DEPARTMENT OF THE INTERIOR
Hubert Work, Secretary

U. S. GEOLOGICAL SURVEY
George Otis Smith, Director

PROFESSIONAL PAPER 153

STUDIES OF BASIN-RANGE STRUCTURE

BY

GROVE KARL GILBERT

UNITED STATES
GOVERNMENT PRINTING OFFICE
WASHINGTON
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PREFACE

By George Otis Smith

In the death of Grove Karl Gilbert on May 1, 1918, American geology lost one of its greatest investigators. Although gradually failing in physical strength, he maintained during his last years the same clearness of conception, the same power of analysis, and the same lucidity of expression that had been characteristic of all his previous work. He so wisely conserved his failing health and so regulated his working hours that the quality of his product was not impaired.

The present paper represents the partial fruition of a broad plan to reexamine critically the subject of Basin-Range structure. The chapter on the Wasatch Range is complete. That on the Fish Springs and House Ranges is nearly complete. It was Mr. Gilbert's purpose, I believe, to review and condense the chapter on the Kern River fault and perhaps also that on the Klamath region. This he was not able to do, and the manuscript is published essentially as he left it.

Geologists and physiographers the world over, I am sure, will welcome Mr. Gilbert's mature judgment as set forth in these pages on the validity of a concept which, as a young man, he first gave to the scientific world in 1874. His last paper is thus an amplification and clarification of one which he wrote more than half a century ago. The cycle is now complete.

STUDIES OF BASIN-RANGE STRUCTURE

By G. K. Gilbert

Chapter I. INTRODUCTION

Between the Wasatch Mountains and the Sierra Nevada lies a region traversed by numerous minor mountain ranges. Alternately with the ranges stretch valleys floored by detritus, and the whole system exhibits a rough parallelism. It was early recognized that these mountains are of a peculiar type. Because the district of interior drainage to which Frémont gave the name Great Basin is also bounded on the east and west, approximately, by the Wasatch and the Sierra, the system of peculiar ranges was called the Great Basin system, or the Basin Ranges. It was well known, however, that the boundaries of the orographic province are quite distinct from those of the drainage district. Davis has introduced "fault block" as a descriptive term applicable to the type of structure, and "fault-block structure" has partly supplanted "Basin Range structure" in the literature. If with the advance of knowledge geologists shall conclude that the fault-block structure is not the dominant structure of the Basin Ranges, the term Basin Range structure can no longer be used in its original sense and may properly be abandoned.

Volcanic mountains differ from all others in that they are built by the addition of material to the earth's surface. Leaving them out of account, we may classify mountains broadly as diastrophic and residual. A coordinate classification of valleys distinguishes the diastrophic from the erosional. A simple conception of a system of diastrophic ridges and valleys is that of parallel folds created by tangential compression of the crust. A contrasted conception is that of a plateau dissected by parallel streams, where the resulting valleys are erosional and the resulting ridges residual. Such simple systems of corrugation are, however, ideal rather than actual.

Folding is but one of several diastrophic processes capable of producing mountain ridges and valley troughs, and whatever the process of production the forms are modified by erosion, or by erosion and deposition, during their development. The hypogene forces that make mountains and the epigene forces that make plains work coincidently and in antagonism, and mountains result only when diastrophism is more active than gradation. If diastrophism is feeble its product may never achieve a rank above that of hills. As strong diastrophism wanes and eventually ceases, the epigene forces resume dominance, continuing the work of sculpture which they began on the inception of the deformation and finally reducing ridges and troughs to a common plain.

In the creation of the Appalachian Mountains folding was a leading factor. Stratified rocks were pushed into parallel folds, some of the folds were overturned, and thrust faults were developed. The sculpture that accompanied and followed the deformation was largely a work of selective erosion, valleys being opened in weak rocks and ridges being developed from resistant rocks. The ridges as we know them are related to the folds but are not upfolded crests, and the valleys are related to the folds but are not downfolded troughs. The valleys are erosional and the ridges residual. The system of valleys and ridges, the visible corrugation of the district, has been carved from a complex rock body which owes its structure to tangential compression. A characterisitc feature—a feature observable wherever the rocks are sedimentary and have escaped metamorphism—is that each ridge and valley trends with the strike of the strata. It was through comparison with Appalachian characters that the characters of the Basin Ranges were first recognized and described.

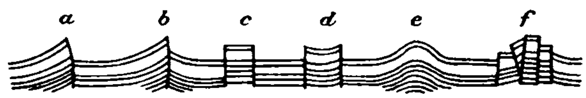

Figure 1.—Diagram of generalized mountain sections, discounting denudation

In outlining the development of knowledge and opinion as to Basin Range structure I find it impossible to avoid the apparent egotism of beginning with my own work. In the summers of 1871 and 1872 I accompanied topographic parties of the Wheeler Survey, passing rapidly through parts of Utah, Nevada, California, Arizona, and New Mexico and gleaning geologic data by the way. A preliminary report was published in 1874 and a fuller report in 1875. The following passages, the first quoted from the preliminary report and the second from the final, summarize my impressions and generalizations as to the Basin Ranges:

> The sections accumulated by our geological observers admit of the following classifications (see fig. 1):
>
> 1. Faulted monoclinals occur, in which the strata on one side of the fault have been lifted, while those on the opposite side either do not appear (*a*) or (less frequently) have been elevated

a less amount (*b*). Two-thirds of the mountain ridges can be referred to this class.

2. Other ridges are uplifts limited by parallel faults (*c*), and to these may be assigned a few instances of isolated synclinals (*d*), occurring under circumstances that preclude the idea that they are remnants omitted by denudations.

3. True anticlinals (*e*) are very rare except as local, subsidiary features, but many ranges are built of faulted and dislocated rock masses (*f*), with an imperfect anticlinal arrangement.

Not only is it impossible to formulate these features by the aid of any hypothetical denudation in such a system of undulations and refoldings as the Messrs. Rogers have so thoroughly demonstrated in Pennsylvania and Virginia, but the structure of the western Cordillera system stands in strong contrast to that of the Appalachians. In the latter, corrugation has been produced commonly by folding, exceptionally by faulting; in the former, commonly by faulting, exceptionally by flexure.[1]

To begin with the simplest generalization, the ranges are a system not indeed formed at the same time but exhibiting certain common characters over a great area. They are parallel; they recur with some regularity of interval; they are of moderate dimensions.

Second. The ridges of the system occupy loci of upheaval and are not mere residues of denudation; the valleys of the system are not valleys of erosion but mere intervals between lines of maximum uplift. Within the ranges there are indeed eroded valleys, and the details of relief show the inequality of erosion due to unequal resistance, but there is not on a grand scale that close dependence of form or durability that must maintain were the great features of the country carved by denuding agents.

Third. The movements of the strata by which ridges have been produced have been in chief part vertical along planes of fracture and have not involved great horizontal compression. There are some notable local exceptions to this, but considering the prevalence of faulted monoclinals, which demand no horizontal motion, the existence of the feature as a distinctive one need not be questioned.

Fourth. We may say, without fairly entering the field of speculation, that the forces which have been concerned in the upheaval of the Basin Ranges have been uniform in kind over large areas; that whatever may have been their ultimate sources and directions, they have manifested themselves at the surface as simple agents of uplift, acting in vertical or nearly vertical planes; and that their loci are below the immediate surface of the earth's crust.[2]

In a classification of mountain forms and structure, published in 1877, Powell characterized the Basin Ranges in essentially the same manner, in a statement based in part on his own observations.

The field work of the Geological Exploration of the Fortieth Parallel was executed in 1867 to 1873 and covered a belt of country 100 miles wide, from the eastern base of the Rocky Mountains to the eastern base of the Sierra Nevada. Its first publication on the geology of the Basin Ranges appeared in 1870 and contained descriptions of individual ranges by King, Hague, and Emmons. The descriptive work was completed in a volume by Hague and Emmons which was issued in 1877, and the broader generalizations were published the following year by King, from whom I quote:

These remarkable quasi-parallel mountain bodies separated from each other by depressed valleys, which are occupied by fresh-water Tertiary and Quaternary beds, are a series of mountain islands lifted above desert plains. They have given rise to considerable discussion, and there is already some difference of opinion between Powell and Gilbert on the one hand and myself on the other. In volume 3, of this series, in a brief sketch of the Green River Basin, I alluded to the Basin Ranges as a series of folds. Powell and Gilbert have called attention to the abundant evidence of local vertical faults and the resultant dislocation into blocks. One of the most common features of the Basin Ranges is a mountain body composed of a steeply or gently dipping monoclinal mass, edged on both sides by the horizontal desert formations, the back of the monoclinal mass consisting of inclined planes of strata, while the other face of the mountain body consists of an abrupt cliff, evidently the result of a vertical fault, which has been more or less modified by a comparatively recent erosion. The frequency of these monoclinal detached blocks gives abundant warrant for the assertions of Powell and Gilbert that the region is one prominently characterized by vertical action; yet when we come to examine with greater detail the structure of the individual mountain ranges it is seen that this vertical dislocation took place after the whole area was compressed into a great region of anticlinals with intermediate synclinals. In other words, it was a region of enormous and complicated folds, riven in later time by a vast series of vertical displacements, which have partly cleft the anticlinals down through their geological axes and partly cut the old folds diagonally or perpendicularly to their axes.[3]

King then describes the relations which the axes of folds within the several ranges bear to the trends of the ranges and proceeds to the following generalization:

While this brief description, from the complicated nature of the facts, may fail to convey a full idea of the state of things on the Basin Ranges, yet a careful scrutiny of the axis lines, as laid down upon analytical maps X, XI, and XII, will show (*a*) that the region is one displaying a continuous series of folds of Paleozoic and Mesozoic rocks; (*b*) that the general trends of these axes approach more nearly a meridian than an east and west line; (*c*) that the axes themselves often display broad general curves traced through a hundred miles, their grander convexities being turned to the west; (*d*) that in detail the axes are further subject to minor sinuosities obviously due to longitudinal compression; and (*e*) that the whole region had been most irregularly invaded by a series of faults which are east and west, north and south, northeast-southwest, and northwest-southeast. The result of this complicated interlacing system of dislocation is that all the ranges of the Great Basin are broken into irregular blocks, sections of which have sunk many thousand feet below the level of the adjoining members. It frequently happens that anticlinal or synclinal axes have been the loci of the fissure planes and that in the accompanying dislocations halves of folds are left in long, well-defined monoclinal ridges. When a fold is cut, either diagonally or transversely, by a fault, there is not infrequently a considerable horizontal displacement, as may be seen in the case of the West Humboldt, where the anticlinal axis is displaced 5 miles horizontally, and in the case of Piñon Range, where there is a still greater lateral movement.

That these faults were not contemporaneous with the great folding period is obvious from their relations to the axis.

[1] Gilbert, G. K., U. S. Geog. and Geol. Surveys W. 100th Mer. Progress Rept., 1872, p. 50, 1874.

[2] Gilbert, G. K., Report on the geology of portions of Nevada, Utah, California, and Arizona, examined in the years 1871 and 1872: U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, p. 41, 1875.

[3] King, Clarence, U. S. Geol. Expl. 40th Par. Rept., vol. 1, p. 735, 1878.

Parallel faults often cut blocks which could never have been formed if the faults were contemporaneous with the folding. When we remember that the Eocene and Miocene Tertiary rocks which have been laid down within the hollows of these post-Jurassic folds have themselves been thrown into waves and inclined positions up to 40° and that these Tertiary beds are often violently faulted, it is evident that in extremely modern geological history there has been sufficient dynamic action to account for the system of faults.[4]

The recognition of two principal epochs of disturbance helped greatly to clarify conceptions of range structure and constituted a valuable contribution to this subject.

The next contribution was by Dutton, whose "Geology of the High Plateaus of Utah" appeared in 1880. In order to characterize vividly the structure of the Plateau province, to which his field belonged, he contrasted it with the structures of two adjoining mountain systems, the Park province of Colorado and the Basin Range province on the west. I quote two passages:

Yet in some portions of this great expanse of territory there are important flexings and warpings of the strata. This is particularly true of the Basin Ranges. But a very significant distinction is necessary here. These flexures are not, so far as can be discerned, associated with the building of the existing mountains in such a manner as to justify the inference that the flexing and the rearing of the ranges are correlatively associated. On the contrary, the flexures are in the main older than the mountains, and the mountains were blocked out by faults from a platform which had been plicated long before, and after the inequalities due to such preexisting flexures had been nearly obliterated by erosion. It may well be that this anterior curvation of the strata has been augmented and complicated by the later orographic movements. But it is not impossible to disentangle the distortions which antedate the uplifting from the bending and warping of the strata which accompanied it, and it is only the latter that we can properly associate and correlate with the structures of the present ranges. These present no analogy to what is usually understood by plication. The amount of bending caused by uplifting of ranges is just enough to give the range its general profile, and seldom anything more. The same fact is presented in the noble ranges of Colorado. Along their flanks the sedimentary strata roll up, usually with a single sweep, and high on the slopes are cut off by erosion. The typical anticlinal axis is not a characteristic feature of the Rocky Mountain system.

The type section of the Park Mountains of Colorado, as given by the late A. R. Marvine, shows a series of broad platforms, uplifted with a single monoclinal flexure or fault on either side. The width of these platforms varies from 20 to 45 miles, and from these masses the individual mountain piles have been carved by erosion. The restored profiles obtained by replacing the material removed by erosion are not indeed horizontal nor straight lines but ordinarily convex upward, with slight curvature, becoming abrupt or even passing into a great fault at the margin of the uplift. Inasmuch as almost any configuration of the strata which is convex upward, be it ever so little, is called an anticlinal, these platforms would probably be so characterized by most geologists. But what a contrast to the short, sharp waves of the Appalachians! If we analyze the form carefully, it will become apparent that we have to do with a structure which has nothing in common with a true anticlinal except this slight convexity and which possesses characters which the true anticlinal does not.[5]

The Basin Ranges are many in number and inferior in magnitude to those of Colorado, though of no mean dimensions. They are strongly individualized, each being separated from its neighbors by broad expanses of plains as lifeless and expressionless as Sahara. It is as difficult to find a type form representing the construction of these ranges as for those of Colorado. Yet there are common features of almost universal prevalence among them and at the same time thoroughly distinctive of the group. There is on one side of the range sometimes a single great fault or more frequently a repetition of faults throwing in the same direction while upon the other side the strata slope down to the neighboring plains and there smooth out again. There is much variety in the details of the dislocations, and so complicated do they become in certain localities that they sometimes mask the general plan until we carefully unravel it. The strata also are almost invariably tilted to high degrees of inclination, thus contrasting strongly with the low and almost insensible slopes of the plateaus. Hence on one side of the range the slope of the profile is along the dip of the strata; on the other side it is across their upturned edges.[6]

The idea that the Great Basin district, corrugated by folding at the end of the Jurassic period, had been reduced by erosion to a condition of low relief aids the conception that the mountains of to-day were created by the later and disruptive deformation. It is distinctly Dutton's addition, although King had paved the way for it by pointing out that the district had furnished a great body of sediment to Cretaceous seas farther east.

A study of Quaternary lakes in northern Nevada and adjacent parts of Utah, Oregon, and California, which was carried on by Russell in the years from 1880 to 1885, gave him large opportunity for observation of the external features of Basin Ranges, and his reports contain much new orographic material. His characterization of the general structure follows the lines of his predecessors and serves only to show that his observations supported no dissent, but his generalizations amplify the subject by recognizing what may be called a subtype of Basin Range structure. In the great lava field of the Columbia-Snake Basin the lava is largely disposed in horizontal beds, so that the body of effusive material has a stratified structure and its upper surface constitutes a plain. In a district bordering the plain Russell found a system of mountain ridges composed of the same material but with the beds inclined, and these ridges he described as portions of the original plain which had been dislocated by faulting and tilting. There was no evidence of folding, and he therefore inferred that the lavas had been erupted after the post-Jurassic period of folding described by King and before the Tertiary and post-Tertiary period of deformation by fracture.[7]

[4] Idem, pp. 742-743.

[5] Dutton, C. E., Geology of the High Plateaus of Utah, pp. 47-48, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1880.

[6] Idem, p. 51.

[7] Russell, I. C., A geological reconnaissance in southern Oregon: U. S. Geol. Survey Fourth Ann. Rept., p. 443 (especially), 1884.

It is a remarkable fact that during this development of a theory as to the essential structure of the ranges the observers who reported the existence of faults gave no adequate statement of the evidence on which their determinations were based. In a local description I said:

Worthington Mountain * * * is remarkably acute in its cross section. The strata are nearly horizontal but incline slightly to the east and pass completely through so as to appear on both sides. * * * At the southern end the limestones of its section are uncovered and spring abruptly from the talus of gravel. I can conceive of no erosion that should have left this thin segment as the remnant of an inclined table or of a fold. Its narrowness, its straightness, and its isolation mark it as a mass of strata thrust upward between two faults—strata of which the companion parts lie beneath the débris at its foot.[8]

Emmons, in his description of the Wasatch Range, says: "Nor could one imagine an erosion which would leave an abrupt wall of 7,500 feet in height on one side of a valley nearly 20 miles wide."[9] In 1890 I had occasion to consider the relation of the Quaternary Lake Bonneville to diastrophism and wrote: [10]

In the district of the Great Basin the characteristic structure of mountain ranges is one in which faults play an important part. Foldings of strata are not wanting, but the greater features of relief appear to have been wrought by the displacement of orographic blocks along lines of fault. Sometimes a mountain range consists of a great block of strata cut off along one side by a profound fault and inclined in the opposite direction until it descends beneath the plain constituted by the alluvial deposits of the adjacent valley. More frequently there are other faults within the range, trending parallel to its length and having throws on the same side with the throw of the greater fault at the base.

It was probably these internal faults which originally suggested the structure of the ranges as faulted orographic blocks; but the structure was soon connected with a certain set of topographic features and came to be recognized by means of these. A range consisting of a faulted block generally has a bold front on the side of the fault and is less abrupt on the opposite slope. On the side of the bold front the line separating the rock of the mountain from the alluvium of the valley is simple and direct, while on the opposite side it is tortuous. On the side of the fault the strata usually dip away from the adjacent valley; on the opposite side, toward it. It was not until after the structure had been discovered and described by several geologists that the more decisive evidence afforded by the fault scarp was brought to bear. The writer first became aware in the summer of 1876 that lines of faulting may sometimes be traced upon the ground by means of low cliffs or scarps due to displacement of so recent date that the atmospheric processes of sculpture have not yet restored the ordinary forms of topographic detail. Since that time he had observed many such scarps in various parts of the Bonneville Basin and in other portions of the Great Basin, and the observation has been still further extended by others, especially by Russell.

The observed fault scarps for the most part follow the outcrops of fault planes whose position had previously been inferred from the configuration of the adjacent mountains, but they have served also to betray a number of faults whose existence might otherwise not be suspected.

These meager and in part belated statements contain the only indications of the grounds of our faith, and this despite the fact that the recognition of faults by means of physiographic characters was practically novel. Their failure to satisfy the real needs of the subject was shown by the discussion which arose a decade later.

In 1900 Spurr made a geologic reconnaissance in the Great Basin, crossing it in an east-west direction on three different lines, and the following year he published a discussion of Basin Range structure. His paper treats of the structure of individual ranges as observed by himself and others, gives a history of deformation in the province, considers the relative ascendancy of erosion and deformation and the relative ascendancy of erosion and faulting, gives a history of the development of the fault theory as applied to the ranges, and closes with the following analysis and summary: [11]

The present writer, seeking the foundation of facts on which rests the fault theory of the origin of the Basin Ranges, has been obliged to fall back almost wholly on the original work of Mr. Gilbert, who appears to have conceived the hypothesis. The views of subsequent investigators seem to have been based chiefly on the a priori assumption that all the scarps of the region were necessarily fault scarps, and much of the literature has been prepared with little or no personal acquaintance with the field.

Analyzing Mr. Gilbert's reasons for the propounding of the hypothesis, moreover, we find them almost wholly physiographic. The frequently abrupt ascent of the mountains from the level desert and the proximity of the great fault scarps of the Colorado Plateau seem to have suggested the idea. They may be epitomized as follows:

(1) The ranges are principally monoclinal blocks. (2) These blocks are limited on one or both sides by scarps. (3) These blocks and scarps can not have been formed by erosion and must therefore be fault scarps.

On this foundation there rests a great superstructure of theory and deduction.

The refutation of these points may be summarized from the foregoing pages:

1. According to the accumulated record of observation, ranges consisting essentially of a single monoclinal ridge are exceedingly rare. The writer does not remember a single instance where such a structure was persistent when followed sufficiently far along the strike. The apparent monocline almost invariably merges into a synclinal or anticlinal fold, of which it constitutes one of the limbs.

2. The writer has undertaken to show that the mountain fronts studied are, in general, not marked by great faults, and, conversely, that the ascertainable faults are very rarely attended by simple fault scarps.

3. In regard to the impossibility of erosion producing the desert ranges as we have them, especially the monoclinal ridges, the writer finds chiefly the most normal type of erosion in the Great Basin. In this point, however, he is glad to call the opinion of Mr. Clarence King to his aid, who has shown that in the Fortieth Parallel region the monoclinal ridges are in most cases parts of anticlinal or synclinal folds and can be traced into them longitudinally.[12]

[8] Gilbert, G. K., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, p. 37, 1875.

[9] Emmons, S. F., U. S. Geol. Expl. 40th Par. Rept., vol. 2, p. 345, 1877.

[10] Gilbert, G. K., Lake Bonneville: U. S. Geol. Survey Mon. 1, pp. 340–341, 1890.

[11] Spurr, J. E., Origin and structure of the Basin Ranges: Geol. Soc. America Bull., vol. 12, pp. 264–266, 1901.

[12] Spurr here gives reference to "Geological Exploration of the Fortieth Parallel, vol. 1, p. 737," but I fail to discover on that page any allusion to erosion. On the contrary, King describes certain portions of the Gosiute and Peoquop Ranges as monoclinal and interprets them as the western halves of anticlinals, the entire eastern halves "having been dislocated downward out of sight."—G. K. G.

The conclusion is that the topographic forms of the Great Basin, as we see them, are the net results of compound erosion active since Jurassic times, operating on rocks upheaved by compound earth movements which have been probably also continuous during the same period. Only the more recent faults or folds find direct expression in the topography, as in most others deformation lags behind erosion. This is true chiefly of the local movements, which produce faulting and folding, and not of vast general upheavals and depressions, which seem relatively rapid. But folding and especially faulting are of irregular speed, while erosion is more uniform, so that local deformation may outstrip erosion for a time but in any long period is likely to be beaten itself. Thus of the faults in the Great Basin, among them even some post-Pliocene faults, nearly all have no direct expression in the topography. Nevertheless, some Pleistocene faults are expressed in the topography, and these have sometimes a very great displacement, as in the Colorado Plateau.

In the case of the Grapevine Mountains the range appears to have been already in existence in pre-Eocene or Cretaceous times. In some of the mountains of erosion which have not suffered comparatively recent deformation, as has the range just mentioned, their ancient origin is still more clear, for the Tertiary beds rest against their bases unconformably, generally occupying only the present valleys and not being found in the mountains. Therefore the main system of ranges was probably laid out in pre-Tertiary times. It was at the close of the Jurassic, so far as we can judge from the rather scant evidence, that the Great Basin region was uplifted above the sea and plicated. During the Cretaceous the region was probably a land mass, and this was very likely the period when many of the ranges were differentiated. Their regularity is no more than one would expect in view of their resulting from parallel folds and is not so striking as in the Appalachian region. To explain this early dissection we must assume a greater precipitation than now and must conclude that the country was traversed by many rivers. Subsequently the climate became arid and the water supply was not sufficient to remove the detritus from the valleys, which filled up, so that for a long period the reverse of differentiation, or leveling, has been going on. Nevertheless the Tertiary rocks show that warping, folding, and faulting went on continuously all through the Tertiary into the Pleistocene and is even now progressing. To this warping, doubtless, the Tertiary lake basins were due.

According to this conclusion these mountains are not simple in origin and structure. However, the writer would compare the typical Basin Range to the less compressed portions of the Appalachians and the Alps. Among the exceptional types of ranges the Funeral Range type is conspicuous. This has a structure similar to that of a portion of the Jura Mountains, as described and figured by Professor Davis.[13]

It is not easy to summarize the considerations which cause Spurr to infer erosion where others have inferred dislocation, but they are in part illustrated by the following passage:

The Ombe Mountains are situated at the extreme western edge of Utah, near the Nevada line. According to Mr. King,[14] the structure in the southern portion is an anticlinal fold, which has a northeast-southwest strike and thus diverges from the general north and south trend of the range. Northward this fold is succeeded, on account of this divergence, by the adjacent synclinal. Still farther northward the entire range has a uniform westerly dip, apparently representing one side of the next anticlinal fold, the other side having been removed by erosion. The east face of this portion of the mountains is a steep escarpment several thousand feet high, which is supposed by Mr. King to be a fault scarp. Mr. Hague, who has described in detail the range and from whose descriptions Mr. King's conclusions are presumably drawn, does not mention the fault, although agreeing with the description already given of the folds.

From the above, especially the fact of the ridge being for at least a portion of its length synclinal, it is probable that the mountains, on the whole, are due to erosion.[15]

Davis's first contribution to the subject took the form of a critical review of Spurr's paper.[16] Afterward he twice visited the Great Basin in order to study the physiography of the ranges, and each visit was followed by a publication.[17] The three papers are of signal value in that they furnish definite physiographic criteria for the recognition of mountain faces which have been produced by faulting. Some, perhaps most of the criteria had doubtless been used by one or another of the earlier observers. Their recognition of faults marginal to the ranges would otherwise have been impossible, but the criteria had not been formulated, and their formulation was essential to demonstrative and convincing diagnosis of individual ranges.

In the following abstract of Davis's results no attempt is made to preserve his terminology, and the sequence of his presentation is also ignored. It is to be observed, moreover, that some matters which might properly receive mention are omitted because I shall have occasion to cite them in other connections.

1. On the assumption (*a*) that a normal fault of orographic magnitude is gradually produced in a region initially of low relief and underlain by homogeneous rock, (*b*) that the disjoined crust blocks are at the same time tilted in the direction toward the (relatively) uplifted block, (*c*) that the drainage conditions are such that débris from the lifted block is deposited on the thrown block, and (*d*) that the rate of faulting is such that the dissection of the rising block keeps pace with it, there will result: (*a*) The horizontal plan of the mountain base—the line of contact between the rising block and the deposited detritus—will be a line of simple curvature. (*b*) There will be a definite change of slope along this line. (*c*) There will be carved in the mountain block a series of canyons, and these will hold their V section to the mountain base. (*d*) The interstream ridges will end abruptly at the mountain base, their ends being alined along that base. (*e*) The ends of the ridges, if unmodified by erosion, will be triangular facets, having the slope of the fault plane. Their modification by erosion will tend to dissect them by steep, short canyons, between which there will be triangular facets.

2. If the faulting is more gradual, or if after a period of activity it becomes slower, the dissecting canyons

[13] Davis, W. M., Physical geography, p. 168, 1899.

[14] U. S. Geol. Expl. 40th Par. Rept., vol. 1, p. 736, 1878.

[15] Spurr, J. E., op. cit., p. 221.

[16] Davis, W. M., Science, new ser., vol. 14, pp. 457-458, 1901.

[17] Davis, W. M., The mountain ranges of the Great Basin: Harvard Coll. Mus. Comp. Zoology Bull., vol. 42, pp. 129-177, 1903; The Wasatch, Canyon, and House Ranges: Idem, vol. 49, pp. 17-56, 1905.

will not hold the V section to the mountain base but will broaden their beds, and the flood plains within their wider mouths will be continuous with the alluvial fans outside the mountain base. The spur ends will still be alined, but in their maturer sculpture the definite facets will not appear.

3. When the movement creating the mountain has ceased the broadening valleys of dissection will eventually coalesce in their lower parts and the separating spurs will then no longer reach the line of the fault; the mountain base, or rock base—the line separating visible rock bodies from the alluvial slope—will be sinuous, winding in and out among sprawling spurs, and the features peculiar to an uplifted ridge will be lost.

All the typical characters under paragraph 1 are subject to modification by local conditions, and especially by inequality in the power of the rocks that constitute the uplifted block to resist the agencies of sculpture.

Wherever the mountain range is composed of bedded rocks and the structure lines are oblique to the margin of the range, the margin is presumably determined by a fault, for in a system of residual ranges, determined by selective erosion, the margins run parallel to the lines of structure. As it is quite possible that a marginal fault may coincide with the strike of the beds it dislocates, faulting is not disproved by accordant structure lines, but discordance of structure lines is a character indicative of faulting.

Davis discusses also the topographic development of the back slope of a titled block, as well as that of a block lifted between two faults. His formulation of criteria is largely deductive, but all the criteria were tested by observation, and his papers illustrate their application in the diagnosis of range type by a number of examples.

