressive. For a number of miles it did occupy the full width of the broad upper valley of the South Fork (fig. 40), and below the junction of the Mono Creek branch the ice was more than 5 miles wide and 1,500 to 2,000 feet deep; but farther downstream it dwindled to a narrow ice tongue which, northeast of Hoffman Meadow, was entirely confined within the inner gorge, here only ½ to 1 mile wide and about 1,500 feet deep. At its junction with the Middle Fork glacier, the South Fork glacier had much the lesser volume of the two branches.

At Selden Pass, striae and chatter marks on the bedrock show that ice from the head of Bear Creek basin moved southward into the South Fork system. Evidently the ice in Bear Creek basin was much higher than that in the South Fork.

During deglaciation, the Mono Creek glacier, following its separation from the main trunk glacier in the valley of the South Fork, left a remarkable series of seven crescentic frontal moraines at the lower end of Vermilion Valley (fig. 41). These ridges enclose a 3-mile long meadow, and the swales between them also are occupied by narrow strips of meadowland. Traced up the south side of Vermilion Valley they unite into several straight lateral moraines extending for about 2 miles.

In investigating potential dam sites, the Southern California Edison Company in 1924 drilled a series of eight test holes in this area of frontal moraines. The line of holes apparently began near the axis of the valley and extended east-northeast in a nearly straight line across the remainder of the valley. The eight holes penetrated, respectively, 180, 116, 77, 74, 62, 25, 5,

FIGURE 41.—Moraine of the later glaciation, one of the series deposited by the Mono Creek glacier in the lower part of Vermilion Valley. The direction of ice movement was left to right. Photograph by G. K. Gilbert.

and 2 feet of unconsolidated material, including boulders, gravel, and sand, probably both glacial and glaciofluviatile material older than the Wisconsin as well as of Wisconsin age. The hole nearest the axis of the valley was still in unconsolidated material at the 180-foot depth (written communication, D. H. Redinger September 15, 1924).

Immediately east of Vermilion Valley, and at levels 1,500 feet or more above its floor, is another series of moraines, disposed in a fan shape. They converge eastward, and across the divide between Mono Creek and Bear Creek they unite to form lateral moraines on the north side of Bear Creek valley. These moraines graphically record the fact that the Bear Creek glacier, on rounding the great right-angled bend in its valley, at higher stages overrode the crest of Bear Ridge to the north and contributed ice to the Mono Creek glacier.

FIGURE 42.—Well-developed lateral moraine of the later glaciation, deposited by the glacier which occupied the valley of the South Fork of the San Joaquin River. Near the mouth of Vermilion Valley.

West of Vermilion Valley is a third cluster of moraines (fig. 42): a concentric system of large, curving ridges, the convex sides of which are directed northeastward—up the valley of Mono Creek rather than down it, as in the case of the much smaller Vermilion Valley moraines. These moraines are now deeply notched by Mono Creek (fig. 43). They are the right lateral moraines of the South Fork glacier, and mark the successive borders of the ice which, following the separation of the trunk glacier and the Mono Creek branch, for a time bulged a short distance into the newly evacuated lower Mono Creek valley (fig. 44).

Prominent and almost continuous lateral moraines define the upper levels of the South Fork trunk glacier.

FIGURE 43.—View eastward up the glacially modified canyon of Mono Creek. The high hanging valley on the right is the First Recess, and beyond it appear the entrances to the other hanging canyons known as the Second, Third, and Fourth Recesses. At the right is a "sapline" with frost-riven cliffs above and slopes of exfoliating granite and talus below. Photograph by G. K. Gilbert.

East of Hoffman Meadow are several parallel moraines with definite crests. The highest moraines, traced north-northwestward, end on a spur at the edge of the San Joaquin Canyon, at an altitude of 6,600 feet, east of the mouth of a hanging valley. These moraines in places follow ridges of granite, but on the whole they are laid irregularly, cutting across the drainage lines and ridges at an angle. In several places an indistinct moraine was found just outside the main Wisconsin moraine, and in general parallel to it, suggesting the record of an early maximum of Wisconsin glaciation, similar to the record on both sides of the Little Yosemite Valley (Matthes, 1930a, p. 58–61).

At the junction of the Middle and South Forks, the uppermost lateral moraine on the north side of the South Fork is unmistakable although it is not strong.