After Davis's visit to the Wasatch and other ranges and before the printing of his second paper, the material of the paper was communicated in oral abstract to the Geological Society of America as part of a symposium on Basin Range structure. In continuance of that discussion Johnson wrote on the structure of block mountains in New Mexico,[18] dealing particularly with the fault systems of the Sandia and Magdalena Mountains. The displacement in each of these areas is distributed through a large number of faults, which agree in the direction of their throw but differ as to the amount. The mountain range, in each area, exists because the displacement on a particular plane is large.

The second of Davis's papers was followed in 1904 by a contribution by Louderback.[19] He studied a group of ranges near Humboldt Lake, Nev., with special reference to the question of structural type. As compared with the work of the Fortieth Parallel Exploration his study had the advantage of specially focused attention. It differed from that of Davis in that it included features of internal structure as well as of external form. Its geographic field comprised the Humboldt Lake Range, the adjacent intermont valleys, the southern part of the Star Peak Range, and a portion of the East Range called Table Mountain.[20]

The body of each range consists of Triassic and Lower Jurassic strata, which are folded and faulted. They are also somewhat altered and are invaded by plutonic rocks. Collectively the Mesozoic strata and intrusive rocks are called the bedrock complex. Above the bedrock is an unconformable series of volcanic rocks, comprising rhyolite and tuff below and basalt above. Although the areas covered by this series are not now continuous they are correlated by means of common characters, and it is believed that they were originally connected, the lavas covering a large part of the district. Prior to the epoch of eruption the surface had been reduced by erosion to a condition of low relief; after the spreading of the basalt it was a gently sloping plain. The deformation that created the existing ranges and valleys took place after the epoch of eruption, and its type is expressed in the present attitudes and relations of the volcanic beds. The basalt surfaces in particular serve to characterize the deformation. No folds are thus shown but many faults, and the faults are normal. The eastern slope of the West Humboldt Range is sheathed by basalt, which inclines in unbent blocks to the east. The west slope exposes little besides the bedrock complex with its ancient folds but nevertheless affords evidence of the later faulting. There are minor features of sculpture interpreted as consequent on relatively recent normal faulting because not yet adjusted to the distribution of more or less resistant rock masses. The line of the mountain base runs independently of the strikes of Mesozoic strata; the mountain gorges are narrow to the mountain base, where they end abruptly; the mountain spurs also end abruptly along the same line; and these characters serve to indicate the position of a marginal fault. The history and structure thus indicated are portrayed by Louderback in diagrams.[21]

The Star Peak Range stands en échelon with the Humboldt Lake Range, its western base touching the eastern base of the Humboldt Lake Range where their ends overlap. The line of contact is also a

[18] Johnson, D. W., Block mountains in New Mexico: Am. Geologist, vol. 31, pp. 135-139, 1903.

[19] Louderback, G. D., Basin Range structure of the Humboldt region: Geol. Soc. America Bull., vol. 15, pp. 289-346, 1904.

[20] The East Range of Louderback appears on the Fortieth Parallel maps as the Pah-Ute Range. The Humboldt Range of Louderback, which is made up of the Humboldt Lake and Star Peak Ranges, is the "Koipato or West Humboldt Range" of the Fortieth Parallel maps and is quite distinct from the Humboldt Range of the Fortieth Parallel maps, which is 150 miles farther east. The southern parts of both ranges appear on the topographic map of the Carson Sink quadrangle published by the U. S. Geological Survey. On that map Louderback's "East Range" is entitled Stillwater and his "Humboldt Range" Humboldt.

[21] Louderback, G. D., op. cit., p. 308.

fault line, and the relative uplift is on the side of the Star Peak Range. The dislocation is interpreted as an element of the later period of deformation, although the basalt does not contribute its direct evidence at this point. Elsewhere the presence of a fault following the western base of the range is indicated by the same features as in the Humboldt Lake Range and in addition by the occurrence of a fresh scarp in the alluvial apron just outside the mountain base.

Table Mountain, east of the Humboldt Lake Range and separated from it by a wide valley, bears a cap of volcanic rocks in which the beds are nearly horizontal. The basaltic surface is not a simple plane but is composed of a number of minor plane elements, which stand at different levels and are separated by sharp vertical breaks or by channels of erosion. The slopes on both sides of the table are occupied chiefly by the bedrock complex, but on the west there is a partial covering of basalt. This cover is not a continuous inclined sheet but is a series of horizontal bodies constituting steps, and there is evidence that a compound fault separates the tabular mountain from the valley west of it.

The alluvial surface of the valley between the Humboldt Lake Range and Table Mountain is interrupted in one place by a small ridge that is a miniature of the Humboldt Lake Range. It has the same trend and is composed of the same bedrock complex, with an overlying body of similar volcanic rocks, which dip eastward and are sliced by parallel normal faults. The valley west of the range contains two allied occurrences, in one of which the lava beds dip to the northeast and in the other to the north.

This relatively detailed local study serves to verify, so far as the features of one locality may verify, several of the results of earlier studies, and it adds materially to the mental picture of Basin Range structure. By the aid of the volcanic beds the results of earlier and later deformations are clearly differentiated, and the later deformations are shown to be alone responsible for the greater features of the existing relief. At the same time the block faulting is shown to be less simple than would be understood from some of the earlier descriptions and to correspond essentially to the type described by Johnson. Instead of a system of simple, broad, tilted blocks, each one of which determines a range by its higher edge and a valley by its lower, there is a more complicated system of dislocation and one which involves a less extreme contrast in altitude between the structural mountains and structural valleys.

In a series of papers,[22] the first of which appeared in 1908, Keyes advanced and amplified the theory that the Basin Ranges are largely remnantal, their prominence having resulted from differential degradation, in which the wind has been chief agent. The ranges exist because their rocks are harder than those of the intermont valleys. They have steep fronts because deflation is at a maximum along their bases. Alined truncation of mountain spurs is not demonstrative of faulting, for it may result also from eolian widening of valley plains by lateral corrasion. Keyes's citation of localities indicates that the theory was developed among the desert ranges of New Mexico, but it has been applied also to the mountain system of the Great Basin. Speaking of the Great Basin, he says:[23]

> The present mountains seem to owe their existence not so much to general flexing or to recent and profound faulting as they do to the differential effects of true desert leveling, in which the most resistant rocks longest retain the highest elevations.

In another place,[24] after discussing the relative efficiency of erosional processes, he concludes:

> The American arid country was at the beginning of the present geographic cycle essentially a peneplain recently uplifted. This conclusion is believed to be amply attested by the great remnantal plains which are still found standing high above the existing plains surface. Above the latter more than 4,000 feet rises, for instance, the unique Mesa de Maya. The numerous plateau plains of the dry region appear to have a like significance.
>
> The evolution of the present relief expression of the desert country is not believed to be from a surface initially of rugged mountainous topography and through the sculpturing agencies of running water but is thought to be from a plains surface through eolation principally.
>
> The origin of the Basin Ranges and of the desert ranges generally is therefore regarded as due in the main to extensive and vigorous differential deflation on a region that had been previously flexed and profoundly faulted and then planed off, bringing narrow belts of resistant rocks into juxtaposition with broad belts of weak rocks, the former now forming the desert highlands and the latter the desert lowlands, or intermont plains.

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[22] Keyes, C. R., Arid monadnocks: Jour. Geography, vol. 7, pp. 30–33, 1908; Some relations of the older and younger tectonics of the Great Basin region: Iowa Acad. Sci. Proc., vol. 15, pp. 145–146, 1908; Differential effects of eolian erosion upon rock belts of varying induration (abstract): Science, new ser., vol. 29, pp. 752–753, 1909; Erosional origin of the Great Basin ranges: Jour. Geology, vol. 17, pp. 31–37, 1909; Relations of present profiles and geologic structures in desert ranges: Geol. Soc. America Bull., vol. 21, pp. 543–564, 1910; Fault scarps of the Basin Ranges (abstract): Science, new ser., vol. 33, p. 466, 1911; Critical criteria on Basin Range structure: Science, new ser., vol. 37, p. 226, 1913; False fault scarps of desert ranges: Geol. Soc. America Bull., vol. 26, p. 65, 1915. The subject receives attention also in the following papers: Base-level of eolian erosion: Jour. Geology, vol. 17, pp. 659–663, 1909; Deflation and the relative efficiencies of erosional processes under conditions of aridity: Geol. Soc. America Bull., vol. 21, pp. 565–598, 1910; Deflation scheme of the geographic cycle in an arid climate: Geol. Soc. America Bull., vol. 23, pp. 537–562, 1912; Arid plateau plains as features of eolic erosion: Iowa Acad. Sci. Proc., vol. 19, pp. 157–162, 1912.

[23] Keyes, C. R., Geol. Soc. America Bull., vol. 21, p. 549, 1910.

[24] Idem, p. 598.

Of the "fault scarps" of the Basin Ranges he says:[25]

In the instance of the Basin Range type of mountain structure normal faulting on a prodigious scale was long regarded as the principal factor. Its mountain block was considered as upraised. The face of the hard mountain rock rising abruptly out of the less resistant valley deposits was believed to represent a true fault scarp. This hypothesis is not exclusive, nor is it very satisfactory.

A main objection to the theory is the fact that the evidences of recent displacement are seldom ever disclosed at or even near the so-called fault scarps. Whenever the line of major faulting is discovered it is miles away from the mountain foot, out on the intermont plain.

On the theory of general denudation of arid regions chiefly through means of eolic rather than aqueous agencies the belt of maximum deflation is at the foot of the desert ranges, where the mountain meets the plain. Within the limits of this narrow belt the topographic result is a tendency toward a steep, plainlike slope. This piedmont belt chances also to be the horizon where torrential water action is most pronounced, cutting deep canyons in the mountain and spreading out detrital fans on the plains. In the struggle between water and wind for corrosive supremacy the results in the mountain area are a succession of sharp ridges trending at right angles to the range axis, sharply truncated at their lower end by deflative action. The faceted mountain foot thus produced resembles closely the ideal effects of a fault-bounded upraised mountain block the dissection of which is well advanced.

The following passage[26] is preceded by a statement of the work of wind in grading plains:

Whenever bare or hard rock masses are encountered, there is vigorous sand-blast action. Thus, hypsometrically, among the desert ranges, which are all composed of very hard rocks usually devoid of a soil mantle, the notably exposed zone is at the very base of the mountains, or immediately above the surface level of the surrounding plains. This is probably the chief reason why there are no foothills flanking the mountain ranges of the desert, why mountain and plain so sharply meet, and why the bases of the desert ranges are often so abrupt and straight as to suggest at once the presence of fault scarps as an explanation of the steep faces of the mountains.

When we institute search for direct evidences of fault lines which are supposed to give rise to escarpments, we usually look in vain. Although the mountain may be a faulted block the movement, however profound, is commonly discovered to be of ancient date. Its fault plane is found to be far out in the plain, often at a distance of 4 or 5 miles. The intervening space has a smooth and gently sloping rock floor and has every appearance of a marine plain of denudation from which the sea has but recently retired.

In a later note, after ascribing to Spurr an assertion "that no one has ever seen the fault lines blocking out the desert ranges," Keyes[27] says:

With the challenge of the Basin Range hypothesis there has come a demand for citations of concrete examples in support of the theory. Thus far, after the elapse of a full decade and after frequent repetition of the demand, the evidence has not been forthcoming.

Baker's contribution to the subject[28] was based on observations made during three expeditions into different regions of the southwestern part of the Great Basin. Those expeditions were primarily concerned with Tertiary formations and with the history recorded in their deposition, deformation, and erosion. Strata of later Tertiary age have been folded and then beveled by erosion, and the erosion surface cut from them has in places been warped into valley synclines and mountain anticlines and elsewhere faulted. The faulting is in part associated with grabens and in larger part with tilted blocks. The longitudinal profile of a block-faulted range is essentially that of the longer axis of an anticline. Some of the Basin Ranges are structural upwarps. Many of the intermont basins are true spoon-shaped synclines.

In the Death Valley region, where faulting has probably taken place on as great a scale as anywhere in the Great Basin, closely folded Tertiary strata, referred to the Miocene by Spurr and Ball, bound the valley side of the Funeral Range fault. It is difficult to conceive how this folding and thrusting can have been caused by tensional stresses manifested in normal faults.[29]

The recency of the movement to which the existing Basin Ranges owe their forms is such as to leave intact, in large measure, the superficial rocks of the lithosphere, even when these lie high in the zone that was affected by fracture during this deformation. We know this because there is still preserved much of the erosion surface developed previous to this deformation. It also happens that a large portion of this superficial rock is of a competent nature and, without any load, seems quite as likely, or more likely, to break than to fold. The Basin Ranges may very possibly have originated by tangential compression. Their present elevations and structures may be a joint product of the initial intensity of the deformative forces and of the relative resistance to deformation of the strata involved. This is a very elementary conception but is as far as the writer is willing to go on his present data.

The mid-Mesozoic deformation was apparently the most intense, the folds in the Death Valley region and in the Pilot Range being as close as those of the central Appalachians. The first later Tertiary deformation was probably on the whole less intense, although locally noncompetent beds are closely crumpled and overthrust. The writer's studies have not been of such a detailed nature as clearly to separate the effects of these two movements on the older rocks. The most recent deformation is the least intense, at any rate as exhibited on the surface but is the one which is responsible for the present orographic features of the Basin Ranges. What has happened in the zone of flow, or in the zone of combined fracture and flow, during this latest deformation, we have no means of knowing, since erosion has not yet laid bare these zones. But it is probable that in the southwestern portion of the Great Basin the competent brittle rocks at the surface or close to the surface have deformed somewhat differently from the dominantly sedimentary rocks of the Rocky Mountains, the Jura, the California Coast Ranges, the central and northern Appalachians, the Alps, and the Himalayas, which are taken as classic types of tangentially compressed mountains.[30]

The subject of the preceding summary is the development of opinion as to the general nature of the structure of the Basin Ranges. The growth of knowledge of range structure has been mentioned only as it has affected the development of opinion, and problems of primary causation have been avoided. In the chapters which follow I shall present and discuss the results of

[25] Keyes, C. R., Science, new ser., vol. 33, p. 466, 1911.
[26] Idem, vol. 29, p. 753, 1909.
[27] Idem, vol. 37, p. 226, 1913.
[28] Baker, C. L., The nature of the later deformations in certain ranges of the Great Basin: Jour. Geology, vol. 21, pp. 273–278, 1913.
[29] Idem, p. 275.
[30] Idem, pp. 277–278.

personal observations not previously published. Up to a certain point the development of opinion was harmonious, in the sense that each new view was an amplification of the preceding and was accepted by earlier investigators, but the harmony was broken by Spurr and has not since been restored. The stimulus of an antagonistic view sent Davis to the field and focused the attention of Louderback and Baker, and whatever the merits of the view its announcement has been eminently successful in the promotion of critical inquiry. It remains to be seen whether an equal promotion will result from the equally radical contention of Keyes. My own later work received its impulse from Spurr's paper. I went to the field the following summer and visited a number of ranges in central and western Utah. An accident prevented prompt publication of my observations, and the motive for early publication was afterward largely removed by the appearance of Davis's papers, which anticipated many of my results. In returning to the subject at the present time I am able to add the data from a number of brief local studies in Utah, Oregon, and California.

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Chapter II. WASATCH RANGE, UTAH

GENERAL FEATURES

The general trend of the Wasatch Range is with the meridian. As seen from the west it is a bold, high ridge. From the east its aspect is less commanding. Its western face is an escarpment, springing abruptly from the broad, low valley plains. Its eastern flank is joined to a mountainous upland, which has in part the character of a dissected plateau. The drainage of its eastern flank all reaches the western lowland, a small part only passing around the ends of the range and the remainder crossing its axis in a series of deep gorges. Because it is bordered on one side only by valley plains, such as are characteristic of the Great Basin, it has not always been classed with the Basin Ranges, but it is their close ally in history and structure.

With a length of 130 miles, from Nephi to Collinston, it has a general height above the bordering plains of 4,000 feet, and a dozen peaks rise from 1,500 to 4,000 feet higher. Beyond Collinston at the north a low ridge reveals the continuance of the axis of uplift and ties the Wasatch to an unnamed range northwest of Cache Valley. Beyond Nephi at the south the axis is represented for 30 miles by the San Pitch Mountains, a little-studied range of plateau type.

The structure is complex, and our knowledge of it is imperfect. Certain general features were determined by the exploratory work of Emmons [1] and Hague,[2] others have been contributed by Blackwelder [3] and Loughlin,[4] and local details have been added by Howell,[5] Boutwell,[6] Butler,[7] and Hintze,[8] but the work of comprehensive and adequate study has not yet been undertaken. The following sketch of structure and history, which is based on the recorded work of these geologists, is necessarily incomplete and in certain respects is provisional. Such contributions as have resulted from my own recent field work are not here included but will be found in a review at the end of the chapter.

The rocks that compose the body of the range are of Archean, Algonkian, Paleozoic, Triassic, and Jurassic age, and there are large masses of granite. Two notable unconformities have been recognized among the sedimentary formations, but, so far as known, deposition was continuous from Carboniferous to Jurassic time. The Jurassic deposition was followed by a diastrophic revolution. The formations were folded and faulted on a grand scale, and among the faults were extensive overthrusts. The intrusion of the granite bodies is assigned to the same period. The mountains and valleys created by these dislocations were not coincident with the present mountains and valleys. The position of the uplift associated with the intrusions is now marked, it is true, by lofty summits, but the line of the adjacent profound syncline crosses the Wasatch Range, in the latitude of Salt Lake City, at right angles. At the south the axis of an important anticline enters the present range obliquely, and at the north the upbuilding by overthrust is not expressed by the existing relief.

The topography created by dislocation was so far reduced by erosion in Cretaceous time that a transgression by the sea spread sands of Dakota age over worn edges of Jurassic, Triassic, and upper Carboniferous strata. The evidence of that transgression has been found only on the eastern flank of the range. After the retreat of the sea came other crustal changes, and then a long period of relative quiet in which the general movement of detritus was from west to east and a broad area at the east received terrestrial and lacustrine deposits. These deposits, which are referred to the Eocene, rest in the Wasatch district on all formations of earlier date, from Archean to Cretaceous. At the extreme south and also near Salt Lake City their original area appears to have included portions of the Wasatch axis. In the Wasatch district the Eocene strata have been moderately flexed and faulted, and they have been involved in the greater displacements which created the Wasatch Range.

The diastrophism to which the greater features of the present relief are due is clearly post-Eocene, but the date of its beginning can not yet be assigned. Its changes have continued to the present time, but only a small fraction are post-Pleistocene. They appear to have made large progress before an epoch of Pliocene time when lake beds were deposited in a chain of valleys adjoining the eastern flank of the range,

[1] Emmons, S. F., Wasatch Range: U. S. Geol. Expl. 40th Par. Rept., vol. 2, pp. 340-392, 1877.

[2] Hague, Arnold, Northern Wasatch region: Idem, pp. 393-419.

[3] Blackwelder, Eliot, New light on the geology of the Wasatch Mountains, Utah: Geol. Soc. America Bull., vol. 21, pp. 517-542, 1910.

[4] Loughlin, G. F., Reconnaissance of the southern Wasatch Mountains, Utah: Jour. Geology, vol. 21, pp. 436-452, 1913.

[5] Howell, E. E., The Basin Range system of southwestern Utah and southeastern Nevada: U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, pp. 231-264, 1875. (See pp. 231-237, 251-253.) Howell's publication preceded the more comprehensive account of the Provo Wasatch by Emmons (1877), but his field studies (1872) followed those of Emmons (1869), and some of Emmons's results received advance publication by King in 1870. (See U. S. Geol. Expl. 40th Par. Rept., vol. 3, pp. 451-456, 1870.)

[6] Boutwell, J. M., Stratigraphy and structure of the Park City mining district, Utah: Jour. Geology, vol. 16, pp. 434-458, 1907; Geology and ore deposits of the Park City district, Utah: U. S. Geol. Survey Prof. Paper 77, 1912.

[7] Butler, B. S., and Loughlin, G. F., A reconnaissance of the Cottonwood-American Fork mining region, Utah: U. S. Geol. Survey Bull. 620, pp. 165-226, 1916.

[8] Hintze, F. F., A contribution to the geology of the Wasatch Mountains, Utah: New York Acad. Sci. Annals, vol. 23, pp. 85-143, 1913.

but they were even then so far from completion that the lake beds themselves have been faulted and tilted.

One crustal change of the Tertiary system was of a broad or epeirogenic character and resulted in a general reversal of the slopes controlling drainage. The field of Eocene deposition became an upland, and a western district, which had been a field of Eocene degradation, became a lowland. The upland is part of the physiographic province known as the Colorado Plateaus, and the lowland is part of the Basin and Range province. At the north the boundary between the two provinces lies east of the Wasatch Range, but at the south the axis of the range is crossed obliquely by the boundary.

A coordinate crustal change was orogenic—the creation of mountain ridges and intermont troughs. The Wasatch Range was separated from the chain of broad valleys that follow its western base by a great fault.

Such a diastrophic event as the creation of a great fault is not solitary. The force creating it must have other effects, and even if we could conceive of the great dislocation as an initial and causeless occurrence we must recognize the need of a system of crustal adjustments to prevent the formation of a void. It is therefore probable that minor deformations and dislocations have accompanied the major dislocation along the western front of the range; but as yet relatively little is known of them, and it is not easy to discriminate the products of later and earlier diastrophism. Emmons [9] has pointed out that in the region of Timpanogos and Provo Peaks a normal fault parallel to the frontal fault is expressed in the topography of the range. Loughlin[10] observed that a system of narrow ridges and troughs close to the western base of the range near Santaquin corresponds to a system of minor faults that involve Tertiary strata and lavas.

Blackwelder [11] has tentatively referred certain transverse faults in the Ogden region to the later diastrophism. All students of structure in the mining region about Alta and Park City recognize more than one period of faulting, and Hintze [12] regards certain faults of later date as probably synchronous with the frontal fault of the range. None of the structural features that have been thus correlated with the frontal fault are comparable with it in magnitude; their displacement and their linear extent are relatively small.

The existence of the frontal fault, first announced by Emmons, has been recognized by all later students of the structure of the range. It has not been specifically denied by the writers who regard most of the Basin Ranges as residual, although denial is probably implied by certain of their general statements. On the other hand, the discussion by Davis of the physiography of the Wasatch escarpment has made the escarpment in some sense a type, and in that character it warrants a full presentation of the evidence by which it is recognized as a product of block faulting.

Up to the present time only physiographic characters have been adduced in support of the view that the escarpment was created by faulting. In my judgment the physiographic evidence is adequate, but not all are prepared to accept it, and for this reason I shall begin the discussion of the subject by presenting evidence other than physiographic. Afterward several classes of physiographic evidence will be taken up, and in their treatment the phenomena of this range will be used as a text for the discussion of the criteria for the recognition of block-mountain structure.

THE FRONTAL FAULT

NOMENCLATURE

In the terminology of faults this paper follows the recommendations of the committee of the Geological Society of America on the nomenclature of faults, as printed in volume 24 of the society's Bulletin. The confusion caused by diversity of usage may be escaped by the adoption of a standard, and the standard offered by the committee has the important merit that it takes full account of the complexity of the geometric relations and thus enables the user to guard against the confusion that arises from imperfect conception of the relations expressed.

The movements involved in faulting—like all other movements—are relative. To define their directions it is necessary to refer them to some body or place regarded as fixed. As the movements on the plane of the frontal fault of the Wasatch Range have a large vertical component their directions are conveniently indicated as upward and downward; but in that indication the words are not used in their most familiar sense, and for that reason there is possibility of misunderstanding. In the nomenclature of faults the prefix "up" does not imply increase of distance from the earth's center or from the plane of mean sea level but only the direction of movement of the rock body on one side of a fault plane with reference to the rock body on the other side of the same plane. To say that the one body moved upward is the exact equivalent of saying that the other body moved downward. Similarly the statement that the horizontal component of the movement of one faulted body was eastward is equivalent to saying that the movement of the companion faulted body was westward. The movement of each body is referred to the other body and not to a terrestrial meridian.

The waste from a range, including the detritus washed from the range front and that discharged at the mouths of the canyons, is built into a sloping plain known as the alluvial apron. This plain is called also the piedmont plain or simply the piedmont.

[9] Emmons, S. F., U. S. Geol. Expl. 40th Par. Rept., vol. 2, p. 345, 1877.
[10] Loughlin, G. F., Jour. Geology, vol. 21, pp. 447-451, 1913.
[11] Blackwelder, Eliot, Geol. Soc. America Bull., vol. 21, pp. 539-541, 1910.
[12] Hintze, F. F., New York Acad. Sci. Annals, vol. 23, pp. 137-140, 142, 1913.

It may be interrupted by a scarp or scarps running parallel to the rock base of the range and caused by dislocation of the alluvium. Such scarps were originally called fault scarps, but that title has been diverted to another use, and for that reason the scarps in the alluvial apron are in this paper called piedmont scarps. A special section is devoted to their discussion.

LAKE BONNEVILLE

Some of the features of the frontal fault are affected by features of Lake Bonneville. At least twice in Quaternary time the basin west of the range was occupied by a deep lake, the water surface rising from some low level and afterward falling. The last great rise carried it about 1,000 feet above the level of Great Salt Lake, and all parts of the range front and piedmont slope below that level were modified by the attack of shore waves. For about one-fourth of the length of the range the modification was confined to the piedmont and affected only a portion of its slope; for the remainder it included the whole of the piedmont and a portion of the rock face. The rock face was affected chiefly by erosion but in places received a deposit of beach gravel. The piedmont alluvium was superficially reworked, with the washing out of a portion of the finer débris and the rounding and sorting of the coarser, which was so rearranged as to constitute a series of beaches contouring the slope.

The lower parts of the piedmont slope received argillaceous and marly deposits and were made flatter. The material of the piedmont thus includes alluvium, shore deposits, and lake beds, a heterogeneous aggregate for which usage has no less cumbrous designation than unconsolidated formations. In many places in this chapter the short title alluvium is substituted for the more exact phrase.

At the time of the last great expansion of the lake it found outlet across a pass occupied to a depth of 400 feet by alluvium. The alluvium was quickly scoured away, and the lake surface fell to the level of the rock sill at the outlet, where it remained for a long time. That level is marked along the Wasatch front by a shore line of exceptional strength, to which a special name has been given—the Provo shore line. The highest shore line, exceptionally conspicuous because it is highest, is called distinctively the Bonneville shore line. The time during which the lake stood at the level of the rock sill is called the Provo epoch. Certain diastrophic events have known relations to parts of the lake history. If earlier or later than all the wave work they are styled pre-Bonneville or post-Bonneville; if later than the Provo epoch, post-Provo.

An aspect of the Bonneville shore line is shown in Plate 1, *A*. The waves have eroded the range front along a horizontal line, creating a terrace and a cliff or row of cliffs. The Provo shore line is less conspicuous in this view, its most marked feature being a terrace near the center. In Plate 12, *B*, the Provo line is the more conspicuous, appearing as a rock shelf near the base of the spur. In Plate 8, *A*, two lines catch the eye; the upper of the two is the Provo; the Bonneville, near the top of the escarpment, is less easily discovered. The Bonneville and Provo shore lines are marked by color boundaries near the middle of Plate 7, *B*, and cliffs of the Bonneville shore line appear at the right in Plates 4, *B*, and 6, *A*.

PRODUCTS OF FAULT FRICTION

GENERAL CHARACTER

According to the previously cited committee of the Geological Society of America, "A fault, in its simplest form, is a fracture in the rock of the earth's crust, accompanied by a displacement of one side with respect to the other in a direction parallel with the fracture." The fracture surfaces of the two rock bodies are the walls of the fault. Nearly always during the faulting the walls are in contact or partly in contact, and there is friction between them.

A result of the friction is the abrasion of one or both walls. By the abrasion smooth surfaces are produced, with striation in the direction of motion. The striation consists of a system of parallel grooves with intervening ridges, and though typically these are minute, they may also be large, and if so they appear as fluting. The coordinate product of abrasion is detritus, and the detritus remains between the walls, constituting fault rock. The smallest fragments are minute, making collectively a fine powder or, if adhesive when moist, a plastic "gouge"; the largest fragments are "horses"; and between these two extremes are breccias. In general the fragments are sharply angular, but to this rule there are exceptions. In a matrix of gouge may occur "boulders of attrition," with blunted angles and slickensided facets or with forms unevenly rounded. The fragments may be either loose or cemented into a coherent mass. Some fissure veins are bodies of cemented fault rock.

The effects of friction may extend beyond the surfaces of the walls and modify the wall rocks. Near the fracture surface the rock may be made to flow in the direction of the fault movement. Evidence of such flow may appear in the bending of strata, in the welding together of strata with obliteration or obscuration of the partings between beds, in brecciation, in foliation or sheet structure parallel to the fracture surface, and in small areas of subsidiary surfaces of slipping revealed by polish and striation. Where strong and weak rocks are associated the flow of weak rocks may be accompanied by the fracture of strong rocks. Where strong rocks show evidence of flow it is inferred that the flowing took place at considerable depth within the crust. The collocation of faulting with a flowing of the rock adjacent to the fault suggests the border land between what Van Hise has called the zones of fracture and flowage.

The tract of modified wall rock is sometimes called a shear zone, and the name shear zone is also applied to dislocations, equivalent to faults, in which definite walls are not developed but merely sheetlike tracts of crushed or foliated rock.

The opposed walls in any part of a fault may be of like or unlike material. The intervening fault rock may be derived from immediately adjacent wall rock or may consist mainly of fragments unlike the local rock of either wall. The cementing material may be of local origin, or it may have been brought in solution from distant sources and may have reacted chemically on fault rock and wall rock. Much of our knowledge of the petrographic features of faults has been gathered through the exploitation and study of fissure veins.

In the polished and finely striated surfaces—slickensides—it is advantageous to recognize two types, although they are connected by the occurrence of intermediate forms. One is approximately plane or at least has a rectilinear section in the direction of motion; the other is conspicuously flexuous. Plane slickensides are characteristic of the main walls of faults; flexuous slickensides of the slip surfaces of branching and subsidiary fractures. As I interpret the phenomena, the slickensides on subsidiary fractures are flexuous because a small amount of differential movement has not sufficed to obliterate initial irregularities of the fracture surfaces—irregularities that arise from inequalities of rigidity and of strain. If similar irregularities affected the initial surfaces of great faults they have been effaced during the progress of the greater movement. According to this interpretation, flexuous slickensides indicate differential movement of small amount.

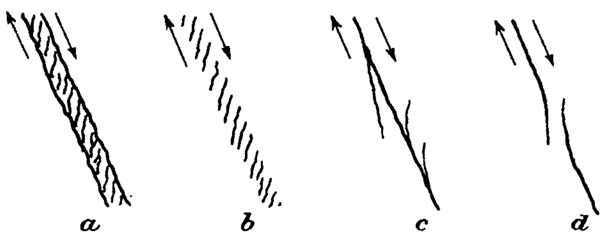

FIGURE 2.—Types of surface cracks associated with the horizontal fault slip which caused the California earthquake of April 18, 1906. Arrows show directions of movement of underlying crust blocks

Successive slippings of a progressive fault may not coincide accurately in position of slipping surface; a single slipping surface in one part of a fault may be represented by a group of parallel surfaces in another part, and all the surfaces may be of the plane type. Where sheet structure is developed within a fault wall there may be small movements on the partings between sheets, and the resulting slickensides may be of the flexuous type.

Slipping surfaces of another class are not parallel but oblique to the main fault surface. Their obliquity follows a law, and the law is illustrated by analogous phenomena connected with the California earthquake of 1906. The fault movement which caused that earthquake was horizontal, on a fault plane trending northwest. The crust block on the southwest side moved northwest. The visible expression of the faulting was mainly in a surface mantle of earth and included a system of oblique cracks, such as are shown diagrammatically in Figure 2. In places (*a*, fig. 2) the fault trace included two walls, with relative displacement as indicated by arrows, and between them a belt of broken earth. The principal cracks within the belt were oblique, as indicated. In other places (*b*, fig. 2) the walls were not developed and the fault trace consisted of a system of oblique cracks, as indicated. From the walls of the fault trace ran branching cracks (*c*, fig. 2), the divergence being at various

FIGURE 3.—Ideal sections of faults and of subsidiary slickened partings, to illustrate the relations of the attitude of the partings to normal faults (*a*) and reverse faults (*b*)

angles but always to the right of one looking along the trace. The trace in places (*d*, fig. 2) swerved to the right and gradually disappeared, to reappear at the left en échelon.

Reid[13] discussed the mechanics of these cracks, showing the relation of their systematic obliquity to shearing strains created in the ground by the shifting of the crust blocks beneath. It would be easy to paraphrase his analysis and apply it to oblique slipping surfaces developed in rock under shearing strain, but the analogy may suffice for present purposes.

The law, both theoretic and empiric, is that the planes of oblique subsidiary slipping surfaces associated with a fault all deviate in the same way from the plane of the fault. In connection with a normal fault their deviation is toward the vertical; in connection with a reverse fault, toward the horizontal. (See fig. 3.) The law applies to oblique slickened partings within the fault rock, as well as to those in wall rock, and is of service in determining the direction of slip on the principal fault plane.

The earlier paragraphs of the preceding elementary account of faults are believed to contain nothing novel. The discussion of slickensides depends largely on my own observations. This statement is not a claim but an admission. The inference that flexuous slickensides indicate small slip and the rule that the attitudes of oblique subsidiary slip surfaces are systematically related to the direction of fault movement were derived largely from the very phenomena to whose interpretation they are to be applied, and I would warn the critical reader of the possible danger of the logicians' "vicious circle."

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[13] Reid, H. F. Report of the [California] State Earthquake Investigation Commission: Carnegie Inst. Washington Pub. 87, vol. 2, pp. 33-35, 1910.

LOCALITIES

Rock Canyon locality.—The most southerly point at which I have examined the base of the Wasatch escarpment in looking for petrographic and structural evidence of faulting is near the town of Provo. In that division of the range the rocks are sedimentary, with a predominance of limestone, and the prevailing dips are easterly at moderate angles. Opposite Provo an anticline appears in the lower part of the escarpment, and with it is associated a quartzite, which is locally the lowest member of the conformable sedimentary series. In the western limb of the anticline the dips are relatively steep—by estimate, 40° to 50°. Figure 4 gives a generalized profile section and is based mainly on observations made from the plain below. The quartzite, which is distinguished from the other rocks by its yellow color, crosses the face of the escarpment as a band and separates blue-gray limestone above from blue-gray limestone below. Between the upper limestone and the quartzite lies a terrace without observed outcrops, which presumably marks the position of a shale, but the lower limestone lies close to the quartzite, leaving no space for a corresponding body of shale. The upper part of the quartzite band shows bedding, with small dip, and it is evident that the formation has a thickness of many hundred feet. The lower part of the band gives less indication as to structure but is apparently conformable with the steeply dipping limestone.

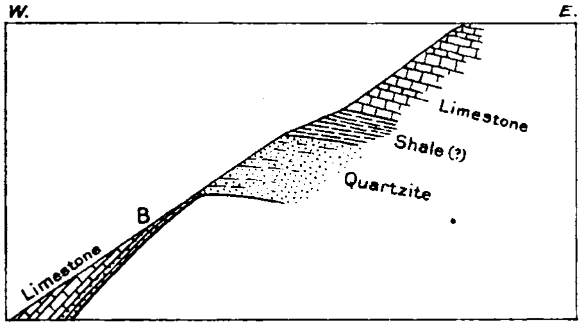


FIGURE 5.—Section exposed at the mouth of Rock Canyon, Wasatch Range, Utah. Q, Quartzite

These features are observable for about 2 miles, with minor variations. Farther south the axis of the anticline retreats from the front of the range toward its heart; farther north the escarpment shows only eastward-dipping limestone. Not far from Provo the escarpment is crossed by Rock Canyon, which exposes the section sketched in Figure 5 and thus aids in the interpretation of the profile section in Figure 4. It is there seen that the quartzite rests unconformably on a core of foliated rock [14] and that the body of quartzite in the outer or western limb of the fold is much thinner than the body in the eastern limb. At the point marked by a cross is an exposure of pale-yellow fault gouge. Near by is a bench of alluvium, built as a delta in Lake Bonneville, and this bench is crossed by a fault scarp parallel to the mountain front. Just south of the canyon the westward-dipping limestone was examined and found to be locally crushed, recrystallized, and shot with white gash veins; and in the part thus altered the bedding planes were not recognized. Slickensides were noted on a fallen block.

The relations of the fault gouge are in doubt. At the point of examination it lies just outside the quartzite and presumably rests against it, but the contact was not seen. The presence of the gouge at other points was indicated by patches of pale color seen from a distance, and all such patches noted are at the boundary between limestone and quartzite. (See B, fig. 4.) That association suggests that the gouge belongs to a fault walled on one side by the limestone and on the other by quartzite, but the sample obtained at the canyon mouth contains no calcareous matter. The designation "gouge" is perhaps not strictly applicable. The material is coherent when moist but after drying crumbles between the fingers. For the following petrographic description I am indebted to Prof. George D. Louderback:

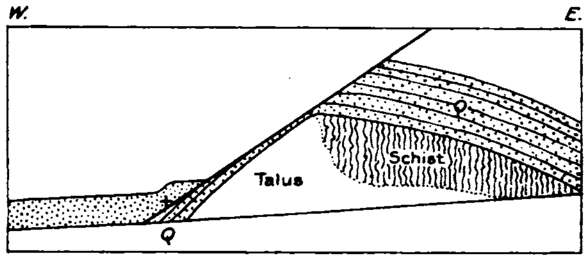


FIGURE 4.—Generalized profile section of the lower part of the Wasatch front near Provo, Utah

> The sample is composed essentially of quartz; other material is of very insignificant amount and apparently of no particular consequence in the interpretation of the material. The quartz is chiefly in the form of angular and irregularly and roughly rounded crystal fragments, varying in size from about one five-hundredth of an inch up to one-twentieth of an inch or larger. Some of it shows granulation in part, frequently about the periphery of the grains. Some of the crystals show distinct strain phenomena. The larger pieces in the material (up to three-fourths of an inch or more) are made up of numerous quartz grains and show the effects of crushing, granulation, fracturing, and strain. In two pieces distinct effects of shearing were noted. The particles of which the larger pieces are made and the small fragments first described show identical characters, and all the peculiarities found in one group can be found in the other. All of the material appears to be the result of the crushing of an original crystalline granular quartz rock. No effects of solution or deposition from solution were observed.

I interpret these features as follows: The anticline belongs to the earlier period of diastrophism and may originally have been a simple arching fold. In the

[14] This rock is a slightly metamorphosed sediment, originally a clay with many embedded pebbles. Howell calls it chloritic schist (U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, pp. 234–235, 1875). Emmons, who calls it clay slate, does not regard its relation as unconformable (U. S. Geol. Expl. 40th Par. Rept., vol. 2, pp. 345–346, 1877). Loughlin, who saw the formation in Rock Canyon and in another canyon farther south, speaks of it as "a conglomerate bed in the quartzite" (Jour. Geology, vol. 21, p. 445, 1913). These conflicting interpretations have aroused doubt in my mind as to my own, but I have had no opportunity to revisit the spot. A different diagnosis of the formation would not affect the discussion of the features ascribed to faulting. The anticline is recognized by Emmons and Loughlin but not by Howell.

later period it was cut away obliquely by a westward-dipping normal fault, and parts adjacent to the fault plane were sheared and partly rearranged. The visible portion belongs to the footwall, and the hanging wall is buried under valley deposits. The position of the main fault plane coincides approximately with the sloping face of the escarpment near its base (inclination 35°), but the rearrangement of the rocks involved slipping on other planes. The observed local alteration of limestone is a feature of the main fault, and so also is the fault gouge.

Fort Canyon locality.—The next point of special examination is 17 miles north of Rock Canyon and 2 miles north of the village of Alpine. Near Alpine the trend of the Wasatch escarpment swings from N. 10° W. to N. 80° W., and the westerly trend is held for 4 miles before the northerly trend is resumed. As shown by Figure 21, the deflection is intimately related to a huge body of granite which occupies all the southward-facing portion of the escarpment. At the base of the granite face are low foothills that contain Paleozoic limestone and sandstone. Fort Creek, which descends from the granite, has divided the foothills, opening a narrow valley called Fort Canyon. The contact of the granite with the foothill rocks is concealed by alluvium, but its position is marked by a groin, and the granite is exposed along the side of the groin. In an outer zone the granite is sheared and close to its outer surface is foliated, the foliation being parallel to the slope, which is at an angle of 29°. No slipping surfaces were discovered. The depth of the modified zone can not be stated, as the unmodified granite was not there seen in place, but the amount of change, as expressed by the development of parallel structure, was seen to diminish with distance from the outer face. Specimens were examined by Mr. Adolph Knopf, who characterizes the less foliated rock as "a crushed granite consisting of microcline, quartz, and chloritized biotite" and the more foliated as "a green schistose rock composed of quartz, feldspar, and epidote." Of the schistose rock he says: "It is probably a crushed facies of a basic variant of the granite represented by the first-mentioned specimen."

Looking northward from this locality I noted in distant parts of the granite face the appearance of structure parallel to the outer surface. This is obscurely shown in Plate 10, *A*, where the granite slope appears at the right.

Draper locality.—Two miles west of Fort Canyon the trend of the escarpment swings toward the north, and farther on it swings toward the northeast. In thus curving it outlines (fig. 21) the southern and western sides of the great body of granite. On the western side the escarpment exhibits a series of large triangular facets (pl. 19, *A*), which are slightly convex in profile and have a slope near the base of 35°. Opposite the village of Draper, which is 5 miles from Fort Canyon, rocks other than granite appear in the lower part of the face. The conspicuous rock is quartzite, but there are also schists; and the arrangement, as seen from the plain below, indicates that the schists lie between the quartzite and the granite. The outcrop of quartzite is about 2 miles long and has a width on the slope of 600 to 800 feet. Several small canyons divide it, showing that its thickness normal to the plane of the facets is several hundred feet. A nearer view, at the mouth of Little Willow Creek canyon, showed it to be traversed by four or more systems of parallel joints.

If the bedding planes were identified, which is not certain, they there strike with the mountain face and dip westward at about 60°. Between Bear Canyon and Crow Canyon were found division planes parallel to the plane of the facet. (See pl. 1, *B*.) These division surfaces bear slickensides of the plane type, and the plates of quartzite between them are brecciated. Many other polished surfaces were seen from a distance, and it is inferred that the outer face of the quartzite as a whole is part of the footwall of the frontal fault. Near the mouth of Little Willow Canyon a miner's prospect hole has exposed a fault rock in such position as to indicate contact with the quartzite, although the actual contact was not exposed. The material, examined microscopically by Mr. Knopf, is thus described:

> The specimen contains large quartz grains showing marked strain shadows; the remainder of the rock consists of fine-grained sericite. This rock evidently represents a shear zone altered by thermal waters; possibly the rock has been strained subsequent to mineralization, but this is not certain.

Mill Creek locality.—Mill Creek issues from its canyon 12 miles north of Draper and 5 miles south of Salt Lake City. The contour of the range front is there notably simple, with a slight convexity. The trends of range front near the canyon are N. 17° W. and S. 25° E. Each side shows a triangular facet; that on the south is especially well developed and has a slope of 29°. The rocks of the mountain are sedimentary, and the stronger strata are limestones, sandstones, and quartzites. They are mapped by Emmons as "Upper Carboniferous." They strike eastward, nearly at right angles to the trend of the front, and dip northward at 60° to 70°. Half a mile farther south the strata determine a group of furrows on the facet of the mountain front, but near the canyon they do not reach the outer face, which is occupied by a breccia. Just inside the canyon mouth and south of the creek the strata abut against a wall of breccia (see pl. 2, *A*), which there has a thickness of 150 to 200 feet. North of the creek the brecciated tract (see pl. 3, *A*) is perhaps 300 feet wide but does not extend far up the face and is not definitely limited on the inner side. Either it includes large masses of strata or the boundary between it and the unfractured sedimentary rocks is very irregular. In part the breccia is wholly quartzitic; in larger part the matrix and some of the included fragments are calcareous. It exhibits many partings with slickensides. All observed slickensides are flexuous (see pl. 4, *A*), and their dips are steeper than the slope of the outer face of the breccia, which is also the outer face of the range (see pls. 3, *A*, and 4, *B*).

My interpretation of the phenomena is as follows: The triangular facets, rising from the base of the range with a slope of 29°, are part of the footwall of the frontal fault and have lost little by weathering. The body of breccia by which they are faced is a shear zone within the footwall. The observed slickensided surfaces, with relatively steep dips, do not belong to the main fault but represent subsidiary yieldings within the grinding footwall.

Beck's Spring locality.—Near Salt Lake City the general trend of the range front is northerly, but just north of the city, near Beck's Spring, a broad spur projects 3 or 4 miles westward. The spur has a basement of Paleozoic rocks like those in the adjacent part of the range, but its superstructure is of Eocene (?) conglomerate, and a post-Eocene fault separates it from the range. The west face of the spur is steep (pl. 8, *A*) and is met abruptly by the flat plain of the valley. In one place a line of cemented alluvium clings to the face about 40 feet above the plain, marking a former line of junction of spur face and plain. Above the line the slope is approximately that of talus; below the line it is steeper, except as modified by fresh-fallen débris. (See pl. 5, *A*.) The steeper part is composed of limestone breccia, with slickensides on several parallel planes. (See pl. 5, *B*.) The slickensides are of the plane type, and their dip is 70°. In one place, where the base of the cliff is almost free from talus, thermal springs rise, the water issuing from cavelike openings in the breccia. Back of the breccia occur limestones with high dip to the south; and a one place the beds bend toward the zone of the slipping planes. In notes of these limestones made long ago when the possible significance of the feature was not appreciated, I find mention also of their brecciation.

My interpretation of the phenomena follows: The steep western face of the spur is a fault scarp. The dip of the fault plane is 70°. The latest slip, between the spur and the alluvial plain, amounted to 40 feet. Before it occurred there was a period of rest in which the slope of the spur face was reduced by erosion. Presumably the entire throw, of about 1,500 feet, was accomplished in parts, with intervals of no movement, and the wasting of the face maintained its slope near the angle of rest. After each partial movement a strip of fault rock was exposed, as at the present time, but the exposure was temporary.

Ogden Reservoir locality.—Of the rocks exposed in the escarpment the one that best resists the agencies of erosion is quartzite. For that reason it best preserves the evidences of fault friction. Where a considerable body of it occurs at the base of the escarpment its features are usually significant of faulting. A thick quartzite, identified by Blackwelder [15] as of Cambrian age, reaches the base at several points north

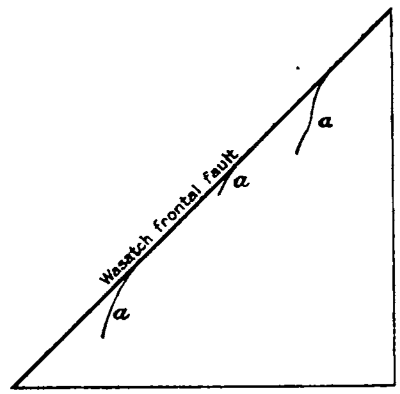


FIGURE 6.—Diagrammatic profile section of rock surface near Ogden Reservoir, Utah, showing the relation of subsidiary slipping surfaces to the footwall of the Wasatch frontal fault

of Weber Canyon, and at three of these I have examined it. The three localities have so much in common that accounts of the local details may advantageously be preceded by a statement of the common features. The formation is 1,000 to 1,500 feet thick and is

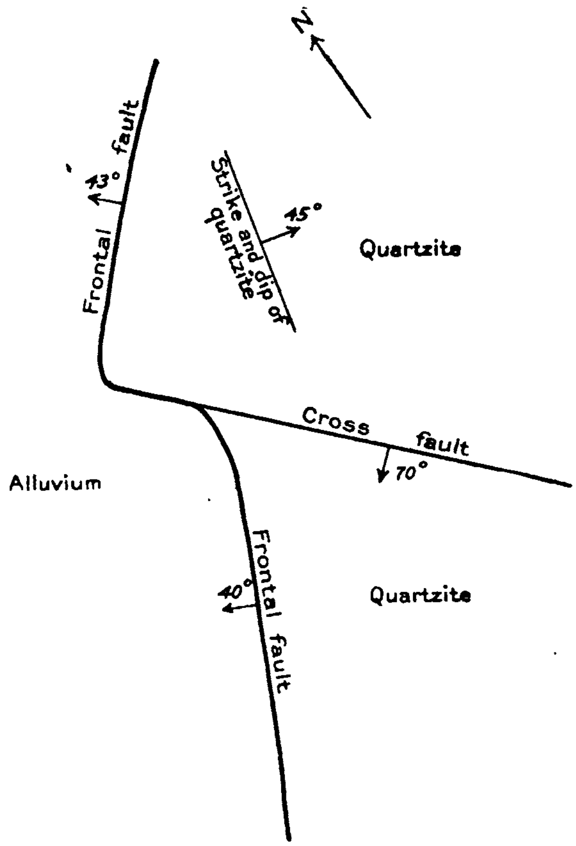


FIGURE 7.—Ground plan of faults near Ogden Reservoir, Utah, showing the relation of a cross fault to the frontal fault of the Wasatch Range

rather coarsely stratified. It rests unconformably on dark gneisses called Archean. Much of the gneiss is hard and tough and comparable with the quartzite

[15] Blackwelder, Eliot, New light on the geology of the Wasatch Mountains, Utah: Geol. Soc. America Bull., vol. 21, pp. 518-527, 1910.

A. BONNEVILLE SHORE LINE NEAR LOGAN, UTAH

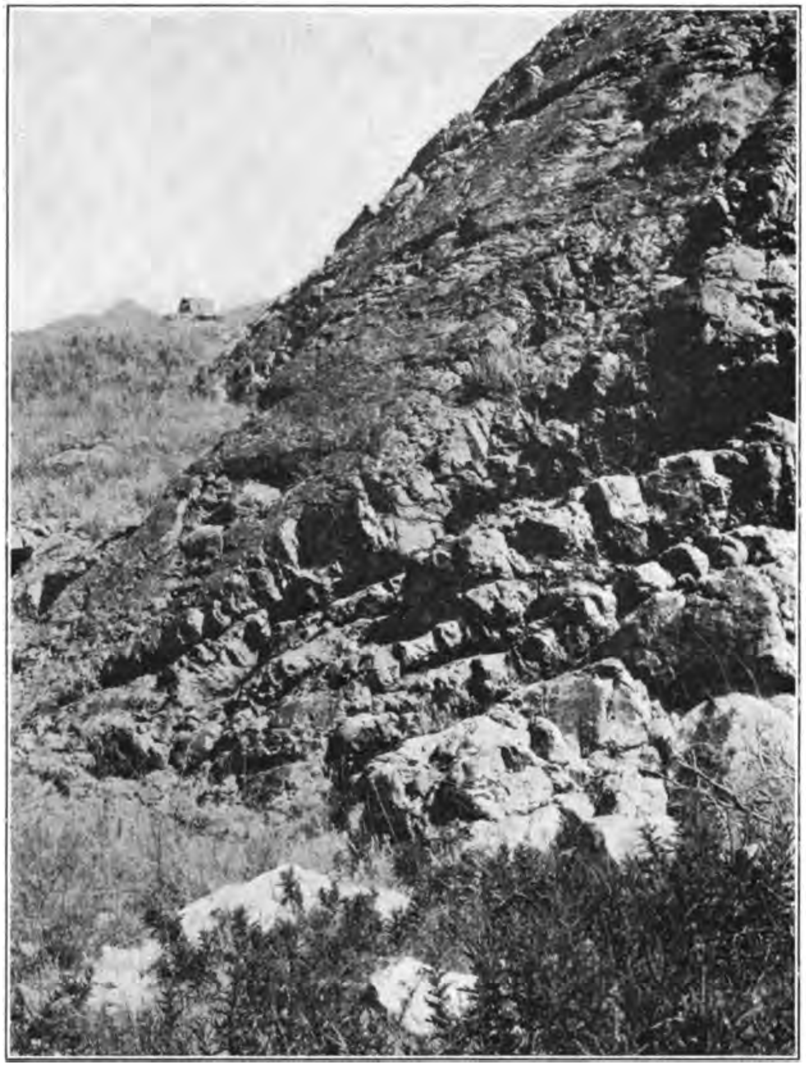
The shore line appears as a cut terrace with cliffs above. Lower down the Provo shore line is shown, but less clearly. The shore lines are carved on the west face of the Bear River Range, which is a fault scarp

B. SHEAR ZONE OF WEST FACE OF WASATCH RANGE, NEAR DRAPER, UTAH

The rock is quartzite. It has a sheet structure parallel to the sloping face, and the parting surfaces bear slickensides. The face is part of a facet of the Wasatch escarpment that appears at the right in Plate 19, *A*

A. SHEAR ZONE AT MOUTH OF MILL CREEK CANYON, WASATCH RANGE, UTAH

The shear zone makes a wall athwart the canyon, the outer face of the wall being part of the faceted mountain front, as seen in Plate 4, *B*. The view shows the inner face of the wall, with steeply dipping strata abutting against it



B. SLICKENSIDES AT BASE OF WASATCH ESCARPMENT NEAR CITY RESERVOIR, OGDEN, UTAH

The rock is Cambrian quartzite, and the exposed face is part of the footwall of the frontal fault of the range. The general dip of the strata is backward and to the left, but near the polished surface the strata are bent down toward it

A. SHEAR ZONE AT MOUTH OF CANYON

A mass of breccia, including blocks of strata and divided irregularly by slickened partings. This view overlaps the one beneath. A detail is shown in Plate 4, *A*

B. HIGH-DIPPING PALEOZOIC STRATA IN NORTH WALL OF CANYON

The view overlaps the one above and shows the relation of less disturbed strata to the rocks of the shear zone. The strata dip down into the canyon wall. For views of the opposite canyon wall see Plate 2

MILL CREEK CANYON, WASATCH RANGE, UTAH

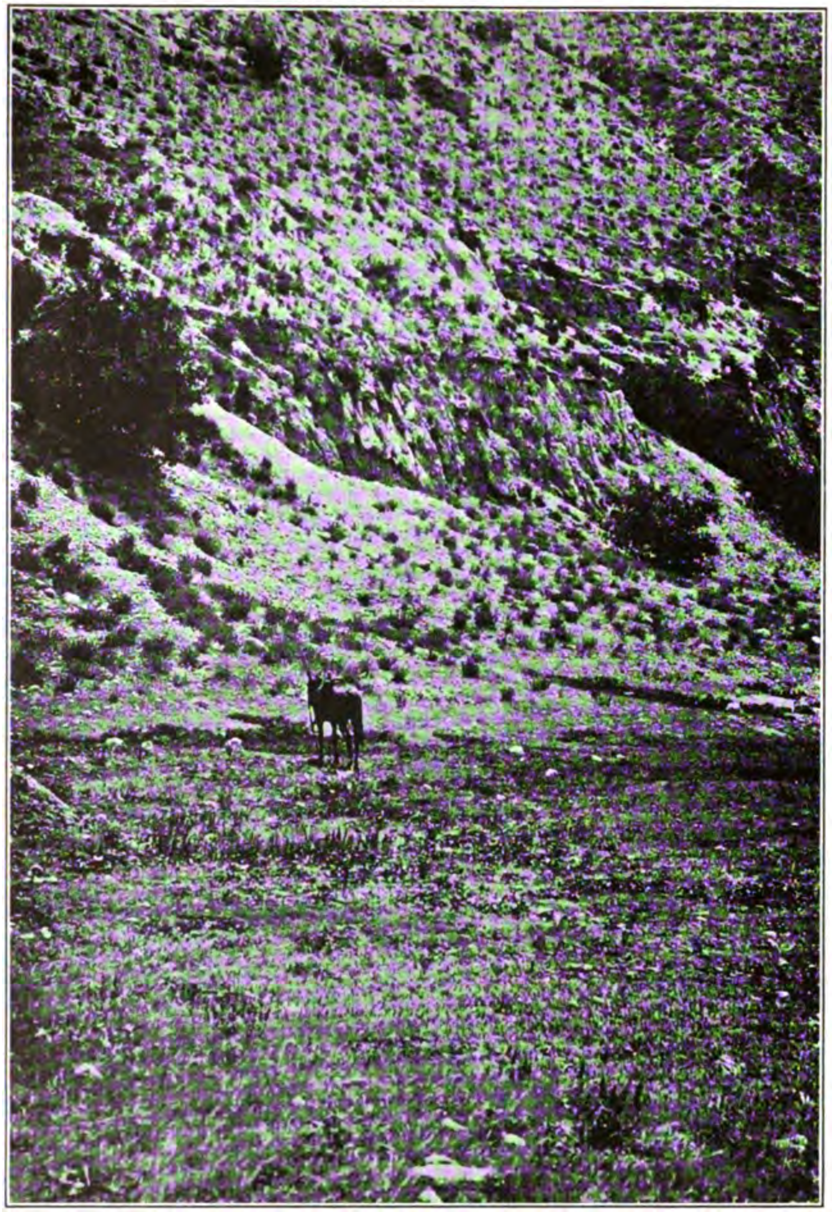
A. SLICKENSIDES

A detail of the shear zone shown in Plate 3; one of many slickened partings. The rock is a breccia of quartzite and limestone fragments, and the polish is preserved only on the quartzite