FIGURE 44.—Mono Meadow, one of the many meadows characteristic of the rough, unequally glaciated floor of the valley of the South Fork, San Joaquin River.

It meets the multiple lateral moraine of the Middle Fork at an altitude of 6,000 feet above Rattlesnake Lake.

### GLACIERS ON KAISER RIDGE

Eastward-trending Kaiser Ridge presents an interesting contrast in that it has been severely glaciated on the north side and only mildly on the south side.

Glaciers of the south side were relatively small, separate ice bodies. One of the larger ones headed on Kaiser Peak, altitude 10,300 feet, and occupied the valley between Bear and Line Creeks. This glacier was 2½ miles long and descended to 7,400 feet. Its lower positions are indicated by conspicuous loops of moraine, and similar loops define the limits of the smaller Deer Creek, Line Creek, and Home Camp Creek glaciers. Nellie Lake, which lies in a cirque without headwall, although surrounded by mountains of moderate declivity, is impounded by a strong moraine dam, outside of which, on somewhat lower ground, is another much larger and higher morainal embankment.

About 2 miles east of Kaiser Pass, a narrow ice tongue originating at about 10,000 feet descended low enough to coalesce, in part, with the Big Creek glacier. Its terminal portion pushed westward across a divide into the valley of the North Fork of Big Creek, which was ice free. This glacier reached a length of 3½ miles and a lower limit of 7,700 feet. It left a complex of moraines, some of which border Badger Flats. Other moraines, including the right laterals of the Big Creek glacier, have effected the diversion of a stream in the upper valley of Big Creek to the drainage of the North Fork. The trail, which goes south from Badger Flats, passes through the part of the lower valley left streamless by this diversion.

Still farther east on Kaiser Ridge, broad shallow cirques at 10,000 to 10,500 feet contributed ice to the Big Creek glacier, by way of the valley of the East Fork.

On the north side of Kaiser Ridge lay a rank of glaciers that coalesced, along the crestal part of the range, into an almost continuous mantle of ice. At lower altitudes these glaciers, 2 to 4 miles in length, separated into individual lobes, which terminated in valleys on the upland, at altitudes of 7,400 to 4,100 feet. In the eastern part of the range, the glaciers joined the South Fork trunk glacier, at altitudes of 7,500 to 8,500 feet. The lateral moraines of the trunk glacier cut straight across the lower valleys of Kaiser Ridge, marking the well-defined level at which the lateral moraines of the tributary glaciers on Kaiser Ridge abruptly terminate.

The largest glacier on the north side of Kaiser Ridge occupied Kaiser Creek valley. It headed in a series of cirques stretching for 5 miles along the crest of Kaiser Ridge, south of Kaiser Peak Meadows. The ice descended to an altitude of 7,100 feet, about ¾ mile below Sample Meadow. This glacier left an exceptionally fine morainic record, its recessional moraines marking stages not only in the shrinkage of the confluent ice body but also in the final dwindling of the little individual glaciers into which it eventually separated. That the Kaiser Creek glacier at one time was voluminous enough to spill over the saddle east of Sample Meadow, and thus joined the San Joaquin trunk glacier, is attested by the prominent ridges of moraine that descend from the hill to the southeast of the saddle.

Outside the prominent outer morainic loop of the Kaiser Creek glacier is another loop consisting of isolated boulders 50 to 100 feet apart. This loop appears to be an older moraine from which the finer material has been washed away. Yet this moraine is not comparable in age to the moraines of the earlier glacial stage, for its boulders rest on ground resembling that occupied by the younger moraine, that is, ground which has not disintegrated deeply enough to produce pinnacles and crags, but which still shows the smoothing effects of ice. This moraine therefore properly may be regarded as representing early Wisconsin time. It is analagous to similar moraines noted in various places in the Yosemite region.

At Twin Lakes, east of Kaiser Peak, some of the granite erratics of the Wisconsin stage that rest on limestone bedrock have become perched on pedestals, due to relatively rapid reduction of the surface of the limestone by solution and frost action (fig. 45). One boulder 5 feet high and 7 feet long stands on an 8-foot pedestal.