B. SHEAR ZONE AND FACETS

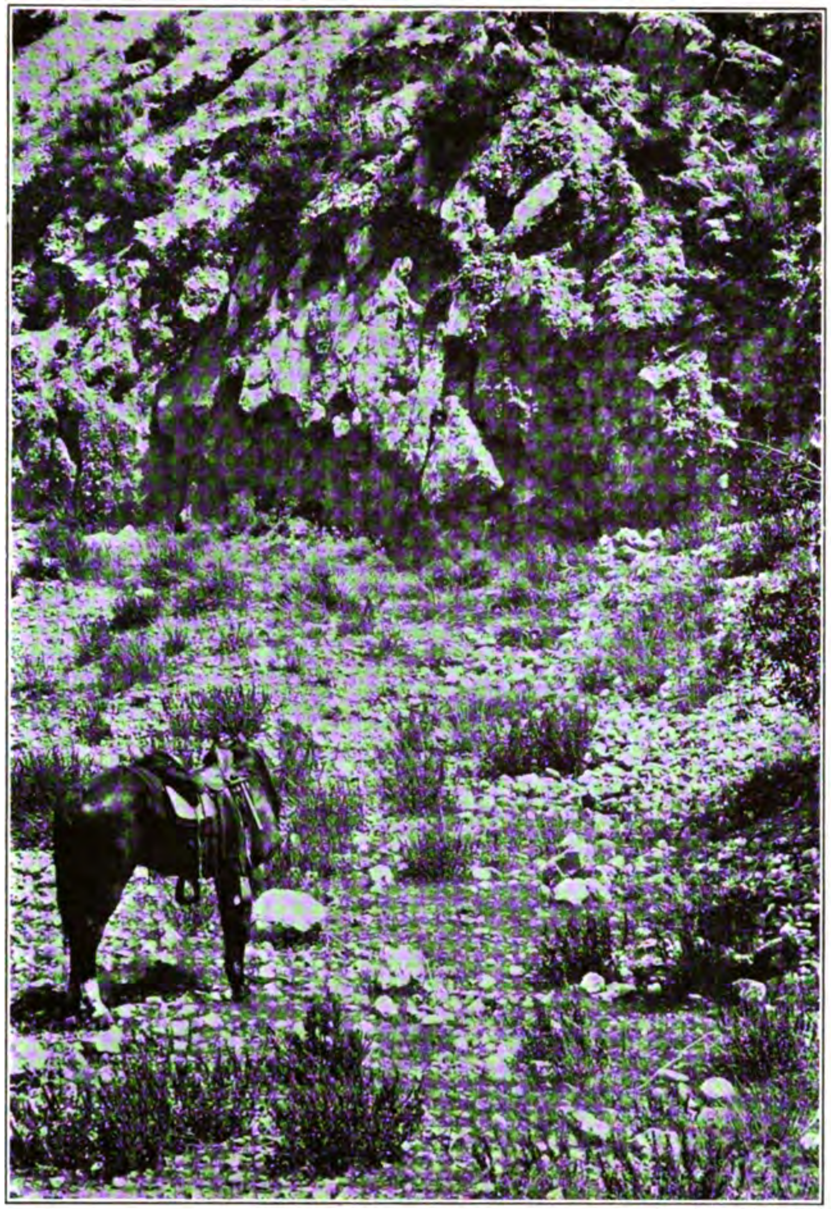
At the left is the south wall of the canyon. The crags in the foreground show the shear zone of the frontal fault, otherwise exhibited by Plate 2, *A*. The even profiles sloping toward the right are of facets of the range front. The cliff at the base of the nearer facet is a shore cliff of Lake Bonneville

FAULT PHENOMENA IN MILL CREEK CANYON, WASATCH RANGE, UTAH



A. GENERAL VIEW

The exposure is at the base of the fault scarp (pl. 8, *A*) bounding the City Creek spur on the west and has been made by a late movement on the fault. The fault rock is a limestone breccia

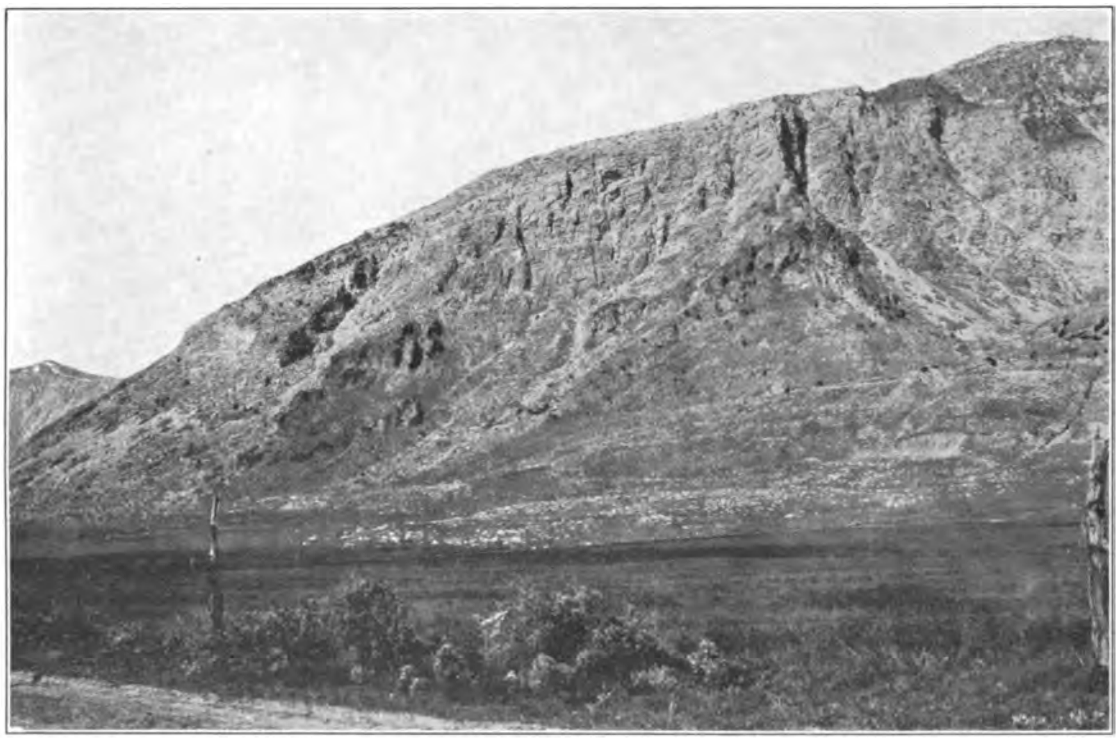


B. NEARER VIEW, SHOWING SLICKENSIDES

EXPOSURE OF FAULT ROCK NORTH OF SALT LAKE CITY, UTAH

A. VIEW FROM THE NORTH

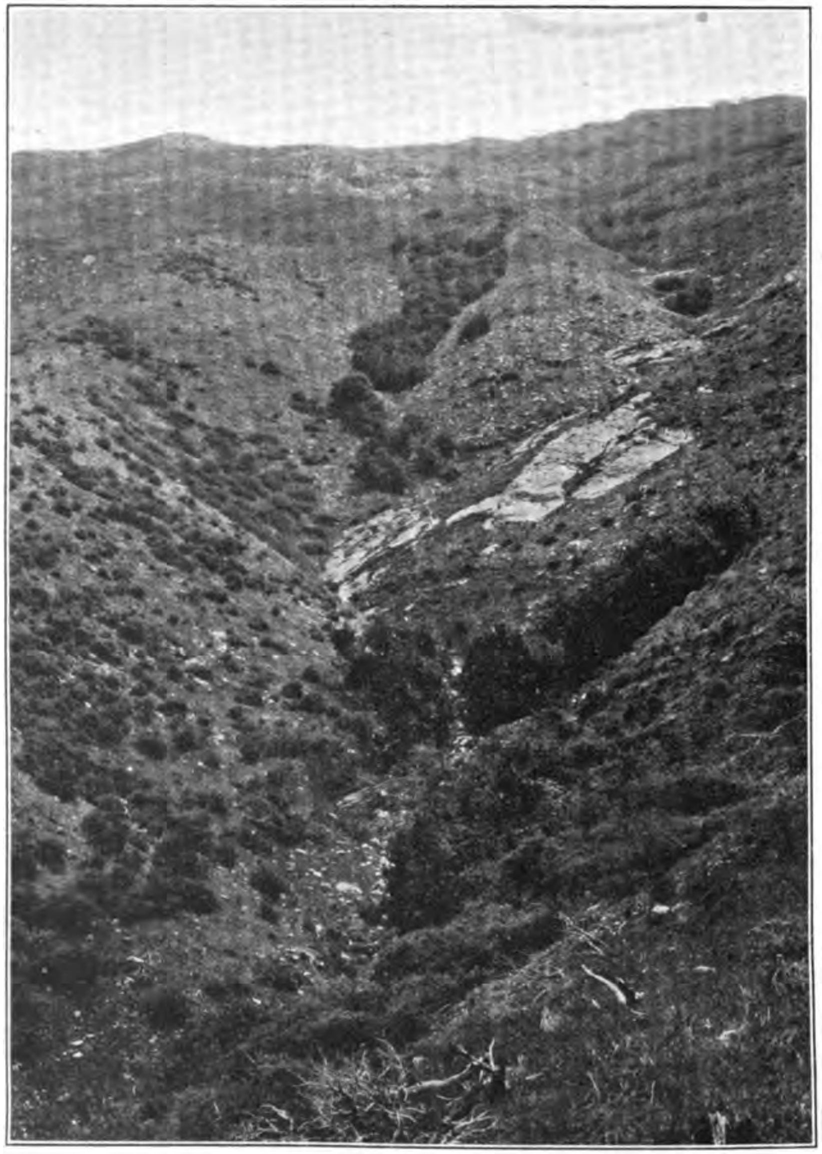
The gully at the left follows a shale outcrop. Cambrian limestone appears at the left of it, and Cambrian quartzite at the right, both dipping eastward. (See section in fig. 9.) The quartzite has been broken over, crushed, and dragged down toward the west. The sheared rock, a fault breccia including large horses, sheaths the mountain face at the right. The bluff on that face is a shore cliff of Lake Bonneville



B. VIEW FROM THE SOUTHWEST

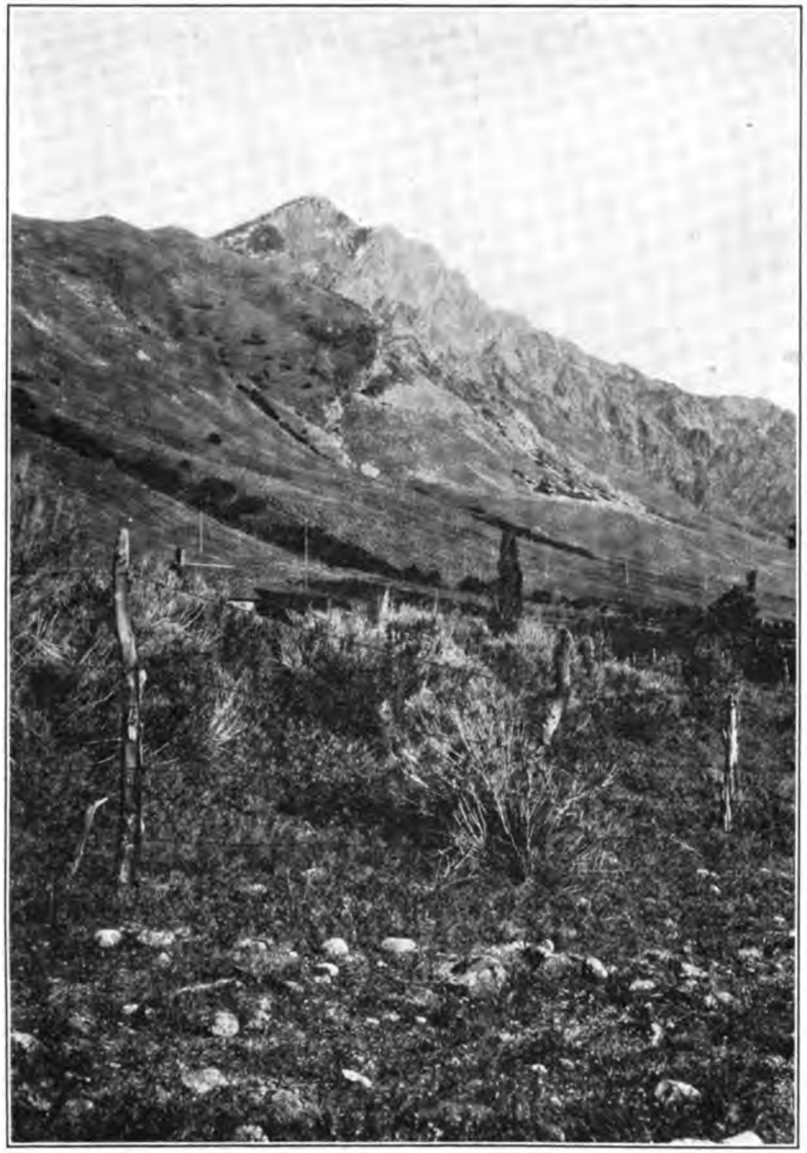
Outcrop of Cambrian quartzite, dipping backward. Below it are Archean gneisses, partly masked by talus. At the left the outcrops are overplaced by the fault rock described above. The alluvium of the foreground is crossed by piedmont scarps

FAULT PHENOMENA NEAR JUMP-OFF CANYON, WASATCH RANGE, UTAH



A. A PSEUDO-ANTICLINE IN CAMBRIAN QUARTZITE

Compare with Figure 10



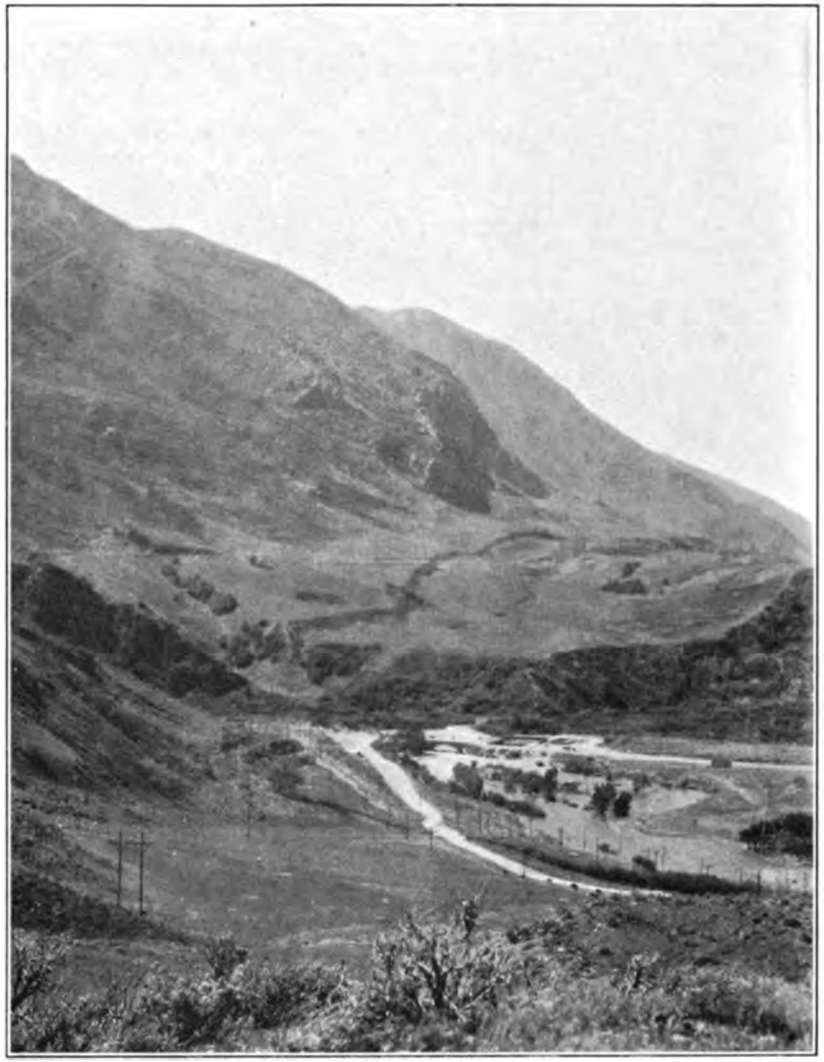
B. GENERAL VIEW FROM THE NORTH

The pale rock at the sky line is Cambrian quartzite, dipping eastward. Below it, at the right, are Archean gneisses. The nearer part of the quartzite is sheathed by sheared rock of the frontal fault of the range. For further explanation see Figure 11

FAULT PHENOMENA OF WASATCH RANGE NEAR WILLARD, UTAH

A. WESTERN ESCARPMENT OF CITY CREEK SPUR, WASATCH RANGE, UTAH

It is a fault scarp. The hanging valley belongs to a topographic development older than the fault. The face has been washed by Lake Bonneville; the higher of the two conspicuous shore lines is the Provo. The flat plain of the valley, occupied by lake clays, meets the steep face with little intervention of alluvial apron



B. WEST FACE OF WASATCH RANGE NEAR OGDEN, UTAH

Ogden River, which rises east of the range, here issues from its canyon. Outside the canyon it has opened a valley through a delta previously built by it in Lake Bonneville. Piedmont scarps run parallel to the base of the range front. The same scarps are shown in Plate 17, *B* in strength, but it weathers more rapidly. Above the quartzite is a shale several hundred feet thick, and above that a heavy body of limestone. The range is composed of a number of large tectonic blocks separated by faults, and the three occurrences of quartzite pertain to three distinct blocks. In all of them the attitude of the formation is about the same. The formation dips eastward at 30° to 50°, and its strike is oblique to the range front. In the southern part of each block it crops out as a rugged cliff, overlooking a tract of gneiss; in passing northward the outcrop approaches the plain and at the same time descends; and the outcrop ends where the rock base is bordered by the alluvium of the plain. At and near the base of the escarpment the formation shows modification of various kinds. The line of the rock base is convex toward the valley where it passes the quartzite, but the convexity is not of large amount. Its existence is emphasized by the fact that above the base line the quartzite is brought into strong relief by the relatively rapid weathering of the formations that inclose it.

The southern of the three localities is a short distance south of Ogden Canyon, and near it stands a reservoir of the municipal water system of the city of Ogden. The quartzite there appears at the rock base for nearly half a mile, and its surface shows many patches of slickensides. Some of these patches are plane (see pl. 2, *B*) and coincide with the outer face of the rock, but a greater number curve downward into the rock. The general slope of the rock face is 35° to 45°, and the striation of plane slickensides descends this slope without recognized obliquity—that is, the strike slip of the fault is very small or zero. Brecciation is not conspicuous to the unaided eye. In the sheared zone the reconstruction is so perfect as to give the appearance of flexure and flow. At a few points the strata are bent downward near the slipping surface, becoming thinner as they curve; and in one place they are so welded that bedding planes are obliterated. Subsidiary slipping surfaces, with slickensides, curve downward from surfaces parallel to the fault in the manner indicated at the points marked *a* in Figure 6. The zone in which shearing is shown is everywhere thin—at most a few feet in thickness—and there are places where the strata seem to have been merely broken across and ground to smoothness without any internal change. No fault rock was seen; the observed evidences of shearing all belong to the footwall.

A special feature of the locality is the offsetting of the plane of the frontal fault by a cross fault. The relations of the faults are shown in plan in Figure 7, where it will be noted that the strike of the frontal fault changes abruptly at the junction of the cross fault. It is to be noted also that each division of the frontal fault meets the plane of the cross fault with a curve. The curved surfaces bear the marks of fault friction and must have been shaped while the footwall and hanging wall were in contact. The cross fault is therefore at least as old as the frontal fault. If it is older, we have here an example of the control of local details of the frontal fault by preexistent structures of the terrane—a subject to receive attention in another section. If it is not older it was formed at the same time, and its occurrence serves to illustrate the general fact that faulting is not a solitary phenomenon but is necessarily accompanied by other changes.

The offset of this cross fault affects the entire face of the quartzite and also a limestone cliff above. It is associated with a shallow groove on the escarpment which guides storm water; and the descending water has washed out fault rock so as to open a cleft and expose parts of the walls of the cross fault. On the north wall I found the direction of the slip recorded by striae and made a rough measurement of their direction. The south block moved downward and westward. In Figure 8 the relations are shown diagrammatically, as projected on the plane of the cross fault.

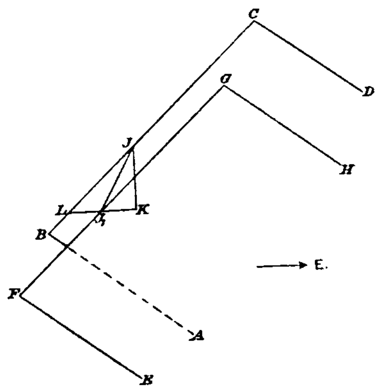


FIGURE 8.—Diagram of elements of the cross fault near Ogden Reservoir, Utah

A portion of the north wall, *ABCD*, is bounded by bedding planes, *AB* and *CD*, and by the frontal fault, *BC*. The corresponding portion of the south wall is *EFGH*. J_1 on the south wall corresponds to *J* on the north wall. The slip is JJ_1, the dip slip *JK*, and the strike slip KJ_1. Although the strike component of the displacement, as referred to the northern block, is westward, the offset, LJ_1, is eastward. The amount of offset, roughly measured, is 90 feet; the strike slip is a little greater, and the dip slip about twice as great. The offset in the limestone face, seen only at a distance, seemed to be the same as that in the quartzite, indicating that the fault movement was without rotation.

Jump-off locality.—The second of the quartzite bodies is crossed by Jump-off Canyon near the place where it begins to descend and reaches the rock base about 2 miles south of North Ogden Canyon. Plate 6, *B*, gives a view of its western face from the southwest, and Plate 6, *A*, a view of its northern end from the north. The section in Figure 9 passes through the apex of the quartzite as represented in Plate 6, *A*. A quantity of quartzite has been torn from the fractured edge of the formation in the footwall and dragged down so as to rest in part against the fractured face of the gneiss. The fragmental mass contains large blocks that might be called horses, but their boundaries are indefinite. Though they retain traces of bedding they are traversed, in common with the rest of the mass, by partings, ascribed to shearing, which are approximately parallel among themselves and are thought to be parallel to the plane of the fault. The partings undulate after the manner of flexuous slickensides and are fluted in the direction of their dip, but no striae were found on them. As all the exposures examined have been washed by the waves of Lake Bonneville, it is thought that striae may have been ground away. From these broad parting surfaces small subsidiary partings curve downward into the rock.

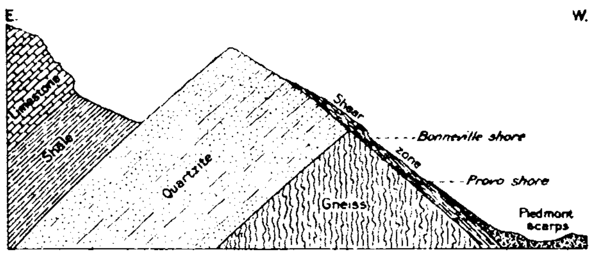


FIGURE 9.—Section of west front of Wasatch Range north of Jump-off Canyon, Utah

At a short distance south of the line of section the facing of dragged rock is connected with the upper part of the quartzite bed by a curve, giving the appearance, as seen from the plain, of continuity. This feature will be referred to again in connection with an allied feature seen near Willard.

Still farther south the facing of disturbed rock comes abruptly to an end, terminating in a scarp which faces southward (seen at left of center in pl. 6, *B*); and beyond that scarp appears the normal outcrop of the eastward-dipping quartzite, with its basement of gneiss.

In this locality the footwall is not exposed in such a way as to afford a direct measurement of the dip of the fault. From the partings ascribed to shearing the dip is estimated at 33°. The entire visible body of brecciated and sheared rock is thought to belong to the footwall.

Willard locality.—The northern of the three localities is near the town of Willard, and the quartzite outcrop reaches the rock base a little north of Willard Creek canyon. Here also fragments have been torn from the quartzite body and dragged down in the direction of the fault movement, and among the fragments are blocks that would be called horses if encountered in a mine. In at least one of the larger blocks a structure has been developed parallel to the fault plane. The finer material has the character of breccia. There is room for doubt as to the position of the footwall. The entire body of dislocated material may belong to the uplifted block, and if so the footwall surface has been effaced by weathering and erosion; or part of the dislocated material may properly be called fault rock, and if so the footwall surface has escaped recognition. The first-mentioned alternative is regarded as the more probable, chiefly because of the coarseness of the material. Where fault rock was definitely recognized at other points along the mountain base it was found to have been ground much finer.

No direct measurement of the dip of the fault could be made. Indirect measurements gave angles ranging from 33° to 37°.

Conditions near the upper edge of the quartzite outcrop are complicated by a feature that belongs to the earlier diastrophism. The plane of the Willard overthrust, discovered by Blackwelder,[16] here touches the quartzite, and it is probable that the quartzite body had been locally modified before the inception of the frontal fault. For that reason there is doubt as to the interpretation of the pseudo-anticline described in the next paragraph.

Beyond the end of the continuous outcrop of quartzite a shallow ravine reveals a small patch of the same rock. The relations of the patch to the greater body are concealed by alluvium and beach deposits. There is an apparent pitching anticline, the axis of which makes a considerable angle with the strike of the neighboring quartzite. Plate 7, *A*, gives a view from below, the camera having been directed up the slope. The diagram in Figure 10 is made from a notebook sketch. At *a* and *b* are planes of bedding. At *c* are partings parallel to the outer surface and ascribed to shearing. At *b* shearing and bedding planes intersect at an angle. No striae were seen; the surfaces are smooth but have the habit of surfaces ground by beach sand. At many points on the arch are minor partings of moderate extent, which enter the rock

FIGURE 10.—Profile section of pseudo-anticline near Willard, Utah

obliquely, and these all dip to the right. They show that the direction of the shearing force was from left to right. This simulation of an anticlinal fold by the association of bedding with shearing structure suggests that the arch observed near Jump-off Canyon may not in fact be that which it seems, a fold of strata.

In Figure 11, a diagram to explain Plate 7, *B*, a heavy line marks tentatively the outcrop of the Willard overthrust. The overthrust dips toward the left, and Algonkian formations (A) at this point overlap the Cambrian quartzite (Q). The distant outcrop of the quartzite shows a high dip, the nearer a low dip. The different attitude of the nearer outcrop may

16 Blackwelder, Eliot, op. cit., pp. 534-536.

have been acquired in connection with the formation of the overthrust; and it is also possible that the upper part of the nearer quartzite is a separate body, the overthrust plane, or an accessory thrust plane, passing below it. The sheet of fault rock, exposed at F, also underlies the detrital slope between and above the old shore lines, B and P.

North Ogden fire clay.—A few rods north of North Ogden Canyon a body of fault gouge is worked as fire clay by means of an open pit. About 1½ miles farther north is an older opening in similar material. Between the two openings are indications of a linear outcrop, continuous for nearly half a mile. All the occurrences are on faces of scarps in alluvium that have the habit of piedmont scarps. Their line traverses the alluvial apron of the range.

The southern opening reveals no boundary of the formation but shows a horizontal extent in all directions of more than 50 feet. The northern opening

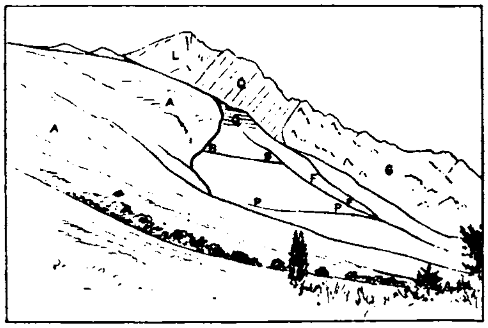


FIGURE 11.—Diagram to explain Plate 7, *B*. G, Archean gneiss; A, Algonkian; Q, Cambrian quartzite; L, Cambrian limestone; F, fault rock; B, Bonneville shore line; P, Provo shore line; heavy line between A and Q, outcrop of Willard overthrust

shows a short contact with alluvium on the side nearer the mountain, the surface of contact dipping toward the mountain. Not far away is a bench tentatively ascribed to a landslide, and it may be that the gouge at this opening has been affected by such a movement. The indication of linear outcrop is a whitish band, corresponding in color to the gouge, which appears on a steep alluvial slope where the slope is made still steeper by recent faulting. The place was not visited. The relations of the linear and the southern outcrops to the rock base are accordant with the hypothesis that the gouge is a fault rock of the frontal fault, and the hypothesis finds further support in the occurrence on the mountain face of quartzite, which is the material of the gouge.

The material is yellowish white and closely resembles that found at the mouth of Rock Canyon. (See p. 14.) It consists of angular fragments of quartzite, without cement. In a sample sorted by sieves, one-half by weight was found to have diameters under 0.5 millimeter and one-eighth under 0.1 millimeter. After wetting and drying it coheres, but the cohesion is feeble.

DISCUSSION

Visible discontinuity and offsetting of bedded rocks on the two sides of an intersecting plane is direct evidence of faulting. In a massive rock such evidence is usually not available, and the geologist depends on that which is less direct. If he finds a surface of separation and on that surface slickensides he infers faulting, and he also infers faulting if he finds a massive rock traversed by a shear zone. In all occurrences that involve two adjacent terranes faulting is inferred without question, either from visible dislocation, or from a surface of separation with slickensides, or from the intervention of a shear zone. The evidence of a fault may include all the items mentioned, with duplication of some of them. There may be a shear zone bounded by slickensided walls; that shear zone may be bordered by other zones of shearing within the wall rocks; and the wall rocks may be so constituted that dislocation is directly demonstrable.

Along the western base of the Wasatch Range the evidence is less full. In all the localities described a shear zone is found. In some of them it is bounded on the outer side by a definite surface (wall) with slickensides. In some a second shear zone (fault rock) occurs outside the wall. A second wall surface and a second wall rock are not seen, and dislocation is not directly observed. Nevertheless the evidence seems to me adequate. The phenomena are all explicable on the hypothesis that they were produced by faulting and that the western fault block is concealed by valley deposits. So far as I know, there is no alternative hypothesis to be discussed.

The shear zones contain many slipping surfaces of small area which are oblique to the principal plane of faulting. Without exception they indicate that the fault is normal, the hanging wall having descended.

Some of the shear zones contain deformations of the nature of flow. Strata of quartzite have been bent and stretched or have been welded together. The process of flow probably involved crushing and reunion, but the preservation of continuity while the forms of strong rocks were changed implies such coercion as is given by a heavy load of superjacent rock. The deformations were produced at a considerable depth beneath the surface. In some of the gouges, on the other hand, finely divided quartzite has not been reunited, nor even bound together by a cement; and the condition of these indicates formation at small depth. Despite the great contrast between the two groups of facts they are really harmonious—under the hypothesis that faulting on this plane created the entire escarpment. If the faulting began when the tops of the valley block and mountain block were at about the same level, that part of the footwall which is now visible at the base of the escarpment lay initially at a depth beneath the surface roughly equivalent to the present height of the escarpment plus the amount of degradation of the mountain block, and the frictional effects in that part of the footwall were conditioned by the corresponding pressure. As the faulting progressed the pressure on that part of the footwall gradually diminished, with the result that deformation within the wall rock ceased after a time, and the products of the earlier high-pressure dragging were thus fixed for continuous preservation. But between the fault walls friction continued, and the fault rock was ground finer and finer. That part of the fault rock near what is now the base of the escarpment was worked over, with gradually diminishing pressure, until finally it was freed from contact with the hanging wall, and when that stage was reached it had been reduced to the gritty powder of the gouges.

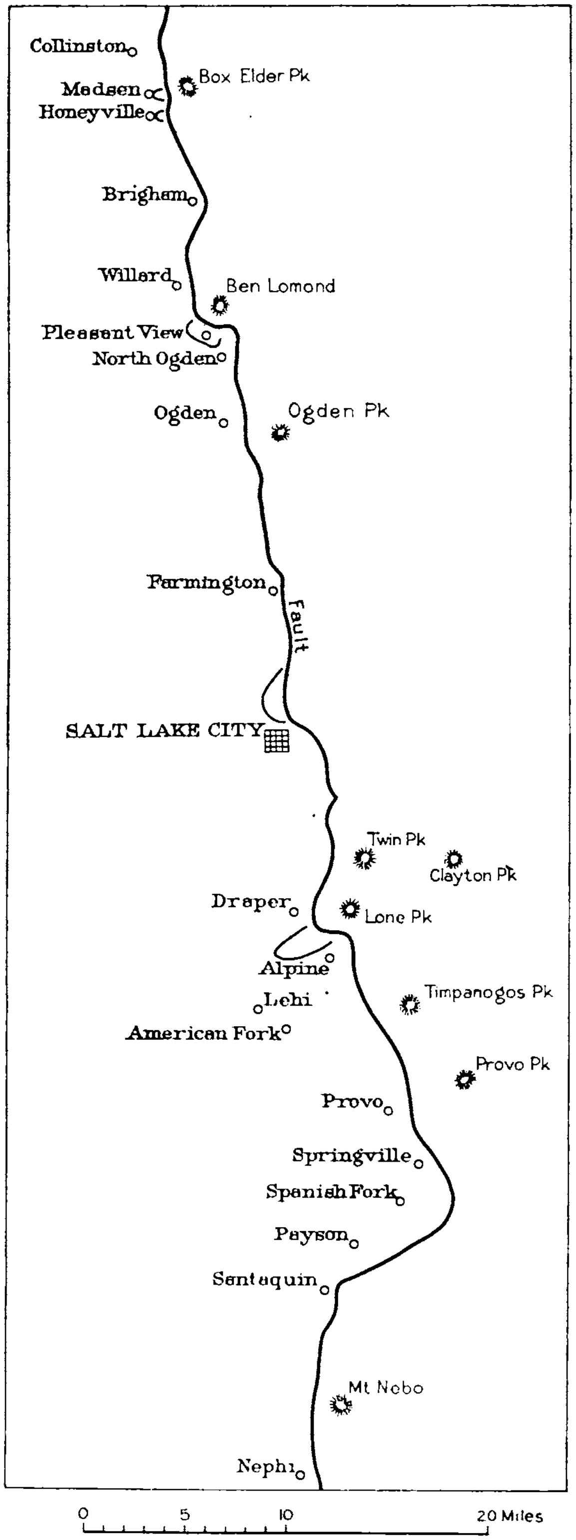


FIGURE 12.—Map of frontal fault of Wasatch Range, Utah

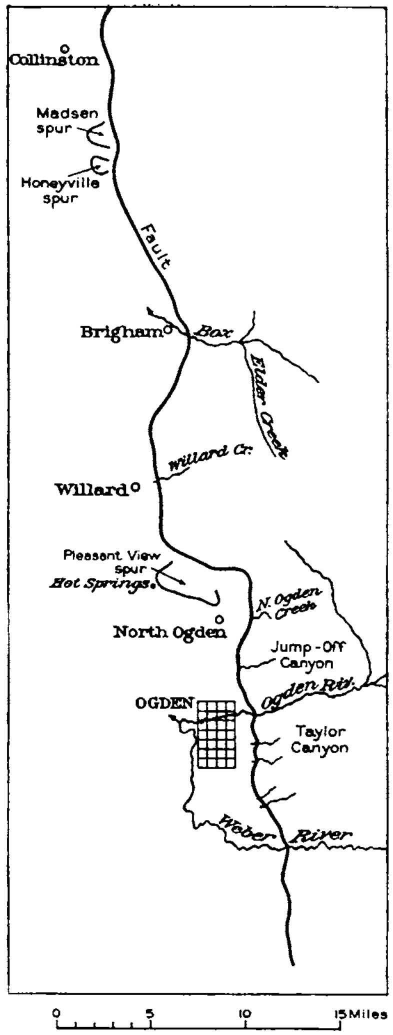


FIGURE 13.—Map of that portion of the frontal fault of the Wasatch Range north of Weber Canyon, Utah

OUTLINE OF THE FAULT

In characterizing ranges that have a bold front due to faulting I wrote in 1890: "The line separating the rock of the mountain from the alluvium of the valley is simple and direct."[17] The statement is perhaps defensible because the context compares such a line with the corresponding line on the back slope of a range consisting of a tilted block; but it is fair to say that my conception of the flexuosity which may affect fault outlines has been materially enlarged by

[17] Gilbert, G. K., U. S. Geol. Survey Mon. 1, p. 341, 1890.

more recent studies of the Wasatch front. As the outlines drawn in Figures 12 and 13 are based in part on reconnaissance maps and in part on rough traverses, they have no claim to accuracy, but the general impression they convey is not misleading. The line of the fault is crooked. It not only curves through considerable arcs but in two places turns sharply at right angles, and in three other places its course runs for miles athwart the general direction of the fault as a whole.

Some of the deflections, but not all, are evidently associated with preexistent structural features. The outward convexity of the outline in passing certain quartzite bodies has already been mentioned. One of the greatest deviations occurs in passing around the granite body north of Alpine. That body, the outcrop of which is mapped by Emmons as oval, with a longer (northeasterly) axis of 15 miles and a shorter axis of 6 miles, is exposed through a vertical range of 6,000 feet, and its base is not seen. One-fourth of its area projects beyond the general

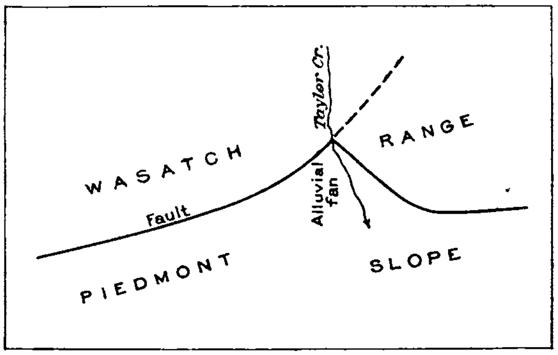


FIGURE 14.—Ground plan of Wasatch frontal fault at Taylor Canyon, Utah

line of the range front in its vicinity. It is easy to surmise that these convexities were induced by the ability of the quartzite to resist the deformation and abrasion that affected weaker formations and by the ability of the huge and strong granitic mass to resist the stresses that initiated the fault fracture.

The small jog in the line near the Ogden Reservoir (p. 16) is definitely connected with a cross fault that was not made after the frontal fault and may have been made before. A mile farther south is an angular notch that is probably connected with a fault belonging to the internal structure of the range. At the apex of the notch (see fig. 14) is Taylor Canyon, and the notch is partly occupied by the alluvial fan of Taylor Creek. These relations suggest that the notch is part of the canyon mouth and was eroded from the mountain block by the creek, but there is no merging of the canyon with the notch. The canyon does not flare but holds its V form to the rock base and there ends abruptly. Furthermore, the line of the fault is outlined by a fresh post-Bonneville piedmont scarp, a feature whose significance will be discussed in another section. The scarp testifies to local depth of alluvium, and its presence at the head of the fan (see pl. 9, *B*) implies a steeper descent of the suballuvial rock slope than would accord with the grade of the canyon bed. In the south wall of the canyon there is a discordance of dips indicative of a dislocation of some sort, and although I observed the dips only from a distance I regard it as probable that an ancient fault, with high dip, has the course indicated by the broken line in Figure 14 and coincides in direction with the northeast face of the notch in the escarpment. If such a fault existed before the starting of the frontal fault it may have determined the notch by giving to a wedge of rock a weaker attachment to the footwall of the frontal fault than to the hanging wall.

For other deflections of the fault line I have no specific explanations to suggest. Doubtless a fuller knowledge of the internal structure of the range would lead to other suggestions, but it is probable that after all the plausible relations to structure had been discovered a large share of the deflections would remain unexplained because the structural features to which they are related are not now visible.

The conditions under which an extensive fault occurs are almost necessarily complex. Whatever the primary force, and however simple, it loses simplicity in transmission through a heterogeneous crust. In the actual field of the fault weak rocks seek adjustment by flow, and by partial yielding they not only increase the strain in hard rocks but modify its distribution and diversify its direction. For these reasons the surface of eventual fracture is neither plane nor of simple curvature. As soon as movement takes place the walls cease to be fitted one to the other. A prominence of one wall leaves the companion hollow and becomes opposed to an incompatible surface. Adjustments are then necessary to preserve contact. If the prominence is of strong rock strongly set, it may plow a furrow in the opposite wall; if of weak rock, it may be split off or ground away. A prominence of strong rock with a backing of weak rock may be forced back into its wall, adjustment being effected chiefly by the flow of weak rock. After much movement the walls will become fluted in the direction of the slip; between the walls will occur products of attrition, and within the wall rock will be tracts affected by the internal changes that have aided in the adjustment.

With such a conception of the immediate mechanism of a great fault, it is easy to understand that details of configuration may depend on elements of structure not revealed at the surface. The huge body of granite that determined the Wasatch salient near Alpine may be assumed to have remained with the footwall, because the major part of the bulk lay on that side of the general line of the fault. Had its major part lain in the hanging wall, it might all have remained with that wall and thereby have deflected the fault line toward the east, creating a reentrant; and if so, the factor determining the reentrant would be concealed along with the hanging wall under the valley deposits. Where level formations bury deeply a foundation of complex structure and a long fault is afterward formed, the ground plan of the fault may be determined wholly by features of the foundation and thus involve complexities out of harmony with the character of the formations in which the relief is expressed.

From present knowledge it is not easy to determine whether the Wasatch fault, with its crooked trace, is exceptional or whether it represents the type of major faults in the Great Basin. No faults of similar extent in the region have yet been mapped in detail. Dutton's map of displacements in the plateau province [18] includes a number of long faults, and all the lines drawn swing in simple curves, but the lines were based on reconnaissance studies and plotted on a reconnaissance map. An outline of the Wasatch fault that I drew in 1890 is nearly as simple in its curvature.[19]

Whether the Wasatch fault is exceptional or typical in its contour, it is evident that great simplicity of basal outline is not an essential characteristic of faulted range fronts.

On the other hand, the phrase "simple and direct" may properly be used in a relative sense when basal outlines of faulted fronts are compared with rock bases shaped chiefly by erosion. The erosive outline, as will later be shown, is greatly influenced by the arrangement of drainage lines and by the distribution of strong and weak rocks; the fault-block outline is independent of drainage lines and its adjustment to rock texture is partial and local; and these differences serve to make the erosive outline comparatively tortuous and the fault outline comparatively direct.

DIP OF THE FAULT

At the Warm Spring locality the dip of the fault plane is 70°, but the locality is exceptional. The fault there seen is not, properly speaking, the frontal fault of the range but is a subsidiary displacement outlining an associated but distinct crustal block. All measurements of dip on the frontal fault proper give lower angles. The records of dip already cited are as follows:

At Rock Canyon	35°
At Fort Canyon	29°
Near Draper	35°
At Mill Creek Canyon	29°
At Ogden Reservoir	35°–45°
Near Jump-off Canyon	33°
Near Willard	33°–37°

A few other observations are of similar tenor, 35° being noted at the mouth of Ogden Canyon and 30° near Provo. Lower dips occur about the Lone Peak salient. The measurement at Fort Canyon, 29°, was on the southern face of the salient, and that near Draper, 35°, on the western face. Between the two places lies the rounded apex of the salient, and the dips diminish toward the apex, where the angle indicated by the rock profile is 20°. Traces of fault friction were not observed at the apex, but there is much evidence that the original form of the granite body is well represented by the present contours and profiles near the rock base. From the apex of the salient to a high crest in the direction of Lone Peak the granite presents a blunt edge that separates the southerly and westerly faces. Those faces are relatively steep, but the profile of the edge itself is gentle. It is also convexly curved, from 10° in its higher part to 20° at the rock base. It would appear that in the process of faulting this edge cleaved the descending block, as the unyielding granite prong plowed a furrow through the weaker rocks of the hanging wall. As thus conceived the local dip of 20° has an exceptional local cause. If the local profile of the granite should be explored below the surface it would probably be found to steepen.

With the omission of the observation on the salient the measurements of dip give an average of 33.4°.

Consideration of the throw of the fault, which might logically follow consideration of the dip, is deferred to page 50, because it involves data to be presented in the sections that immediately follow.

FAULT-BLOCK SPURS

CITY CREEK SPUR

To the general fact that the fault front of the range is bordered by valleys and valley deposits there are exceptions. A number of spurs that are associated with the range but are not part of it invade the valleys, and these will now be described, beginning with one just north of Salt Lake City. Topographically the City Creek spur is a member of the range. Some of its higher slopes are continuous with slopes of the range, and City Creek, which rises in the range and flows to Jordan Valley, crosses the spur obliquely on its way. Structurally the spur is distinct, being separated from the range by a fault, which is continuous with the frontal fault of the range. The spur is also structurally distinct from the valley, being bounded on the north, west, and south by a curving fault. It consists of a tectonic block that stands lower than the adjacent block of the range and higher than the adjacent block or blocks of the valley.

The spur has a length, parallel to the range, of 6 miles, and a width, measured from the base line of the range, of 3 to 4 miles. At the west, where its steep face overlooks the flat delta built by Jordan River in Great Salt Lake, its height is about 1,200 feet, and there is a gradual rise toward the range. The upland is hilly and may be described as a dis-

[18] Dutton, C. E., Tertiary history of the Grand Canyon district: U. S. Geol. Survey Mon. 2, atlas, sheet 3, 1882.

[19] Gilbert, G. K., U. S. Geol. Survey Mon. 1, pl. 45, 1890.

sected plateau. It is divided unequally by the incised valley of City Creek, the northern division being the larger.

In the adjacent part of the range the rocks dip at high angles toward the south and southeast. Just south of the spur lies the axis of a great syncline, which crosses the range from west to east, and along the axis are strata of Jurassic and Triassic age. Opposite the north end of the spur are metamorphic rocks referred by Emmons to the Archean. The interval is occupied by Paleozoic formations that dip away from the Archean and toward the synclinal axis. The Paleozoic rocks include much limestone and a smaller amount of sandstone and quartzite.

The upland of the spur is occupied by a Tertiary formation, which the Fortieth Parallel atlas correlates with an Eocene formation on the eastern flank of the range. This correlation is to be regarded as tentative, for Emmons [20] in his text does not indicate it, but I know of no facts to contravene it. The formation consists in large part of coarse conglomerate but includes also finer beds. The pebbles and boulders are chiefly of sandstone and limestone

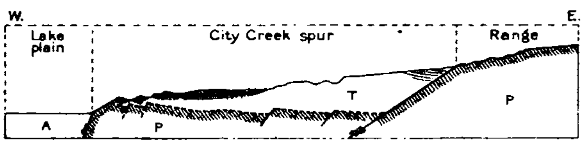


FIGURE 15.—Diagrammatic section of City Creek spur of Wasatch Range, Utah. A, Alluvium and lake beds of Jordan-Salt Lake Valley; T, Tertiary conglomerate and sandstone; P, pre-Cretaceous rocks, mainly Paleozoic

and show the imperfect rounding characteristic of alluvial fans. The cement is chiefly calcareous. In the western escarpment of the spur the conglomerates are seen at the top, and below them lie Paleozoic rocks that dip steeply toward the southeast. The Paleozoic belt, about 3 miles long, includes a large stratigraphic range. Although no contacts were observed, it is evident that the conglomerate rests unconformably on tilted and eroded Paleozoic beds. Presumably the tectonic block constituting the spur is composed largely of older rocks and bears the Tertiary beds as a capping formation. (See fig. 15.)

The Tertiary formation has suffered much disturbance. As it yields rather easily to weathering agencies the full determination of its structure would be difficult, but nearly all observed outcrops show notable dips, which reach 50° or 60°. In one place a broad syncline was noted, with northerly axis. In another place the repetition of a particular sequence of beds seemed best explained by assuming the presence of several faults. In another place the hypothesis of a graben seemed best to explain an occurrence of conglomerate between hills of Paleozoic limestone. The direction of dip most frequently recorded is eastward, and only that direction was noted in the place where faulting was inferred. The disturbance of the Tertiary cap implies disturbance of the older rocks on which it rests. So the Paleozoic beds were dislocated both before and after the time represented by the conglomerate.

The statement above that the spur is separated from the range by a fault continuous with the frontal fault of the range was made with a mental reservation, for the evidence is not complete. The contact was not seen, its position being at all points masked by waste. The best estimate of the attitude of the contact plane assigns a westward slope of 30°. Tertiary beds that not far from the contact dip toward it at 30° were observed to have less dip as they approached the contact. On the other side of the contact and close to it were seen limestone strata nearly parallel with the contact plane, their strike in this position being nearly at right angles to the strike of the near-by body of similar limestone. These features accord with the hypothesis of a fault, accompanied by dragging of the strata of both walls, but they are not demonstrative, because the structure on both sides is complex. I was told by the late Mr. J. E. Clayton, geologist and mining engineer, that in inspecting a prospector's tunnel near the north end of the spur he had observed a normal fault approximately on the plane of the contact, but my record of his statement contains no details. My acceptance of this meager evidence has been largely determined by the fact that two other spurs, in some respects similar to this one, are demonstrably separated from the range by faults.

The evidence of faulting on the outer periphery of the spur is more satisfactory. Slickensides, breccia, and deflected strata have already been described in the account of the Beck's Spring locality (p. 16). Closely associated with them is a piedmont scarp, which follows or parallels the rock base on the western and northern sides, just as such scarps parallel the rock base of the range through the greater part of its length. A scarp that is similar but less fresh was seen near the southern base. A part of the western face that is composed chiefly of limestone stands as a steep wall (see pl. 8, *A*) and is almost free from cliff waste at its base. The waste has doubtless been buried by deposits of Great Salt Lake and the Jordan delta, but such deposition is so slow in comparison with the wasting of a cliff that the burial is hard to explain without the assumption of local subsidence. At the top of the cliff are hanging valleys (pl. 8, *A*), which are easily understood if the steep face is a fault scarp but otherwise hard to explain.

The highest part of the spur is a graded plain that slopes away from the range. The plain is built of coarse alluvium, and the proportion of limestone

[20] Emmons, S. F., U. S. Geol. Expl. 40th Par. Rept., vol. 2, pp. 374-376, 1877.

débris in this alluvium is greater than was seen in the Tertiary conglomerate. Neighboring outcrops of conglomerate show dips that do not accord with the slope of the plain, and it is inferred that the alluvium rests unconformably on the conglomerate. The alluvium is believed to be a remnant of a fan that has its apex in the mountain canyon of City Creek and to record an epoch in which the base-level for City Creek was 1,500 or 2,000 feet higher than at present. The alluvial fan was part of the alluvial apron of the Wasatch Range at a time when there was less difference in altitude between the range and the flanking valley than there is now. It marks a stage in the development of the range, and during that stage the City Creek spur probably did not exist. It is possible that some remnants of graded plains observed high on the range belong to the same stage, but more possible that they are of earlier origin.

FIGURE 16.—Graded ridges near City Creek spur, Wasatch Range, Utah. (After sketch by author)

Below the summit plain of the spur are valleys of gentle slope and mature development that mark an early stage in the dissection of the upland. To this stage belong the hanging valleys of the western scarp of the spur. They pertain to a base-level somewhat lower than that of the summit plain, and while they were forming the spur must have been in existence. They mark a stage in the development of the fault that separates the spur block from the valley block.

They are correlated tentatively with some well-graded profiles (fig. 16) observed on intercanyon ridges of the range just south of the spur, and also with a dissected terrace (fig. 17) in the neighboring canyon of Red Butte Creek.

If there is warrant for the suggested correlation, the range and spur have similar histories with reference to their base-level of erosion, which is the valley plain, and there has probably been no differential movement between the range block and the spur block since the separation of the spur block from the valley block.

Arranged in order of time, the changes recorded in and near the spur indicate the following elements of local history:

1. A land surface made up of Jurassic and pre-Jurassic rocks, which had been folded and reduced by erosion, had such relief in early Tertiary time that its lower slopes received alluvial deposits, mainly coarse.

2 and 3. The Wasatch Range was differentiated from a valley tract west of it by the initiation of a normal fault—now the frontal fault. The valley block was completely shattered on a relatively small scale. The shattering of the valley block may have preceded or accompanied its separation from the range block.

4. In an epoch of orogenic rest the slope from mountain to valley was graded, with removal of early Tertiary deposits from the range and partial burial of those deposits in the valley.

5. Renewed upfaulting of the range occurred and inception of the outer fault of the spur. In this and later movements the relation of the spur block to the range block was not changed, but they were lifted together with reference to the valley block. The spur block suffered no internal disturbance. City Creek, having previously contributed to the work of grading by building an alluvial fan at the range margin, now incised a channel in the fan, and its course was thus superimposed on the structural features of the spur.

6. In another epoch of rest the drainage of the spur developed mature minor valleys, and some neighboring canyons of the range were broadened.

7. Renewed faulting, on the same lines as in (5), caused streams of range and spur to incise their channel ways, leaving the valley floors of (6) as terraces and hanging valleys. There was concomitant partial grading of fault scarps.

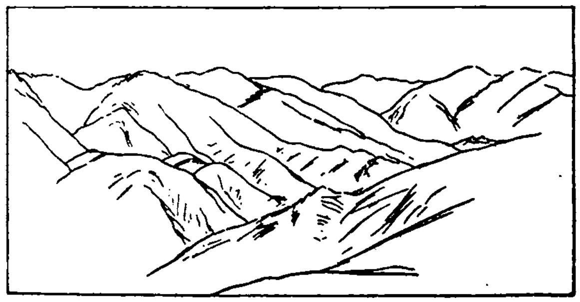


FIGURE 17.—Dissected terrace along Red Butte Canyon, Wasatch Range, Utah. (After sketch by author)

8. The Salt Lake Valley and Jordan Valley were flooded by the Quaternary Lake Bonneville, with reworking of alluvial slopes and fault scarps, up to a height of 1,000 feet, by waves.

9. The latest fault movement, a continuance of (7), disturbed the alluvial and lacustral slopes and created low scarps in them.

PLEASANT VIEW SPUR

Between the villages of North Ogden and Willard, 35 miles north of the City Creek spur, is a spur of somewhat smaller area and of much less height. A little creek from the range crosses it, and on the banks of the creek stands a hamlet once known as Pole Patch but now called Pleasant View. The range front, with its fault line, is here inflected, the general

A. PLEASANT VIEW SPUR AND THE WASATCH ESCARPMENT, WASATCH RANGE, UTAH

The view was taken from a station on the spur and shows the contrast between its plain top and the bold face of the range

B. MOUTH OF TAYLOR CANYON, WASATCH RANGE, UTAH

In the foreground is an alluvial fan built by Taylor Creek in an embayment of the range front. (See fig. 14.) The fan is crossed by a fresh piedmont scarp, 40 feet high. The present channel of the creek is to the right of the scarp

A. SADDLE BETWEEN THE SALIENT AND THE TRAVERSE SPUR

The view is westward from the head of Fort Canyon. At the right is the granite of the salient, with structure ascribed to shearing. A fault separates it from the rocks of the spur, seen at the left

B. ANCIENT CHANNEL OF CORNER CREEK

Corner Creek, following the groin between the salient and the Traverse spur, sinks its channel into the granite of the salient. As the body of the spur retreats down the granite slope successive creek channels are stranded. The view is on the lowest of the stranded channels shown in Figures 22 and 23

LONE PEAK SALIENT OF WASATCH RANGE, UTAH

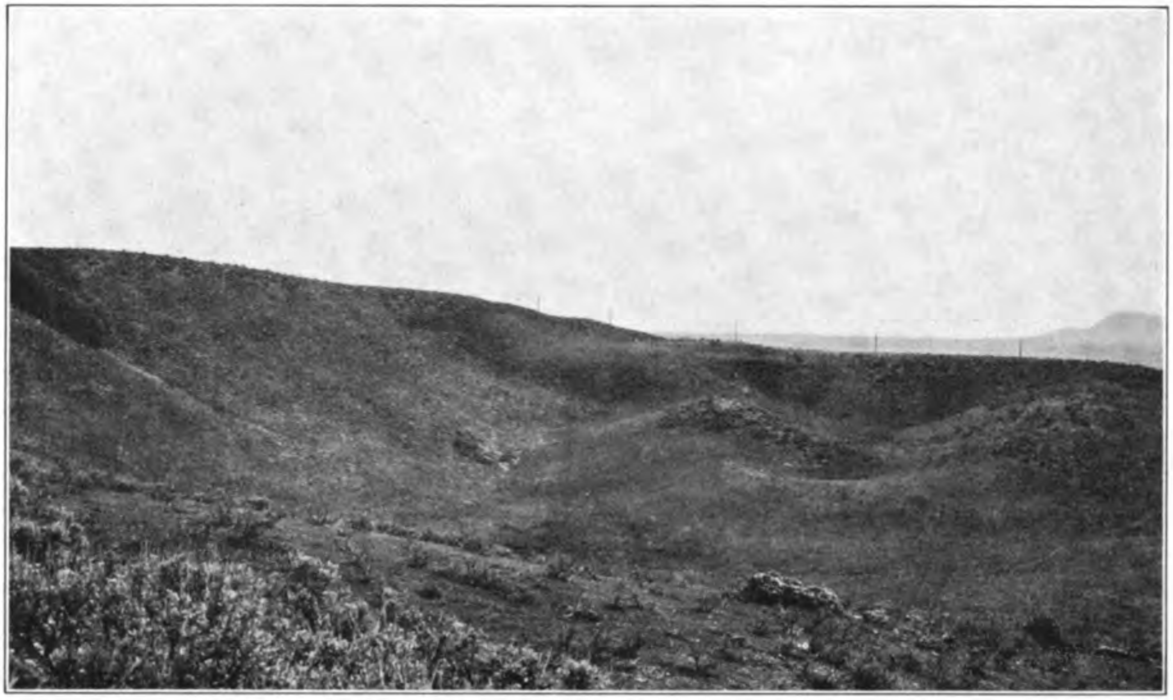
A. CORNER CREEK GROIN

At the right is the Traverse spur; at the left the faceted slope of the Lone Peak salient of the range. Spur and salient are terraced by the Bonneville shore line. In the foreground is a delta plain built by the creek at the Provo stage of Lake Bonneville. A piedmont scarp crosses the delta plain to the bank of the creek. (See also fig. 29)

B. SCARP OPPOSITE HONEYVILLE SPUR

The spur is separated from the base of the range by a belt of grabens, with undrained hollows. The view shows grabens and the high scarp beyond them

FEATURES AT THE HEADS OF SPURS OF THE WASATCH RANGE, UTAH



A. LANDSLIDES AT MADSEN SPUR

The view is westward along the northern face of the spur. The hummocks at the right and the table beyond them have slumped from the higher table at the left

B. SPUR OF DARK GNEISS, NORTH OF OGDEN CANYON

A piedmont scarp passes below its base and is strongly marked on an alluvial fan at the left. The level terrace above was carved out by the waves of Lake Bonneville at the Provo stage. Plate 18 gives details of the piedmont scarp

FEATURES OF SPURS OF WASATCH RANGE, UTAH northerly trend being interrupted for a few miles by a northwesterly trend. As shown by Figure 18, the spur adjoins the face with northwesterly trend and has its longer dimension in the same direction. As shown by the profile in Figure 19, the spur is much lower than the range. Its higher parts rise 200 to 300 feet above the Bonneville shore line, which is here nearly 1,000 feet above the level of Great Salt Lake. Exposures of bedrock occur only on the outer or southwestern half of the spur and are there discontinuous, the surface consisting largely of local fragmental material, sorted and rearranged by lake waves. The conspicuous rocks are quartzite and limestone. To casual observation the structure appears complex, and I did not attempt to decipher it. Both Hague[21] and Blackwelder[22] speak of the rocks as much disturbed, and both correlate them with a quartzite and a limestone that occur high on the face of the range. Hague's map indicates an outer belt of quartzite and an inner of limestone, and Blackwelder's shows the same sequence doubled with a reverse fault between.