### GRANITE CREEK GLACIER

The glacier which occupied the Granite Creek basin during the Wisconsin stage, and which throughout its existence remained separate from the Middle Fork glacier, was fed from sources mostly situated along the east side of the crest extending southward from Triple Divide Peak, at altitudes of 9,000 to 11,000 feet. These sources formed a continuous gathering field which from north to south was almost 8 miles across. The lower part of the glacier was a blunt lobe which lay about a mile southeast of the Clover Meadow Ranger Station, at an altitude of 6,900 feet. From its source on Triple Divide Peak to this terminus the glacier was 9 miles long. Multiple-crested moraines of this glacier are prominent south of Clover Meadow and in the vicinity of Soldier Meadow.

FIGURE 45.—Erratic boulder of granite on a low pedestal of crystalline limestone, near Twin Lakes east of Kaiser Peak. As a rule, boulders of the later glaciation do not have pedestals, but here the bedrock, being limestone, has been reduced at a relatively rapid rate. Nearby, another erratic 5 feet high and 7 feet long stands on a limestone pedestal 8 feet high.

FIGURE 46.—Glacial erratic on floor of Mono Creek Canyon, below First Recess. Photograph by G. K. Gilbert.

### GLACIERS IN CHIQUITO CREEK BASIN

As in the earlier glaciation, Chiquito Ridge developed glaciers only on its northeast side, where they were small, separate ice bodies. Several of these, all cirque glaciers, were clustered on the east and northeast sides of Shuteye Peak, altitude 8,358 feet; three additional slightly larger glaciers, each about 2 miles long, formed farther to the northwest at altitudes of about 8,000 feet, between Little Shuteye Peak and Texas Flat. The lower ends of these glaciers lay at altitudes of 6,850 to 5,700 feet.

Small glaciers also formed in the extreme head of the basin, on Redtop Mountain and Sing Peak, at altitudes of about 10,000 feet; and ice confluent with the Merced glacier flowed 1 or 2 miles into Chiquito Creek basin, where it left beautiful loops of moraine just south of Chiquito Pass. These moraines are crossed by the trail through the pass.

### GLACIERS IN THE BIG CREEK BASIN

In the Wisconsin stage, glaciers again descended the tributary valleys of Big Creek, but the trunk glacier they produced was small and remained separate from the little glaciers on the central and western parts of Kaiser Ridge. In fact, the glacier in the branch valley of Tamarack Creek failed to unite with its neighbor in the East and South Fork branches of Big Creek valley, though at their sources the ice bodies in places were confluent. The Tamarack Creek glacier was 5 miles long and descended to an altitude of 7,400 feet. The Big Creek glacier was over 10 miles long, following the East Fork, and descended to 6,900 feet. Its terminus was approximately in the middle of Huntington Lake.

In the headwater region of these glaciers, a number of hills and ridges over 9,500 feet high, including Black Peak (fig. 47), were nunataks. Here the upland to-

FIGURE 47.—Black Peak, a volcanic knob situated near the head of the South Fork of Big Creek; in the foreground, Long Meadow. The angular blocks of granite in the meadow were dropped by a glacier of the later stage which filled the meadow to within a few hundred feet of the top of Black Peak. Photograph by G. K. Gilbert.

pography has been only slightly modified by glaciation, but it is littered with drift. Long Meadow is truly a "moraine meadow" and with its many scattered granite blocks it presents a peculiar aspect (figs. 47, 48). Moraine ridges, 10 to 20 feet high, are locally conspicuous.

The lower limits of the Big Creek and Tamarack Creek glaciers are marked by conspicuous moraines. The right lateral moraines of the Big Creek Glacier extend westward from the base of Bear Butte. Near Huntington Lake they deploy northward to the mouth of the North Fork of Big Creek, then again run westward as low, rock-crowned embankments along the north shore of the lake. They decline in height very gradually to a point just west of Bear Creek, where they disappear beneath the lake. The left lateral moraines are massive embankments which flank the north base of Chinese Peak. They continue northwestward to the south shore of the lake, obstructing southward drainage and giving rise to a large wet meadow. Finally they dip into the lake at the end of a rocky promontory about 1 mile west of the mouth of Big Creek. Small rocky islands near the lakeshore carry glacial boulders, and a long line of boulders protruding from the lake near its end, marks the crest of a drowned moraine.

FIGURE 48.—View from the summit of Black Peak (see fig. 47) looking down the length of Long Meadow (altitude 9,000 feet). Long Meadow is typical of the many large upland meadows of the San Joaquin Basin.

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