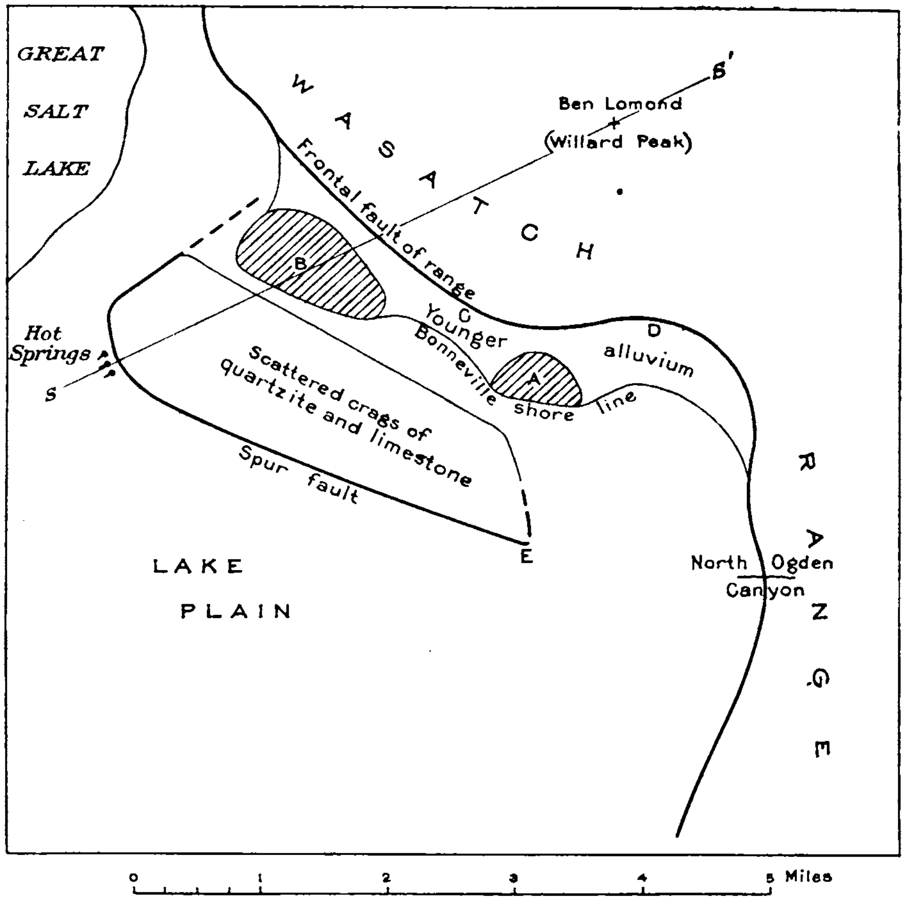


FIGURE 18.—Map of Pleasant View spur, Wasatch Range, Utah. A and B, Tracts of alluvium

Between the tract characterized by outcrops and the base of the range is a belt more than a mile wide occupied wholly by alluvium. In the portion of the belt that is below the level of Lake Bonneville the alluvium has been rearranged by the waves; in the portion above wave action it is possible to make a distinction between younger and older alluviums. The younger alluvium is the modern detrital apron of the range, with characteristic graded slopes, down which flow small streams from the canyons and storm waters from intervening steep facets of the front. The older alluvium had a like origin but is no longer traversed by waters from the range. One tract of older alluvium, marked A in Figure 18, retains the slopes of deposition but stands a little above the present channels, which dissect it. Another tract, marked B in Figure 18, is avoided by the present drainage of the range, which passes around it, and has lost all semblance of the graded slopes that doubtless once characterized it. Its surface is corrugated in a system of subparallel ridges and hollows, with a relief of 25 to 75 feet, and the arrangement of trends is approximately as indicated in the figure. The hollows, although troughlike and long, are not abandoned watercourses: their forms are not erosional, their general direction is not that of the original water-made slopes, and among them are several undrained basins. The corrugation has been given to the tract by some sort of differential movement of the alluvium. As its origin is not of evident importance in the present

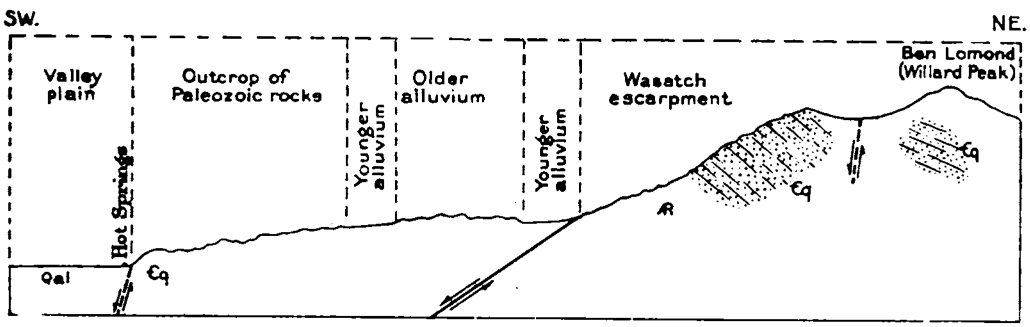


FIGURE 19.—Section of Pleasant View spur and part of Wasatch Range, Utah, along line S-S' of Figure 18. Qal, Alluvium; €q, Cambrian quartzite; AR, Archean gneiss

[21] Hague, Arnold, U. S. Geol. Expl. 40th Par. Rept., vol. 2, p. 402, 1877.
[22] Blackwelder, Eliot, Geol. Soc. America Bull., vol. 21, p. 539, 1910.

connection it is not considered here but is taken up in a section that is devoted to disturbances of the piedmont slopes.

The adjoining face of the range (see fig. 19) has at its base a broad outcrop of gneissic rocks, then a broad outcrop of quartzite, and above that limestones and shales. These rocks necessarily furnish the material of the piedmont alluvium. In both the older and the younger alluvium the conspicuous and readily identifiable materials are quartzite and gneiss, the quartzite being specially distinguished by its pale colors. I did not visit tract A of the older alluvium but was able to compare the material of tract B with that of an adjacent tract of modern alluvium. In both tracts the greater number of boulders and large blocks are of quartzite and the greater number of pebbles are of gneiss, but the proportions are not the same. I estimated the percentages of quartzite and gneiss among the boulders and found about 60 per cent of quartzite in the modern alluvium and 95 per cent in the older. The difference seems too large to be

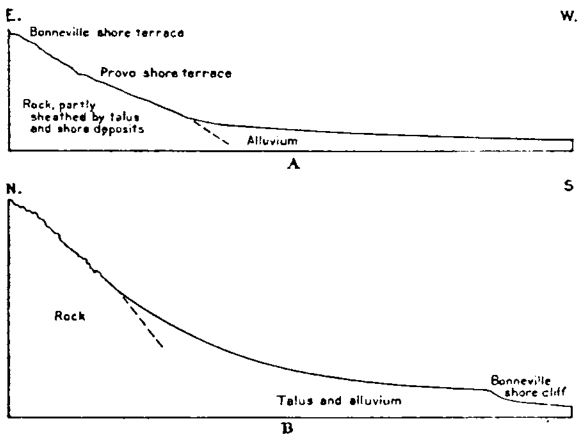


FIGURE 20.—Profiles of base of Wasatch Range, Utah, at points between canyon mouths. Approximate scale; 1 inch=4,500 feet. A, Profile about 1 mile south of Willard; constructed from photographic data. B, Profile at A, Figure 22; copied from photograph

ascribed to accident of locality and gives some support to the inference that at the time when the alluvium of tract B was accumulating the belt of outcrop of the gneiss was narrower than now. On the other hand, the presence of a few boulders of gneiss in the older alluvium shows that the gneiss was not wholly covered while the deposit was being formed. The throw of the frontal fault may have been 1,000 feet less than now at the date of the older alluvium.

The history of the alluvium of tract A was not made out but is believed to differ materially from that of tract B. The piedmont forms are there peculiar in several ways. As a rule an alluvial apron is made up chiefly of conical deposits spread from canyon mouths, and contributions received from intercanyon waste are relatively small, so that the convex elements of contour are opposite to canyons, but in this place there is a pronounced salient of the alluvial apron between canyons. As a rule the slope of the apron near the rock base of the Wasatch Range is so much gentler than the adjacent rock slope that the position of the rock base is closely defined by change of slope, but here the profile (fig. 20, A) shows a continuous sweeping curve from a point high on the range to one low on the apron. As a rule, along this part of the range front, the line of the rock base is paralleled by a fault scarp in the piedmont slope, but just here the piedmont scarp is interrupted. Associated with these features is an element of internal range structure. The range front here exchanges a southward trend for an eastward, but the tectonic block that constitutes the front from Willard to this point does not follow the bending; it ends here and is shown in cross section on the southerly face. Another block, with unrelated dip, adjoins it on the east, and beyond that stands yet another, each characterized by the position and attitude in which it holds the same conspicuous quartzite member. The peculiar phase of the piedmont is opposite the end of the first-mentioned block.

The evidence of a fault between the spur and the range consists in part in the continuity of range features from the escarpment back of the spur to the sheared quartzite at the Willard locality. The outcrops of quartzite and gneiss are visibly continuous, and so is the fresh scarp in the piedmont alluvium, which runs to the point marked C in Figure 18. After disappearing at C the scarp reappears at about D; and between D and North Ogden Canyon it is accompanied by outcrops of fault gouge. (See p. 19.) So the position of the spur lies between two localities that afford evidence of fault friction at the base of the escarpment. Of the same tenor is the relative abundance of gneiss boulders in the newer alluvium near tract B, with its implication of the broadening of the belt of exposed gneiss on the face of the range. The arrangement of quartzite and limestone belts in the spur is also indicative of faulting, although it implies nothing as to the time of faulting or the particular position of the fault plane. In the range the outcrop of the quartzite (the older formation) is west of the outcrop of the limestone, and in the spur also the quartzite, as mapped by Hague and Blackwelder, is west of the limestone. This is the arrangement that would result from dislocation by faulting and not that which would be given by an anticlinal fold.

Hague's map should perhaps not be cited in this connection, because the inference with which it is here associated is not sustained by his text. He wrote of the range in this part as the eastern part of "an anticlinal fold, whose western member has been broken down and carried away," and in speaking of outcrops on the spur he said:

> Broken masses of quartzite and limestone are seen lying, sometimes flat, sometimes tipped up at steep angles, and dipping both east and west. It is evident that these are the remains of the Cambrian and Silurian beds which form part of the western fold, but the masses are too much obscured to afford any definite structure lines which may give the clue to the position of the beds beneath the valley.[23]

[23] Hague, Arnold, U. S. Geol. Expl. 40th Par. Rept., vol. 2, pp. 393, 402, 1877.

The evidence of faulting about the outer margin of the spur is comparatively meager. Despite the irregularity of its surface the spur is a plateau (see pl. 9, *A*), sloping gently toward the southwest, and the plateau top is separated from the valley plain by a relatively steep slope. For more than a mile on the west side the limiting slope abounds in cliffs. The base of the steep slope, mapped in Figure 18 as the position of the fault, is a line of simple character, although it bends from west-northwest to northeast. Close to the rock base, at a point where the plateau front is specially steep, is a group of hot springs. A considerable number of thermal springs in the cordilleran region are so associated with special geologic features as to admit of genetic classification, and these fall into two groups. The source of heat for one group is volcanic; the waters of the other group rise from great depths along faults. Therefore the occurrence of thermal springs is not by itself demonstrative of faulting, but in connection with other evidence it may be regarded as confirmatory.

In Figure 18 the fault line has been drawn with confidence along the base of the plateau front as far as the front contains rock exposures. From one end it has been continued tentatively northeastward toward the base of the range because the plateau and plateau front continue to the base of the range. From the other end it has been turned tentatively toward the north, so as to separate the tract with scattered rock crags from a piedmont tract without visible rock. In this deflection it has been directed toward C, the end of the fresh piedmont scarp, that course being suggested by the fact that the history of the alluvial tract A differs from that of tract B.

TRAVERSE SPUR

From the Lone Peak salient of the range a spur runs westward, as shown in Figure 21. It is about 7 miles long and 3 miles wide, and its highest points are 1,200 to 1,600 feet above the bordering valleys. Its sculpture is mature. Its contact with the range lies along the south face of the granite body of the salient.

The intermont valley invaded by it is invaded from the opposite side by a broader spur of the Oquirrh Range, and the two spurs leave a passage only 2 miles wide. As the two spurs are regarded as a partition that separates Utah Valley at the south from Salt Lake or Jordan Valley at the north, they have been given a single name—the Traverse Mountains. It is possible that they belong together geologically, but so far as now known their structural features are independent. The eastern hills have a basement of sedimentary rocks and are partly covered with trachyte. In the western hills have been found only volcanic rocks. In the following paragraphs the hills connected with the Wasatch Range are called the Traverse spur.

A single stream from the range crosses the spur and by opening through it a steep-sided valley, Fort Canyon, has separated a small eastern part from the main portion. The smaller division contains only sedimentary rocks. The western division shows limestone and sandstone along Fort Canyon and also along part of the southern base, and much of its northwestern base consists of quartzite. All the higher part is known to be made up of trachyte, but the boundaries have not been traced. The age and structure of the sedimentary rocks have not been determined, but there can be little question that the formations are Paleozoic and that they have shared in the early diastrophic changes of the rocks of the range.

The junction of the spur with the range is marked topographically by a sag or groin. In part this sag follows the line of contact, and in part it runs within the spur and approximately parallel to the contact. Where it is not on the contact the details of hill form suggest landslides. (See pl. 10, *A*.) As shown in another section (see p. 39), there is reason to regard this sag as a variant or an equivalent of the fault

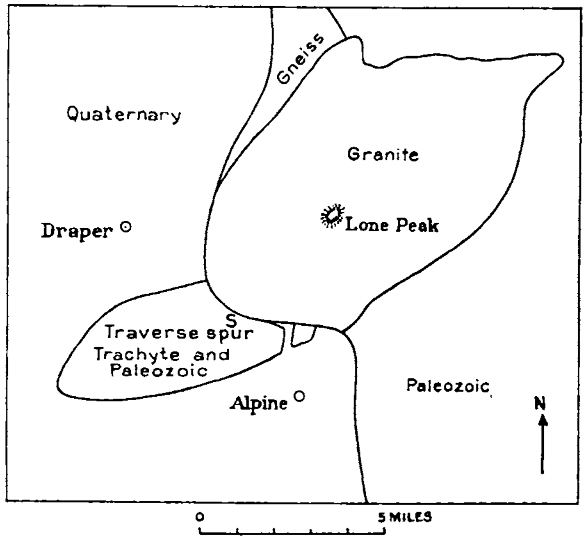


FIGURE 21.—Sketch map of Traverse spur and adjoining part of Wasatch Range, Utah

scarps of the alluvial apron. Post-Bonneville scarps of the usual type follow the base of the range on both sides of the spur and disappear at the junction of spur and range. A careful scrutiny of the alluvial apron of the spur discovered no similar scarp. It is inferred that at the time of the latest movement or the later movements, on the frontal fault, the relation of the spur to the valley was not changed.

The shearing of the granite, near the contact, at Fort Canyon has already been mentioned. A similar structure farther west is suggested by the appearance of the granite slope, as shown at the right in Plate 10, *A*, but I did not visit the spot. Still farther west Emmons[24] found at the contact of granite with trachyte a foliated rock apparently identical with the contact rock at Fort Canyon. He refers it, with such qualification as is implied by the word "doubtless," to the group of Archean schists which flank the granite on

[24] Emmons, S. F., U. S. Geol. Expl. 40th Par. Rept., vol. 2, p. 357, 1877.

the northwest, but the fact that it occurs at the contact gives plausibility to the alternative suggestion that it belongs to the shear zone of the granite.

There is a saddle between the range and the crest of the spur at *S*, Figure 21. The view in Plate 10, *A*, looks toward the saddle from the east, showing the spur at the left and the granite of the range at the right. The drainage line of the sag here runs wholly on the spur. Beyond the saddle the descent is northwestward, and a small stream, aptly named Corner Creek, flows along the groin. The creek for some distance follows the contact and for much of that distance has sunk its channel into the granite. The slope of the granite surface is 20° or less, and the rock resting against it is either trachyte or a product of the decomposition of trachyte (see p. 39), both more easily eroded than the granite. Under such conditions the stream may erode its weaker bank and shift its channel laterally down the surface of the stronger, or it may corrade the stronger rock beneath it and thus intrench itself and establish a permanent channel. The determination of one or the other of these alternatives will depend on several factors, among which are the relative erosibility of the two rocks, the slope of the central plane, and the power of the stream to corrade.

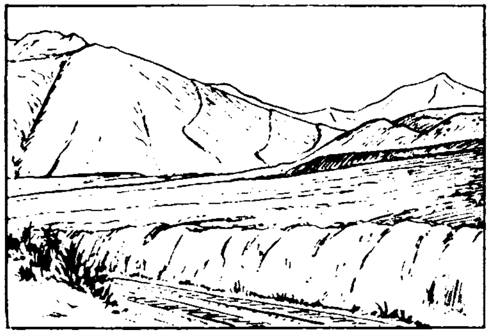


FIGURE 22.—Sketch of Lone Peak salient of Wasatch Range, Utah, from the west, showing spiral furrows. At right, hill of the Traverse spur. In the distance a peak of the Timpanogos Wasatch

On the face of the granite above the creek are anomalous channels, which find their explanation in the channel of the creek. Instead of descending the face in the direction of its general slope they descend obliquely, following lines which approach more nearly topographic contours. They are approximately parallel to the channel of the creek and are in fact ancient channels of Corner Creek, stranded on the face of the salient. They mark former positions on the granite of the edge of the trachyte. In 1901 I sketched the old channels from a neighboring summit on the spur, and the lines of the sketch have been reproduced at *b* in Figure 23. In 1917 a sketch was made from the northern base of the spur, and the lines of this sketch appear in Figure 22. In each figure the sky line of the spur is drawn from a photograph too poor to afford details of the mountain face, and the lines of the sketch have been adjusted to the more accurate data from the camera. The later sketch represents three spiral channels; the earlier represents two, each with a branch. It is probable that the highest line was not recognized in the earlier view and that the branches fall outside the field of the later view. At the time of the earlier sketch I estimated the vertical interval between the creek and the lowest stranded channel at 200 to 300 feet near its lower end and at 500 feet near its head; and I estimated the interval between the two observed old channels at 500 to 600 feet. As shown by Figure 22, the interval below the highest channel is still greater.

Plate 10, *B*, gives a view on the lowest of the old channels. The trench still carries drainage, for it is a gutter, intercepting all precipitation on the slope between it and the channel above, and its V-shaped section indicates that its storm-water stream is efficient. The rounded rim tells of weathering, and its granite shows decomposition, but there is no deep decay.

The stranding of the creek channel is evidently a result of the shifting of the line of contact between the granite and the rock of the spur. On the assumption, for simplicity of statement, that the granite has held its place, the surface of the trachyte has been lowered and with its lowering the position of the creek has shifted down the granite slope. The lowering of the trachyte has been due in part to wasting but in larger part, I think, to faulting. In the intervals between fault slippings the creek has corraded the granite, and occasionally, during a long interval, it has corraded so deeply as to become intrenched. After the next faulting all the water from the granite slope above would be caught by the corraded channel and all the water from the trachyte slope would gather along the newly placed contact line. With further faulting the interspace between the stranded channel and the new contact channel would increase, and with its increase the discharge of the contact stream would become greater; and it is possible that the rhythmic character of the stranding was determined in this way. I would not, however, give emphasis to this suggestion, for epochs of local rest in a period of general diastrophism might be inferred as probable from what we know of the time distribution of earthquakes.

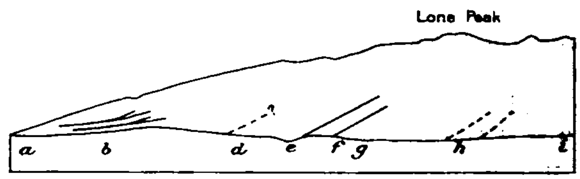


FIGURE 23.—Diagram of southern face of Lone Peak salient of Wasatch Range, Utah. The profile is taken from a distant photographic view. The middle line represents the rock base. From *a* to *g* the base is at contact with the Traverse spur, passing Fort Canyon at *e*. From *g* to *i* it is at contact with an alluvial apron

The fact that the old channels approach one another as they descend affords a clue to the relative effectiveness of faulting and degradation in the lowering of the spur at the contact. Under the assumption that changes in the valley to which Corner Creek discharges have been relatively small, so that the valley has afforded a fairly constant base-level, the lowering of the creek profile should be greatest at its head and diminish downstream, and such a change of grade is of the proper kind to explain the lack of parallelism in the old channels. It is true that the crustal block on which the creek runs may be tilting eastward and that the crustal block of the mountain may be tilting westward, but if such changes are in progress they are probably slower than changes of profile from progressive degradation. If it is proper to ascribe the whole of the convergence to degradation, and also to think of the creek level at the lower end of the groin as stable, then the height of an old channel opposite that point on the creek represents the addition to the throw of the fault since the creation of the channel. The lower end of the highest channel, shown in Figure 23, is opposite the lower end of the groin, and the difference in height has been estimated, with the aid of a photograph, at 1,300 feet. The height of the same channel at the sky line of the picture, above the corresponding part of the creek bed, is estimated at 2,000 feet. The difference between these, 700 feet, is the estimated vertical factor in the change of creek slope since the epoch when the old channel was formed.

The state of preservation of the old channels and especially the fact that they have not been converted into deep gorges but are still inconspicuous notches on the granite face warrant the inference that during the existence of the channels the wasting of that face has made little progress. It is believed that so little has been removed from the general surface that the smooth profiles in Figures 22 and 23 do not grossly misrepresent the shape of the granite mass before it was uncovered. This subject will receive further attention, and additional evidence will be presented in another connection.

In the present connection may be mentioned another set of oblique channels, seen on the southern face of the salient at points farther east. They are represented at *d*, *e*, *f*, and *h* in Figure 23. Their angles of descent are very steep compared to those of the Corner Creek group. The lower end of the channel marked *e* was seen close at hand and was thought to be related to the groin between the granite and the eastern division of the spur, but the higher portion of the same channel did not seem to admit of explanation as an ancestor of the groin. No adequate interpretation of the group has been suggested, and it is mentioned only as a promising subject for future study.

While the waves of Lake Bonneville were making their highest record there was a small bay into which Corner Creek then discharged. They carved rather deeply on neighboring slopes of the range and the spur, and the cliffs they created are now conspicuous features, but they did not carve the shores of the bay. Detritus from the cliff at the north was drifted along the shelf at the base of the cliff and built into a bar across the mouth of the bay, thus separating a triangular lagoon from the lake. Afterward the creek washed out the middle part of the bar, so that it is represented now only by its ends, one of which stands on the range and the other on the spur. The remnants are on opposite sides of the fault, and their present difference in level gives a definite record of the addition that has been made, at this point, to the throw of the fault since the time of the lake. It is 37 feet. During the Provo stage of the lake, 400 feet lower, whatever bay may have at first existed was filled by débris brought by the creek, and through the plain thus formed the creek has since opened its valley. A remnant of the plain is crossed by a fresh fault scarp with a throw of about 15 feet. (See pl. 11, *A*.) From these data it appears that only a part of the vertical change since the time of the higher shore line has occurred since the completion of the lower shore line. The remainder of the change took place during the presence of the lake.

Definite evidence of faulting was not found along the outer margin of the spur. Where the rock at the margin is trachyte the margin may represent the limit of a lava flow, with subsequent shaping by erosion. The lava may not everywhere have a foundation of Paleozoic rock but may rest in part on alluvium or other valley deposits. Except at the east end of the spur, where there is no trachyte, the topographic prominence of the spur may be due wholly to eruption. On the northwest side, where the foundation rocks are best known, they do not stand in well-marked relief above the valley deposits, and the line of separation has been obscured by the work of the waves of Lake Bonneville. Perhaps the best indication of the position of the hypothetic fault is given by a group of warm springs about half a mile northwest of the tract in which the foundation rocks are exposed.

HONEYVILLE SPUR

The village of Honeyville stands in part on a low table that projects as a step from the base of the range. The table is less than 100 feet high, and its width in any direction is between three-quarters of a mile and 1 mile. It is a dislocated tract of valley plain and piedmont slope that has been moved valleyward a short distance, tilted mountainward, and perhaps slightly lifted. Its visible material is gravelly alluvium, partly reworked by waves and partly cemented. The western (outer) half of its surface is nearly level, except for scattered, isolated subconical hillocks. Near the mountain the surface shows ridges, that have a north-south trend, in graben and horst fashion. The corrugation is strongest close to the mountain base and ends in a fresh-looking scarp, the height of which is estimated at 100 to 125 feet. Next to the scarp is a graben which is in part undrained. (See pl. 11, *B*.) The high scarp is about half a mile long and at its south end is curved valleyward, with diminishing height. The western face of the table may have been washed by waves, but the scarps, ridges, and hillocks show no modification by waves. The table was formed after the retirement of the waters of Lake Bonneville.

The hillocks have the same material as the table, including cemented gravel; and blocks of cemented gravel in them are tilted. Apparently they have been pushed up from below, but no adequate explanation of their uplifting has occurred to me. The only related features with which I am acquainted are certain gravel hills that rise above the lake plain a few miles farther south. One of these hills, north of Call's Fort, is cut through by the Ogden & Idaho Interurban Railway, and two others stand near that railway between Perry and Woods stations. As seen from the train they appear to be wholly surrounded by the lake beds of the plain, which is there flat.

The table may be the summit of a crustal block that has recently been disturbed in its relation to other blocks beneath the valley deposits, or the movement creating it may have involved only superficial formations. The dislocation of a crust block would produce a fault scarp about the outer margin, and a fault scarp as recent as the scarp along the mountain base could not have escaped attention, unless it was obliterated by more recent wave action. Such a fault scarp was not noted, and if the margin has been reworked by waves the resulting beaches are inconspicuous. I therefore incline to regard the table as a landslide. The corrugation of a landslide arises chiefly from the breaking away of successive slices of earth. If the table, which is corrugated only along the edge near the mountain, is a landslide it may be assumed that the main body moved all together and practically as a unit and that the ridges started one at a time and later. The slope of the piedmont is here gentle, and the intermont valley is occupied mainly by a lake plain. These features indicate the need of an exceptionally good slipping surface, and they also suggest that the surface may be furnished by a buried lacustrine ooze of even inclination. The hypothesis as thus formulated, however, fails to explain the subconical hillocks.

MADSEN SPUR

A short distance north of the Honeyville spur is the Madsen spur. Its width and length are each somewhat more than 1 mile. Its height near the outer edge is about 200 feet and near the mountain about 300 feet. Its upper slopes join those of the alluvial apron, as indicated in Figure 24. Its visible material is gravelly alluvium, in large part worked over by shore waves, and the details of its form testify to wave action at all levels. Its steepest face fronts toward the west and overlooks a level plain through which winds the incised channel of Bear River. Under the base of the steep face is a group of hot springs with large discharge, and the issuing stream on its way to Bear River follows a deeply sunken channel through the plain. In visiting the locality I neglected to make a close inspection of the springs and failed to observe a rock exposure which, as I now know, was noted by both Frémont (1843) and Gunnison (1850). Frémont[25] says that the springs issue "beneath a conglomerate consisting principally of fragments of a grayish-blue limestone"; and Gunnison[26] characterizes the rock as "conglomerate and limestone." These records, related as they are to waters of high temperature issuing from the base of a tabular spur, indicate unmistakably a fault breccia similar to that at the base of the City Creek spur. (See p. 23.)

From these data I infer that the spur represents a crustal block which at some late but pre-Bonneville stage of the frontal fault of the range parted company with the sinking valley block and joined itself to the rising mountain block. In rising the block carried with it a body of alluvium that had previously been washed from the rising range to the valley, and the lifted alluvium, although exposed to the waves of Lake Bonneville, has not been so long subject to agencies of erosion as to have lost its tabular character. (See fig. 24.)

The northern face of the spur has been greatly modified by landslides, and the resulting topographic forms show no trace of subsequent wave action. The sliding has therefore taken place since the re-

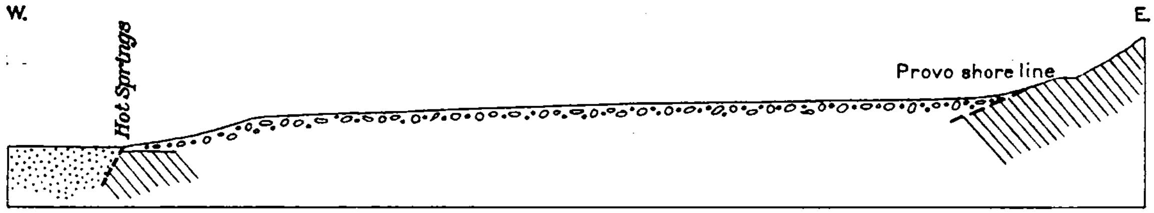


FIGURE 24.—East-west section of Madsen spur of Wasatch Range, Utah. Length of section about 7,500 feet

[25] Frémont, J. C., Report of the exploring expeditions to the Rocky Mountains in the year 1842 and to Oregon and North California in the years 1843–44, p. 159, 1845.

[26] Gunnison, J. W., in Stansbury, Howard, Explorations and survey of the valley of the Great Salt Lake of Utah, including a reconnaissance of a new route through the Rocky Mountains: 32d Cong., spec. sess., S. Ex. Doc. 3, p. 213, 1853.

tirement of the old lake. Nevertheless it has been extensive, and its history appears not to have been altogether simple. The dominant trend of the displaced ridges is easterly, but in the western part of the area are some with northerly trend. Figure 25 shows diagrammatically the disposition of the easterly ridges, which are in two groups. Those of the more ant and earlier-formed group are relatively small and stand at a lower level. Plate 12, *A*, shows the scarp at the head of the series, with ridges of the later group and an associated broader earth block that was tilted forward as it moved.

OTHER SPURS

Half a mile north of Odgen Canyon is a buttress of the range, rather abruptly salient, as indicated in Figure 26, and roughly conical in shape, as shown in Plate 12, *B*. Its rock is an exceptionally hard and tough dark-gray gneiss. Adjoining it in the body of the range are gneisses of paler color which weather more easily. When viewed from a distance it has the appearance of an excrescence of the range, but the nature of its separation from the body of different gneiss was not determined. A piedmont scarp, which follows the rock base of adjacent parts of the range, follows with equal fidelity the somewhat angular base of the buttress. I did not satisfy myself whether the buttress should be classed as an independent crust block or as a knob projecting from the Wasatch block, a knob so strong and hard that it has plowed its way through the hanging wall as the valley block descended.

Most other spurs and flanking tables are associated with canyon mouths from which large streams issue and are remnants of the deltas built by the same streams in Lake Bonneville. They occur in pairs, each original table having been divided by later stream erosion; their gravel is better rounded than that of the alluvial apron, and sections show inclined, "foreset" bedding. These features serve to distinguish them from spurs of diastrophic origin.

South of Santaquin the range is bordered by a group of ridges which have been described by Loughlin.[27] These ridges are parallel to one another and to the range front and are separated by faults with downthrow to the west. The faults, which are demonstrated by stratigraphic evidence, are also expressed in the topography, and the ridges, although too short and narrow to rank topographically with features commonly called ranges, must be classed structurally with the fault-block ranges. They differ in topographic type from the range system of the Great Basin in that the interridge troughs, draining to lowlands at the north and south, are not occupied by belts of detrital plain but are narrow passages between discontinuous bodies of rock.

[27] Loughlin, G. F., Reconnaissance of the southern Wasatch Mountains, Utah: Jour. Geology, vol. 21, pp. 436-452, 1913. (See especially pp. 448-452 and fig. 4.)

SUMMARY AND CONCLUSIONS

The Honeyville table is of doubtful origin and need not be included in a summary of fault-block spurs. The Madsen, Pleasant View, City Creek, and Traverse spurs are the upper parts of crustal blocks that are separated by normal faults from the Wasatch block on one side and from the valley block on the other, so that they stand lower than the one and higher than the other. Their dislocations belong to the later, post-Eocene period of diastrophism, but at least two of the spur blocks show internal faults that were acquired in a pre-Eocene period. The Madsen, Pleasant View, and City Creek blocks are capped in

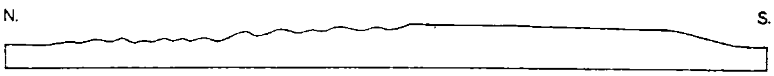


FIGURE 25.—Diagrammatic north-south profile of Madsen spur of Wasatch Range, Utah. The spur is a little over a mile in width and 200 to 300 feet in height

whole or in part by alluvium from the Wasatch Range, alluvium that was once part of the piedmont apron of the range; the Traverse block may or may not have a similar deposit beneath its capping of trachyte. The presence of this alluvium and its dislocation from the general modern alluvial apron of the range show that the spur blocks were once so associated with the valley

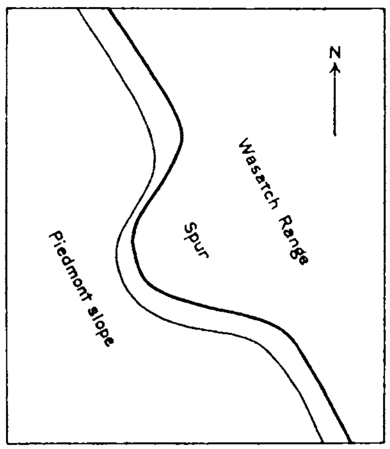


FIGURE 26.—Ground plan of block spur north of mouth of Ogden Canyon, Wasatch Range, Utah. The heavy line shows the rock base; the light line the piedmont scarp

block as to receive the same deposit and have since been lifted with reference to the valley block.

A post-Bonneville piedmont scarp runs between the range and the Pleasant View spur, and the same is true of the Traverse spur and perhaps of the Madsen, the indication being that in the very latest movements these spur blocks have adhered to the valley block. The post-Bonneville scarp runs outside the City Creek spur, showing that in recent time that spur block has adhered to the range block. These diversities in history show that the conditions determining adhesion to the rising range or to the sinking valley were local and variable.

The City Creek spur bears an early Tertiary formation on the back of its body of pre-Cretaceous rocks. The Pleasant View spur is definitely characterized by the absence of a similar early Tertiary cover. The constitution of the Madsen spur is masked by its cover of piedmont alluvium, and that of the Traverse spur has not been adequately studied. At the time of the initial dislocation between the range and the valley the City Creek and Pleasant View blocks went down with the valley block and were thereby protected, wholly or partly, from the erosion to which the rising range was subject. Their condition therefore tells something of the condition of the land at the beginning of the orogenic movement. The surface was in part occupied by dislocated and inclined bodies of older rocks, much reduced by erosion, and in part by early Tertiary terrestrial deposits which had also been disturbed and eroded.

Two of the spurs are associated with pronounced salients of the range. The Traverse spur adjoins the great granite salient; the Pleasant View spur touches an equally marked outward curve of the frontal fault. The Madsen spur is opposite the northern limit of a small embayment of the range front, so that it is associated with a minor convexity of the front. (See fig. 13.) The Honeyville table stands opposite the southern limit of the same embayment. The City Creek spur probably but not certainly covers a local outward swing of the line of the frontal fault. These relations suggest that the local conditions that determined the spurs were the same as or were connected with the conditions that determined the salients. Irregularity in the fracture surface of the great orogenic fault was occasioned by heterogeneity of the faulted terrane. Elements of irregularity in the direction of strike are manifested in flexures of the fault line, and to this class belong the salients. Coordinate with these flexures are irregularities on lines of dip, and as the fault movements were in the direction of the dip there was a constantly renewed discordance between the forms of hanging wall and footwall. Also, because the weight of the overlapping valley block enforced contact, there was a constantly renewed adjustment. As already pointed out, part of this adjustment was accomplished through abrasion and another part through flow. In the upper and less loaded portion of the valley block part of the adjustment may have been affected through fractures that reach the top, and in the thin portion of the valley block near the fault line fractures may have extended from top to bottom, so that fragments of the valley block may have been detached and dislocated. Figure 27 is introduced to illustrate this suggestion by an ideal example. The local dip line is assumed to be straight except at a single place, low down, where a firmly fixed knob of strong rock projects from the footwall. During early stages of the movement (A) weaker rocks of the valley block make the necessary adjustment by flow. At some later stage the knob punches out a piece of the valley block, creating a spur block. If the spur block were merely severed and the valley block moved away from it a chasm would be created (B) like the crevasse of a glacier, but the parts are too heavy to permit this, and their settling yields a condition like that shown in (C), with canting of surfaces toward the range block and a scarp between the spur block and the valley block.

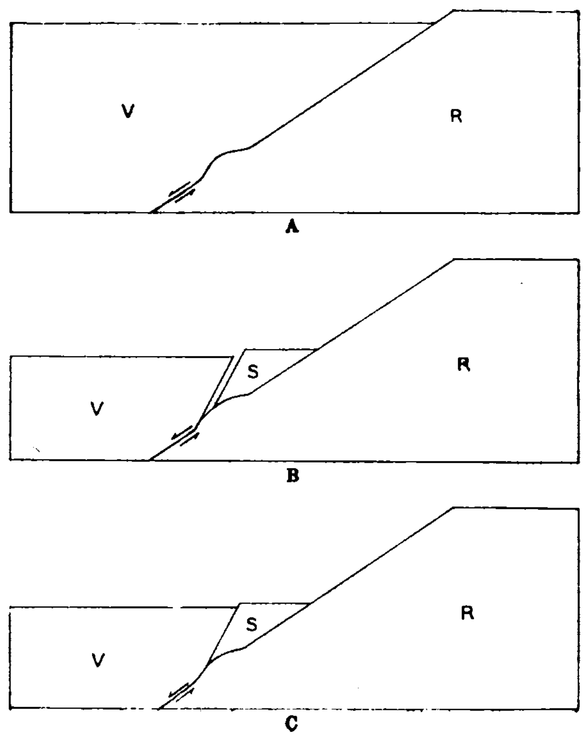


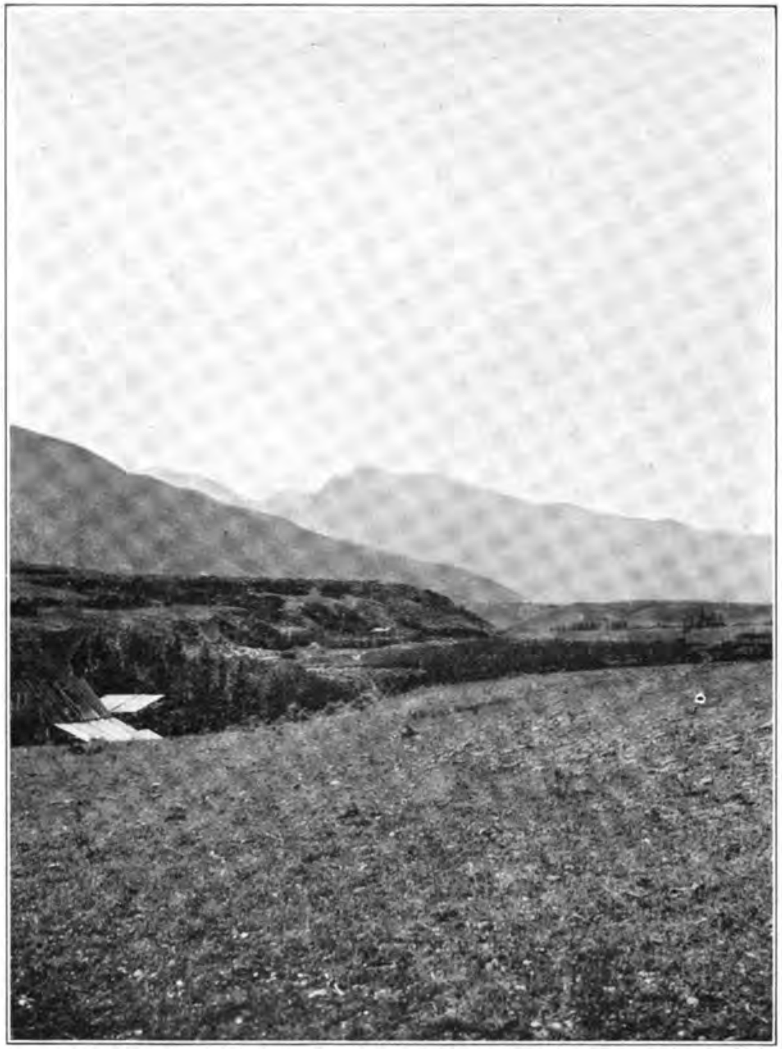
FIGURE 27.—Ideal sections of progressive dislocation of valley block, V, and range block, R, to illustrate hypothetic derivation of spur block S

It is noteworthy that all four of the fault-block spurs are accompanied by thermal springs, whose waters rise along their outer bases. I know of but two localities of thermal springs on the line of the frontal fault of the range. The spur base is lower than adjacent parts of the range base, and the point of issue at each spur locality may be determined by that fact, but that consideration does not explain the scarcity of thermal waters on the long line of the frontal fault. It may be that the outer faults of the spurs are peculiarly favorable for the conveyance of deep penetrating circulation because of the less perfect adjustment there of the fault walls.

The highest recorded temperatures for the thermal springs are, Madsen spur, 134° F.; Pleasant View spur (Red Springs, Utah Springs), 136°; City Creek spur (Beck's Spring), 133°; Traverse spur (Draper Springs),

A SCARPS IN MORAINE

The Pleistocene glacier of Little Cottonwood Canyon protruded beyond the mouth of the canyon and built lateral moraines just outside. The view shows the left or south moraine, with double crest and with dislocations marked by scarps. The scarp at the left, running up from the railway cut, is relatively young and is scantily clothed by bushes. Others at the right are older



B. SCARP AND GRABEN IN ALLUVIAL APRON

View along the west face of the range. The valley features are north of Big Cottonwood Canyon. Between the foreground and the high piedmont scarp is a tract of land dropped below the general level

PIEDMONT SCARPS IN WASATCH RANGE, UTAH

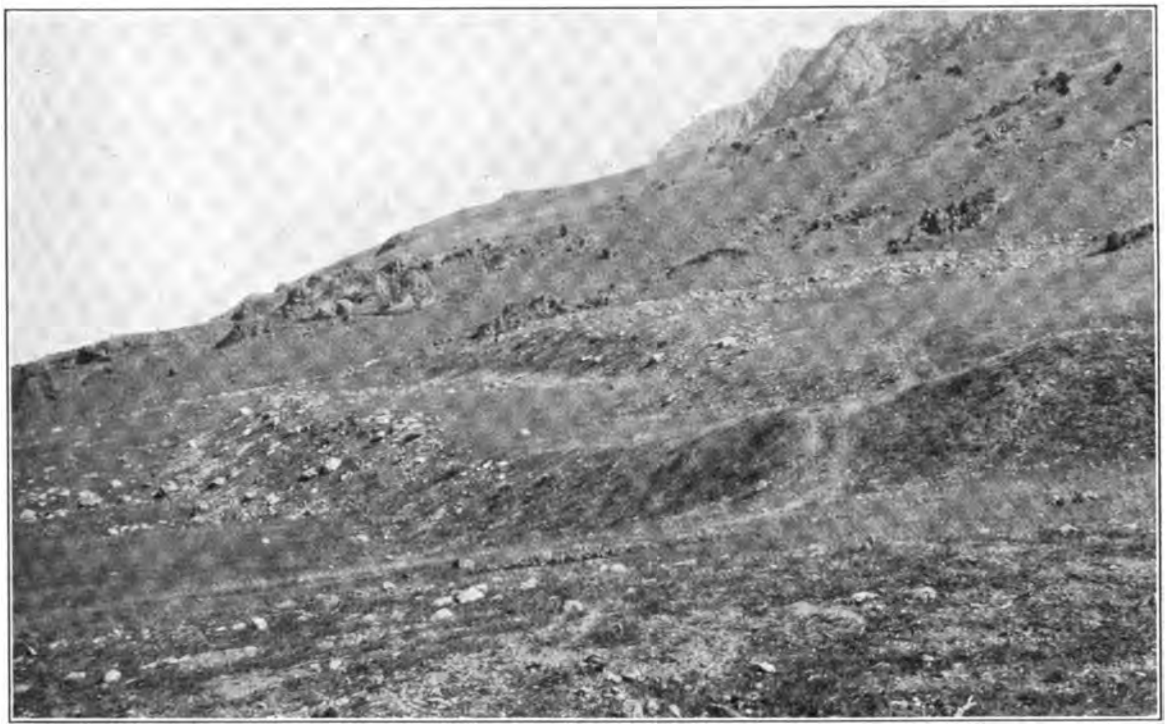
A. SCARPS IN ALLUVIUM

The Wasatch escarpment between Big Cottonwood and Little Cottonwood Canyons shows dissected facets. The piedmont scarp nearest the mountain is at the right the strongest of the series, but in the center and at the left the second scarp is the strongest. At the right of the center the second branches; its upper branch joins the first scarp; its lower branch tapers and nearly disappears. Below the second are several smaller scarps

B. SCARPS AND GRABEN IN MORAINE

The left lateral moraine left by the Little Cottonwood glacier is shown in Plate 8, *A*. The right lateral moraine, here shown, is flat-topped. The principal piedmont scarp crossing it has a companion scarp facing toward the range, and between them is a graben. The view looks northward

PIEDMONT SCARPS IN WASATCH RANGE, UTAH



A. SCARPS NORTH OF OGDEN CANYON

The lower of the two scarps is the younger, as shown by its sharper definition at the top. Compare Plate 17, *B*

B. SCARP ON BONNEVILLE DELTA NEAR WEBER CANYON

While the Lake Bonneville waves were shaping the Provo shore line Weber River built a large delta at the edge of the lake. The piedmont scarps across this delta are high. The terrace above the one pictured is an undisturbed part of the delta. The plain below it is another part of the delta, dropped and tilted toward the range. The highest Bonneville shore line appears as a terrace on the facets of the range front

PIEDMONT SCARPS IN WASATCH RANGE, UTAH

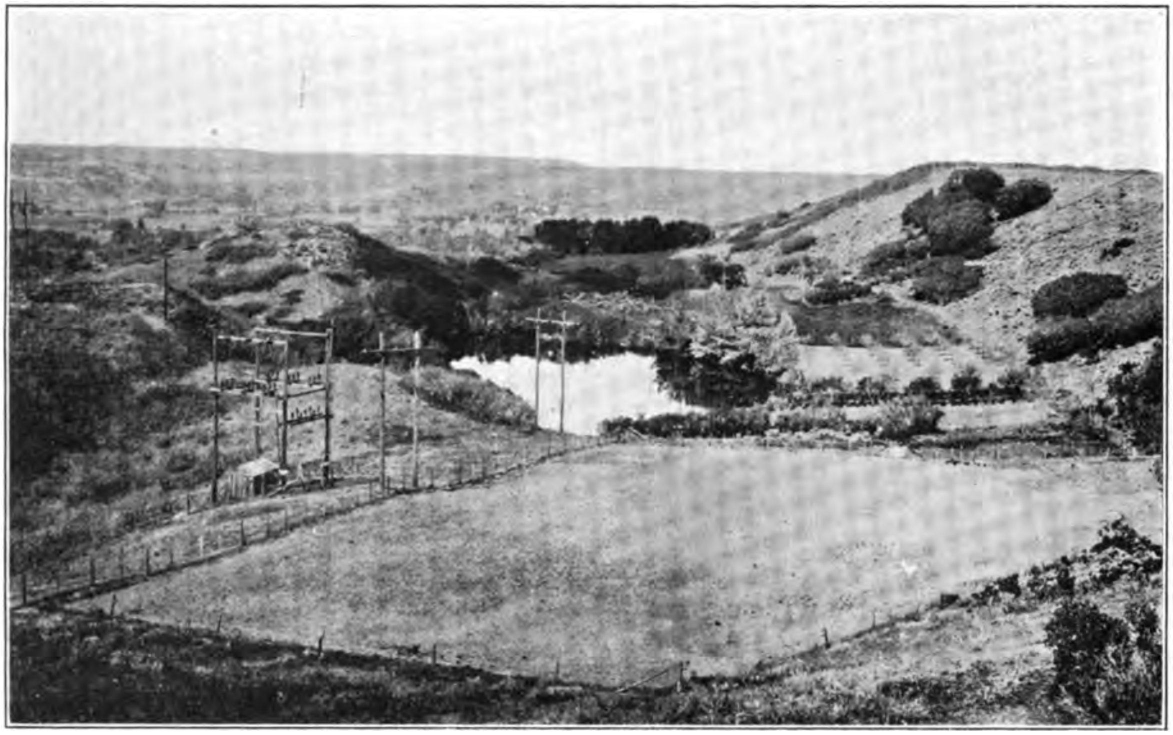
A. SLIDE ON A STEEP HILLSIDE

The material is regolith. The irregular scarp at the head corresponds to unevenness of the surface of unaltered rock over which the body of regolith moved. The bulging mass below is the complement of the cavity above. The slide was started by an earthquake shock, but the principal movement took place later, after the ground had been saturated by rains

B. SLIDE ON A MODERATE SLOPE

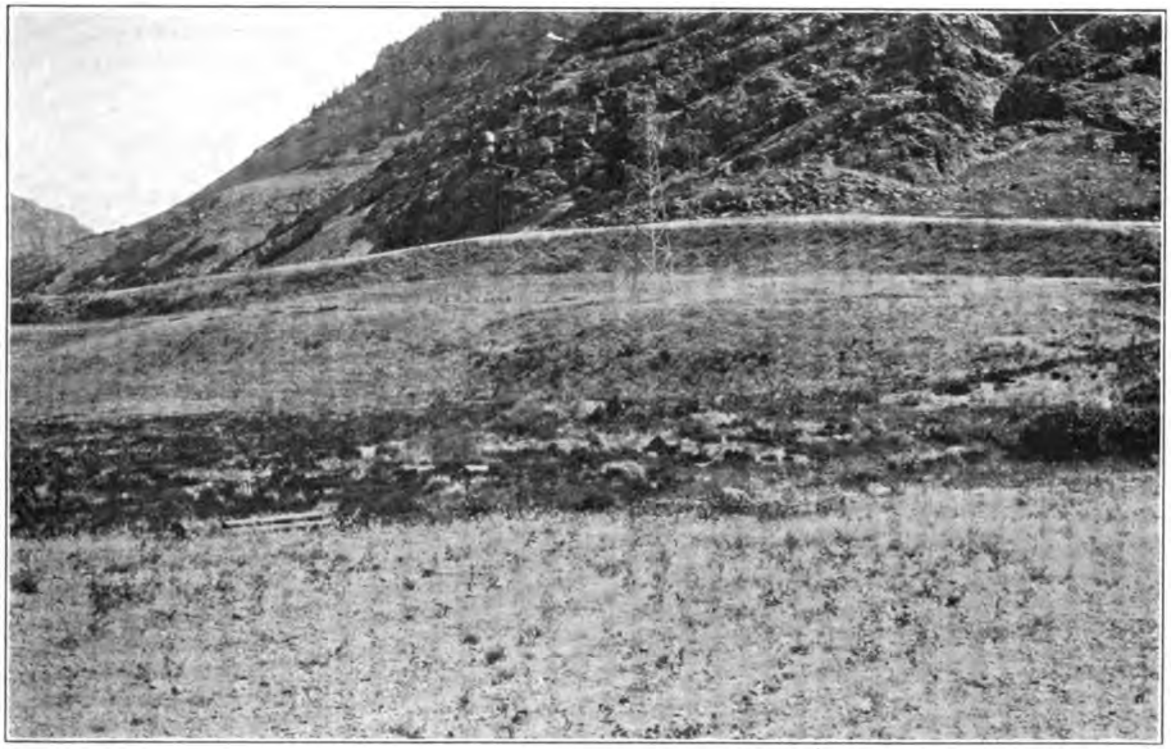
The material is earth, washed from above. A large coherent block inclines forward; other blocks incline backward. The scarp shows lunate forms

LANDSLIDES IN BERKELEY HILLS, CALIF.



A. LANDSLIDE NEAR UINTAH, UTAH

Weber River has carved a valley through a delta built by the same river in Lake Bonneville. The valley walls break away in landslides. The top of one of the slid masses appears at the left in the view as a group of hillocks. At the right is the scarp from which the mass parted. The sag between contained a small pond, which has been enlarged by means of a dam



B. PIEDMONT SCARPS NEAR CITY RESERVOIR, OGDEN, UTAH

At this point are three scarps, as shown by the profile in Figure 32. The view, commanding two of them, is from the crest of the third. The upper of the two shown is the younger, as indicated by its sharper definition. Compare with Plate 15, *A*. The upper scarp is a conspicuous feature in Plate 8, *B*

A. SCARP ALONG SOUTH BASE

B. SCARP ALONG NORTH BASE

PIEDMONT SCARPS ABOUT BLACK SPUR OF WASATCH RANGE, UTAH

The black spur is at the west base of the range, 1 mile north of Ogden Canyon. Its form, shown in Plate 12, *B*, is closely related to the dip of the fault about its base. Where the fault dip is relatively steep (north side) the piedmont scarp is relatively near to the rock base

128°; frontal fault at mouth of Ogden Canyon, 150°. In some springs, however, and probably in all, the temperatures are variable. For the hottest Madsen spring the records range from 128° to 134°, for Beck's Spring from 126° to 133°. The observations of Bradley[28] on the Madsen springs show that the higher temperatures are associated with relatively small volume. He found larger volume and lower temperature (128°) in June, the smaller volume and higher temperature (132°) in November of the same year. Observations of the temperature of Beck's Spring are accordant but are less significant because made in different years and without comparative data on volume. On July 5, 1877, I obtained 126°, and on August 30, 1917, Mr. Sterling B. Talmage[29] found 133°.

As ground-water springs are lowest in autumn, and as the circulation at great depth is less sensitive to seasonal influences, it is safe to infer that the fluctuating temperatures of such thermal springs depend on the dilution of a practically constant discharge of uniformly hot water rising from the depths with a variable discharge of cool ground water. If the volumes of the springs associated with different temperatures were known, and also the ground water temperature, it would be possible to compute the temperature of the undiluted hot water. Lacking these data, we may infer that even the hottest spring water is probably somewhat diluted by ground water, and that the temperature of the water rising along the fault is higher before dilution than any of the recorded spring temperatures. In localities that show no indications of recent volcanism the heat of waters rising along faults is presumably derived from the inner earth's store. The water that rises toward a spring is necessarily part of a circulation; it has received heat in the lower portion of its course and has parted with some of it while ascending. Its temperature as it approaches the surface may be near to but can not equal the rock temperature of the lower part of its course. The mean annual temperature of the air at Salt Lake City is about 52° F.,[30] and this may be assumed as the earth temperature at the surface. The highest recorded spring temperature at the base of a spur is 134°, or 82° above the surface temperature. On the assumption that the local temperature gradient is 1° for each 75 feet, the depth at which a rock temperature of 134° is reached is 6,150 feet. This may be accepted as an underestimate of the depth to which water circulates on the faults that limit the spurs. A probable estimate would include allowance for the water's loss of heat by conduction during its ascent and for the fact that the observations of temperature are made after the rising current has received more or less ground water.

The fault-block ridges near Santaquin, described by Loughlin, have definite trends, parallel to the trend of the Wasatch Range. This description could be applied to one of the fault-block spurs, the Pleasant View. The Traverse spur trends westward, and the others are without notable trend. This difference probably indicates that the Santaquin ridges and the spurs are of distinct types. The Santaquin ridges are small fault-block ranges. The spurs are subsidiary features of the frontal fault of the large range. The relation of the Santaquin ridges to Juab Valley and to Utah Valley suggests that they may constitute an exceptionally high part of the floor of a long intermont trough, that other parts of the floor may be made up of a system of minor fault-block ridges, and that the "valley block," which on earlier pages has been mentioned as coordinate with the range block, may in fact be an elaborate compound of many minor blocks with prevalent north-south trend.

PIEDMONT SCARPS

The structural data set forth in the preceding sections as proof that a fault created the western face of the range are mainly new and receive here their first publication. They were unknown to those who early recognized the fault by means of its physiographic features and to those who afterward discussed the physiographic evidence. So as a matter of history they constitute supplementary evidence, and their function has been to confirm a conclusion already reached. They are here given first place because they are supposed to appeal to the understanding of those geologists whose opinions are little affected by physiographic evidence and the physiographer's reasoning. In the following pages I propose to present and discuss the physiographic data, not primarily for the purpose of adding evidence of the existence of the fault but in order to determine if possible the value and limitations of physiographic characters as criteria for the discrimination of fault-block mountains.

The alluvial slopes that descend from the rock base of the great escarpment are interrupted by small scarps or bluffs which are evidently results of dislocation. When these were first observed in the Great Basin they were called fault scarps, and in my own writings that usage has been continued. By other writers, beginning with Russell, the term fault scarp has been used in a broader sense, being applied to any escarpment created by faulting; and by one writer it has been applied also to escarpments created by differential erosion along lines of faulting.[31] The

[28] Bradley, F. H., U. S. Geol. Survey Terr. Sixth Ann. Rept., p. 199, 1873.

[29] Finding confusion in the records of thermal springs near Salt Lake City, I sent out a letter of inquiry, which fell into the hands of Mr. Talmage. His response included a suite of temperature observations, made Aug. 30–31, 1917, which are worthy of record although, in their fullness, not germane to my text. In the following list the order is from south to north: Salt Lake City warm springs, No. 1, 35° C. (95° F.); No. 2, 36° C. (97° F.); No. 3, 40° C. (104° F.); No. 4, 42° C. (108° F.). Sanitarium Spring, "The Pump," 112° F. (reported by management of sanitarium). Jones's warm spring, 37° C. (99° F.). Beck's hot spring, 56° C. (133° F.).

[30] U. S. Weather Bur. Bull. R, 1908.

[31] Spurr, J. E., Geol. Soc. America Bull., vol. 12, pp. 258–259, 1901.

dominant usage is that of Russell, and it is properly dominant because the term where thus used is self-explanatory. Having now to write of the phenomena to which the name was first given, I feel the need of a distinctive designation and have selected "piedmont scarp." I shall use the name to designate a scarp that occurs on the piedmont slope and that is caused by dislocation. By avoiding the word fault, it involves no implication as to the nature of the dislocation.

Except at two localities the piedmont scarps of the Wasatch occur in unconsolidated formations. Ordinarily they interrupt the slopes of the alluvial apron, and the faces of the scarps are composed of the piedmont alluvium. In a considerable number of localities they interrupt either the alluvial slopes of deltas built at the shore of Lake Bonneville or the slopes of the gravel beaches into which the Bonneville waves rearranged the material of the alluvial apron. At a few localities they traverse glacial moraines. In one of the exceptional localities the scarp is at the rock base and its face is composed of consolidated rock—a fault breccia. In the other it is partly in cemented gravel of a Bonneville beach.

The piedmont scarps are near the rock base and approximately parallel to it. In places a single one is seen; elsewhere two or more. Where several occur they may all face toward the valley or one or more may face toward the mountain. Without exception the scarp nearest the rock base faces toward the valley, and the net vertical shift of a group of scarps is downward on the side of the valley. In many places it is evident that the members of a group were not all made at the same time. The more recent, as a rule, stand at the angle of repose for earth, are sharply defined at the top, and bear only a scant growth of bushes; the less recent are less steep, join the normal piedmont slope above by a curve, and are well covered by bushes. These differences are illustrated by Plates 17, *B*; 18, *A*; 13, *A*; and 13, *B*. In several places it is evident that two or more movements have occurred on the same line.

The more recent movement may be indicated by a relatively steep slope near the base of a scarp otherwise subdued by long weathering; or the difference in date may be shown by the relations of the scarp to stream terraces in an alluvial fan or a Bonneville delta. A scarp may fade out longitudinally and be replaced by another en échelon, either above or below it on the slope. (See pl. 14, *A*.) Where such an offset occurs a strip of alluvium, lying between the two scarps, slopes gently and obliquely from the alluvial plain above the scarps to the alluvial plain below. The relation of the scarps to features of the Bonneville shores and Pleistocene moraines makes it possible to say definitely that some are post-Bonneville and postglacial and others pre-Bonneville.

In some places the alluvial slope is seen to be less steep below the piedmont scarp than above it, and this is probably a general character. In a few places the alluvium close to the base of a scarp slopes toward the scarp. These features, which are illustrated by Plates 17, *B*, 15, *B*, and 15, *A*, serve to show that the amount of vertical descent of the outer block of alluvium, considered as a unit, is usually not only less than the height of the scarp but less than the vertical distance from the base of the scarp to the plane of the upper alluvial slope—that is, the measurement of the distance a–b in Figure 28 ordinarily gives an overestimate of the vertical displacement of the alluvial plain. The maximum apparent post-Bonneville vertical displacement is about 150 feet. The average vertical shift for the Wasatch belt of piedmont scarps is perhaps one-fourth as great.

Where two scarps face each other (see pl. 14, *B*) it is evident that the block of alluvium between them has been dropped farther than the valley block. This is a phenomenon closely allied to the canting mountainward of the upper edge of the lower alluvial

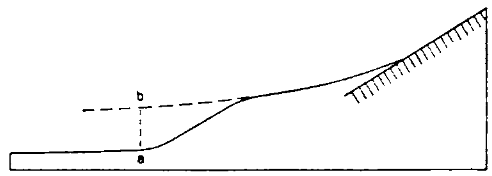


FIGURE 28.—Profile of piedmont scarp, illustrating measurement of throw

block, and account must be taken of the two phenomena in any discussion of the origin of the scarps.

In earlier accounts of piedmont scarps, beginning with my own, they have been regarded as the surface expression of faults. There is, however, an alternative view which is worthy of consideration—the view that the movements creating them are of the nature of landslides. The hypothesis that ascribes the scarps to faulting assumes that a crustal block under the valley is separated by a fault from a crustal block in the range, and that a new movement has occurred, increasing the throw of the fault. The alluvium on the valley block has descended with it, all except the remnant that adheres to the mountain block. The landslide hypothesis assumes no movement of the indurated rocks but only a movement of superficial unconsolidated material.

The landslides with which we are most familiar occur on hillsides and involve a descent of loose surface material over a subterrane of firmer material. Above the head of the moving mass is a scarp (pls. 17, *A*; 12, *A*; and 16, *A* and *B*), the surface of the slide near its head is apt to be canted toward the scarp, and the general surface of the disturbed ground has a gentler slope than before the disturbance. A protuberance at the lower end is the correlative of the hollow created at the upper end. The ground plan of the scarp above may be quite irregular but is likely to be an arc, or a series of arcs, concave toward the slide; and the scarp about the head of the slide is continuous with two scarps that run down the slope and for a distance border the sides of the slide. All these characters are illustrated by one or another of Plates 17, *A*; 12, *A*; 16, *A*; and 16, *B*.

In connection with a study of the California earthquake of 1906 I examined scores of landslides that had been started by the shock. Most of them merely started, moving only far enough to open a crack and develop a small scarp at the head. Presumably they moved during the period of strong agitation—between one and two minutes—and came to rest when the agitation ceased. A comparatively small number moved so far down their beds that the movement must be supposed to have lasted longer than the earthquake; and the movement of these had the character of flow.[33] They were composed of wet earth. The annual climatic cycle of the district in which I examined such slides consists of a wet season and a dry season. The earthquake occurred so long after the beginning of the dry season that there was little water in the ground and none on the surface. In the following wet season many of the slides that had barely started and then stopped resumed their movement. The views in Plate 16 were made after the second movement. It seemed evident that the cracks opened by the earthquake had admitted the rain water necessary to the progress of the slides. From these phenomena I infer that loose material having a surface of such moderate slope that it can retain its position indefinitely if dry and unshaken may flow under gravity (1) if saturated with water or (2) if and while shaken by an earthquake, and that it will be peculiarly fluent when both saturated and shaken.

In accordance with these laws of earth flow it appears possible that the gravel and sand of the Wasatch piedmont move valleyward without the occurrence of a local fault slip. At some depth below the surface they bear water, and the region is not exempt from earthquakes. Thus the landslide hypothesis is not excluded by the qualitative consideration of conditions of earth flow.

The typical form of the piedmont scarp is distinct from the forms of the scarps at the head of undoubted landslides, but I am not sure that the differences are of crucial character. The greater number of undoubted landslides with which I have direct acquaintance have moved over uneven surfaces—surfaces of firm rock under mantles of regolith—and the irregularities of their head scarps have been determined in part by the unevenness of the slipping surfaces. The ordinary landslide is a small unit, and the lunate form of the head scarp is determined by that fact. If the piedmont formations of the Wasatch Range have moved valleyward under the incitement of an earthquake they have moved in broad bodies and their slipping surface has been the smooth footwall of the fault, and it would seem that the head scarps thus produced might be simply flexuous. Thus the landslide hypothesis is not definitely excluded by consideration of the forms assumed by the piedmont scarps.

The superficial landslide is usually characterized by a bluff at its lower end, and the fact that terminal bluffs of landslide type are not associated with the piedmont scarps of the Wasatch shows that these scarps can not be ascribed to the sliding of thin bodies of piedmont deposits. It is conceivable that a shifting of the whole body of valley deposits might occur without producing a terminal bluff. It would, however, raise the surface at lower levels and disturb the relations of streams to graded slopes, and if the movement were conditioned by the agitation of an earthquake there would probably be a notable ridging of the surface. As will be shown later, certain corrugations of the Wasatch piedmont may plausibly be ascribed to earthquakes, but they are confined to a belt near the base of the range.

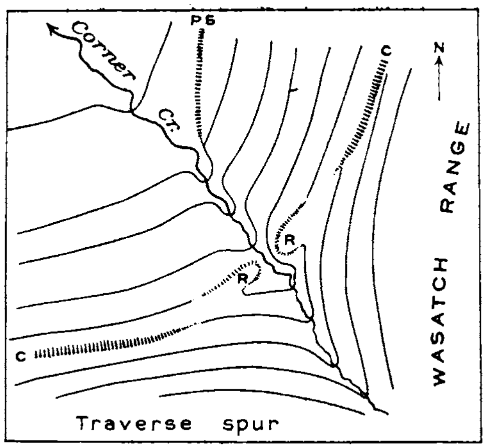


FIGURE 29.—Sketch map of Corner Creek groin, Wasatch Range, Utah. C, C, Cliffs of Bonneville shore line; R, R, remnants of bay bar of Bonneville shore line; PS, piedmont scarp

There are two localities in which the Wasatch piedmont scarps admit of no explanation other than that of faulting. One is at the junction of the Traverse spur with the range, where Corner Creek issues from the groin. A post-Bonneville movement on the fault is there demonstrated by the dislocation of the highest shore line. (See p. 29.) A post-Bonneville piedmont scarp follows the base of the range to the edge of the eroded valley of Corner Creek, its course being directed toward the groin (see pl. 11, *A*), and it does not reappear on the opposite bank of the creek valley, which is on the spur. The relations are shown dia-

[33] For a classification and general discussion of the landslides associated with the California earthquake see Lawson, A. C., Report of the State Earthquake Investigation Commission: Carnegie Inst. Washington Pub. 87, vol. 1, pp. 384-401, 1908.

grammatically in Figure 29. If the scarp had been created by a slumping valleyward of the piedmont deposits it would appear on the alluvial apron of the spur as well as on that of the range. The fact that it occurs only along the base of the range connects it definitely with the post-Bonneville fault movement that is demonstrated by the dislocation of the shore line.

The second locality is opposite the Pleasant View spur. The modern piedmont apron, composed of alluvial fans with well-adjusted slopes, occupies the narrow space, half a mile wide, between the range and the spur. At the head of the apron is a piedmont scarp. It could not have been created by a landslide without visible disturbance of the simple profiles of the fans but is satisfactorily explained as the result of a movement on the frontal fault.

Among the secondary products of the California earthquake of 1906 were systems of small ridges. A previously smooth mud flat of Tomales Bay was left with a corrugated surface, in which the ridges were in part parallel to the earthquake fault and in part transverse to its direction.[33] The ridges stood 1 to 3 feet above the troughs, and their intervals, crest to crest, would be measured in tens of feet. During the agitation the mud, as a quasi liquid, was thrown into waves, and the waves were preserved because when the agitation ceased the mud became a quasi solid. A similar result was observed in a tract within the city of San Francisco, where a tide marsh had been converted into dry land by a filling of earth.[34] The mud beneath was firmer than that of Tomales Bay, and the ridges created by the vibration were broader and higher. Somewhat similar ridges were formed in alluvial flood plains, where the ridges were monoclinal and parallel to the stream channel.[35] The size of the ridges was related to the condition of the alluvium: they were small where the alluvium was very wet and relatively large where it was drier.

With these earthquake ridges may be compared certain features of the Wasatch piedmont. A short distance north of Jump-off Canyon is a piedmont tract of which the general slope is exceptionally low, as the rock base of the range is little above the valley plain. Piedmont scarps are well developed, with one or two grabens, all parallel to the rock base, and outside these is a wider area in which the alluvium has suffered disturbance of a less regular character. Its surface is made up of low, broad mounds and hollows, arranged without recognized system. Among the piedmont scarps are springs, and in some of the hollows are ponds. The ground-water plane must lie near the surface, and if the tract were now shaken by a strong earthquake its surface might be disturbed very much as it has been disturbed at some time in the past. The association of the peculiar topography with the frontal fault indicates that a post-Bonneville slipping or series of slippings on the fault plane has created the piedmont scarps, and that the earthquake vibrations caused by the fault movements, acting through the saturated deposits of the adjacent plain, have created the undulations of its surface.

The delta built in Lake Bonneville by Weber River—a huge body of sand and gravel—has been divided by the modern river. The piedmont scarps across the two remnants are high and multiple, and among them are large grabens, which intercept the drainage from the range. The scarps and grabens are approximately parallel to the range front. On the northern remnant there is also a disturbed district just outside the belt of piedmont scarps, and in that district the general trend of ridges and hollows is at right angles to the trend of the range front. The corrugation of the outside district is on a scale comparable with that of the belt of scarps; the ridge crests stand 40 or 50 feet above the hollows.

Some of the hollows have caught elements of drainage and been deepened thereby, but not all are thus modified, and their forms and relations are such that they can not be accounted for as valleys of erosion. They appear to be products of dislocation, and the only plausible explanation I have been able to suggest is that they have resulted from the quaking of the delta at a time when movement on the near-by fault was creating the piedmont scarps. If this explanation is correct it applies also to the corrugation of the "older alluvium" on the Pleasant View spur, already described (p. 25). Although the hypothesis is the best now available it is advanced as provisional only. The troughs and hollows on the delta and on the spur are not wavelike, as were those of Tomales Bay and San Francisco. They suggest, rather, the breaking of the terrane into blocks and the separation of the blocks. They approach more nearly, perhaps, the corrugation of flood plains by the earthquake, but the flood-plain blocks, which in their separation lurched toward the stream channel, were systematically rotated, so that their backs inclined in a common direction, whereas the ridges formed in the Wasatch piedmont are not systematically tilted. There is also a difference in scale, the Wasatch ridges being much larger than the Californian, but that difference is not specially significant, because the California earthquake, although of high rank, was not of the first rank in intensity. If the ridges of the Wasatch piedmont were made by an earthquake its shock was presumably the most powerful that emanated from the frontal fault during a very long period.

The preceding statement of facts and considerations bearing on the origin of the piedmont scarps has a regrettable prolixity because it is the record of an

[33] Lawson, A. C., op. cit., vol. 1, pp. 78-79, 1908.
[34] Idem, vol. 1, p. 237.
[35] Idem, vol. 1, pt. 2, pp. 400-401.

endeavor to free my own mind from an initial bias in favor of one hypothesis by a thorough examination of its rival. When the piedmont scarp was first observed in the Great Basin, in 1876, it was at once ascribed to movement on a frontal fault, the existence of which had already been inferred from independent physiographic evidence. During the succeeding decade the same association of characters was found in many places, and the piedmont scarp was thought, especially by Mr. Russell and myself, to afford strong corroborative evidence of the fault-block theory of Basin Range structure. When, therefore, one of my colleagues in discussing the structure treated the evidence of the scarp as "no evidence," and others suggested that the scarp might be due to slumping of the piedmont deposits, I was led to suspect that I had been overconfident of the credibility of the witness whose testimony had so strengthened my preconceptions and to review the subject with special care in later field studies.

It appears to me now that because at two points on the Wasatch front the piedmont scarps can be explained only as direct consequences of fresh movements on the frontal fault, the presumption is in favor of that explanation for the scarp at any other point. The possibility that scarps of the same habitus may be produced by dislocation of superficial deposits only can not be denied, but at present it is merely an academic possibility. The correlative features that theoretically should characterize the distal part of a slumping foreland have not been discovered. Moreover, the connecting links between typical piedmont scarps and typical landslide scarps have not been found. So far as the terms of description are concerned the types may seem to overlap, but in habitus—the ensemble of form detail that so often appeals to the eye while it eludes definition—the types are distinct. The Wasatch piedmont region has many landslides. The bluffs created by the trenching of Bonneville deltas slump toward the trenching streams, Bonneville beaches have slid toward the valley, landslides have started from the faces of piedmont scarps, and the alluvial mass uplifted on the Madsen spur has fallen away in a great series of waves, but the scarps created by such surface movements can not be confused by the physiographer with the piedmont scarps.

If anywhere there are scarps of the piedmont type, simple in outline and parallel to the rock bases of mountain ridges, which have been created by the slumping of piedmont deposits, their simplicity of outline has been determined by the simplicity in the contour of the surface down which they have moved. Such simplicity of contour may have been acquired in various ways, but where it pertains to the part of a mountain range buried under the alluvial apron its probable mode of origin is by faulting. An alluvial slump that leaves a scarp of the piedmont type presumably slides on the footwall of a frontal fault; and thus a piedmont scarp, even if directly caused by slumping, affords presumptive evidence of the existence of a frontal fault.

On the other hand, I am disposed to regard slumping as the frequent or constant accompaniment of the making of piedmont scarps by faulting. The earthquake caused by a fault movement is most violent in the immediate vicinity of the fault and is a factor in the readjustment of the unconsolidated formations. Were there no readjustment the outer body of piedmont deposits, in moving away from the remnant that adheres to the footwall, would leave a chasm, and the filling of that potential chasm is accomplished at a time when the whole mass is in a state of agitation. The mobile parts of the mass are the more mobile because of the shaking, and loose beds filled with water behave for the time being as liquids. The visible effect may be restricted to the filling of the chasm or it may extend much farther, and where the piedmont and bordering plain are water-logged they may acquire undulations of the type observed in Tomales Bay. In an account, on an earlier page, of such undulations I have mentioned only a locality near Jump-off Canyon, because there only is the observed relief so pronounced as to be unmistakable, but there are also places where the adjacent lake plain displays a pattern of marsh and pool, or of dry land and marsh, which I think indicative of a relatively gentle undulation of similar type.

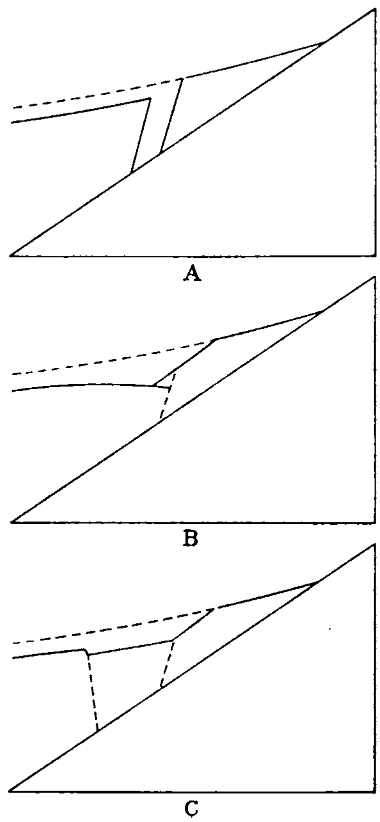


FIGURE 30.—Diagrams to illustrate the simpler types of piedmont scarps

The complexity of the cross profile of the zone of piedmont scarps is ascribed in part to the slumping that filled the potential chasm, and in part to the fact that the scarps made by slips of different dates have not always been on the same lines. The principal elements involved in the adjustments are shown in Figure 30, where diagram A indicates the potential chasm, B a filling of the chasm by spreading and settling of the outer wall, with reduction of the scarp to the angle of rest, and C the separation from the outer (or the inner) wall of a slice which settles and spreads, producing a graben. The more complex profiles exhibit combinations of these elements. In the Wasatch piedmont the best opportunities for the study of the scarps are found on the Bonneville deltas. In general the piedmont slope has lost the simple curves of alluvial deposition through modification by wave attack, with the result that the exact profiles before faulting are not now evident, but the old delta plains of the Provo stage retain their original by a bend of the river, has been sapped by recent action of the river. Scarp *a*, first seen in the view at the eastern edge of this terrace, follows the edge for a space and then climbs the slope, crossing the Provo beach.

Not all scarps and not all parts of the same scarp are at the same distance from the rock base. The distance is roughly related to the dip of the fault plane, being in general relatively great where the angle of dip is small. An extreme example is found at the base of the City Creek spur, where the dip is 70° and

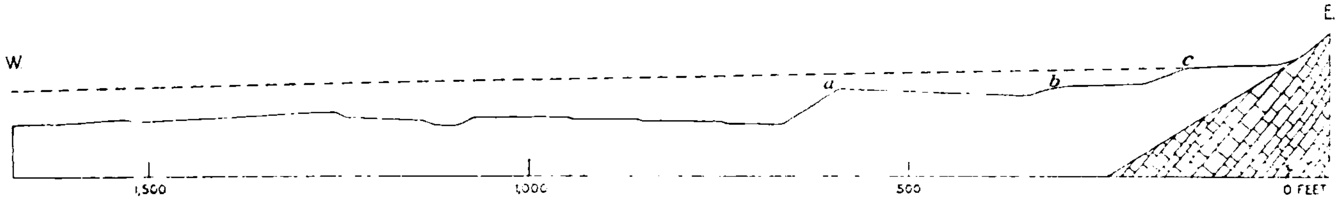


FIGURE 31.—Profile of piedmont scarps on a delta of the Provo stage of Lake Bonneville at the mouth of Rock Canyon, near the city of Provo, Utah. The broken line is a restored profile of the delta slope before faulting

slopes, except as modified by later faulting. The profile shown in Figure 31 was found on a delta near the city of Provo and is drawn to scale. The estimate of vertical shift is about 40 feet. Scarp *a* represents two movements, both more recent than those of scarps *b* and *c*. Some of the small scarps outside of *a* have the same freshness as *a*, and probably all of them were made by the later movements. The sequences were inferred in part from the relations of the scarps to alluvial terraces in the valley of the stream that has trenched the delta. Figure 32, drawn to the same scale, shows three scarps on a wave-dressed slope between the Bonneville and Provo levels. The presence or absence of scarps at lower levels was not determined. At this locality the outer the distance is 0, and the opposite extreme is found at a point on the Mineral Range, where the dip is 19° and the distance is about 1,500 feet. Between these extremes are the two sides of the black spur near Ogden Canyon. By comparing Figure 26 with Plates 12, *B*, and 18, *A* and *B*, the reader will see that the rock face of the spur is very steep where it meets the alluvial apron on the north side and is less steep near the southern base, and that the piedmont scarp runs much nearer to the north base than to the south. These relations suggested a tendency of the alluvium to break apart where it has a particular depth, and explanations in the line of that suggestion were considered, but none appeared adequate. They failed, in particular, to account for the fact that successive

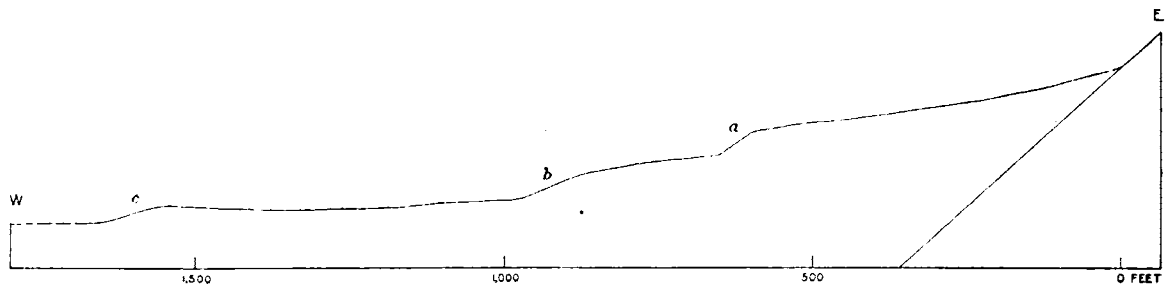


FIGURE 32.—Profile of piedmont scarps near Ogden Canyon, Utah

scarp, *c*, was first made, and the inner scarp, *a*, is the most recent. The sag between *b* and *c* deepens toward the south and has been selected as the site of the city reservoir of Ogden. The view in Plate 17, *B*, was photographed from the crest of scarp *c* and shows scarps *a* and *b*, with the sag below *b* in the foreground. Scarps *a* and *b* appear also in Plate 8, *B*, and scarp *a* is there a conspicuous feature. That view shows the mouth of Ogden Canyon, with a remnant of the delta built in Lake Bonneville at the Provo stage. A stream terrace, carved from the delta movements at the same place are likely to form scarps at different distances from the rock base, the distance for later scarps being in some places the greater, as in Figure 31, and in other places the less, as in Figure 32. The explanation that accords best with the known facts is connected with ground water. The shallow edge of the alluvium is not well supplied with water, but where the alluvium is deep the lower portions are saturated and are correspondingly mobile. The limit between a water supply adequate for mobilization and an inadequate supply is thought to determine the line of parting. The distance of the locus of the limiting condition from the rock base differs from place to place and from time to time and may be affected also by the intensity of the vibration associated with the faulting.

In many places the grabens of the piedmont-scarp belt bear undrained hollows in which water stands after rains. In a few places the graben troughs have intercepted and diverted lines of minor drainage. The southern remnant of the Bonneville delta of Weber River has in this way been deprived altogether of drainage from the range, the grabens guiding part of the water southward and another part northward. It was probably through such diversion that the tract of "older alluvium" on the Pleasant View spur (see p. 25) became isolated, although the hypothetic grabens are not now to be seen. In the position ascribed to them is a graded plain, the modern alluvial apron, and across the plain, near its upper margin, runs a young piedmont scarp.

The groin between the Traverse spur and the Lone Peak salient may have originated in the same way but more probably was established at the time of the eruption of the trachyte that caps the spur. The drainage routes of the groin run partly along the line of contact between the strong granite of the range and the weaker rocks of the spur and partly in the weaker rocks on lines parallel to the contact. If their position had been determined by erosion alone, the drainage streams would either occupy the line of contact, shifting gradually down the granite slope, or would establish permanent channels in the granite. Their partial diversion to channels outside the granite is tentatively ascribed to the creation of grabens by progressive faulting, but the hypothesis has not been tested by determination of the character of the rocks along the border. If those rocks are firm—the limestone, sandstone, and trachyte which probably constitute the body of the spur—they might be expected to retain continuity in moving down the granite slope; but if they are unconsolidated—the products of decomposition and disintegration—their surface might be broken by the formation of scarps and grabens. The hummocky topography shown in Plate 10, *A*, suggests unconsolidated material, and Emmons,[36] after describing the trachyte of the spur, notes that near the contact with the granite "there is found a greenish-white earthy, decomposed rock, in which the only traces of crystallization left are white irregular spots of partially kaolinized feldspar."

The relative ages of piedmont scarps are shown in part by stages of weathering and in part by relations to other features. The most recent have scarcely or perhaps not wholly attained the slope of rest. Their upper edges are sharply defined, and their faces are not fully occupied by vegetation. In those of earlier origin the edges are rounded, the faces have gentler slopes, and the benches above them have been trenched by the drainage, so that the faces are divided into facets. On the aprons of other ranges are seen scarps in all stages of progress toward obliteration, but illustrations of the more advanced stages are not readily to be found along the Wasatch front because the greater part of the piedmont tract has been remodeled by the shore work of the waves of Lake Bonneville. Below the highest shore line all pre-Bonneville scarps have been either obliterated or so nearly effaced that their identification is problematic, and the only unquestioned records are those of post-Bonneville dislocations. The fact that none of the post-Bonneville scarps exhibit extreme senility indicates that the ordinary life of a scarp is longer than post-Bonneville time. Fault-block ranges without piedmont scarps and also parts of such ranges that lack the scarps have presumably felt no paroxysm of growth for tens of thousands of years. Of the entire western front of the Wasatch about three-fourths is bordered by scarps, and the number of separate movements ranges from one to at least four, but no post-Bonneville movements are recorded for the remainder of the front. The longest stretch without piedmont scarps, 16 miles in length, lies between points near Willard and Honeyville. From Willard to Brigham the range front is smoothly molded, as if composed of rocks that weather rapidly, and it is possible that piedmont scarps have been less durable here than elsewhere; but this suggestion does not apply to the front between Brigham and Honeyville, which is bold and rugged. It is not to be assumed that the orogenic forces are there dormant, but rather that strains are slowly growing, to be relieved at some time in the future by a renewal of faulting.

As scarps of dislocation, distinct in type from landslide scarps, piedmont scarps are evidence of recent faulting. As they occur on alluvial aprons close to the feet of mountain fronts, they are evidences of frontal faults. If simulating scarps may be produced by the slumping of piedmont formations the characters that constitute simulation are best explained by assuming that the slipping surface is the smooth footwall of a frontal fault. In the absence of steep slope, the probable cause of a piedmont slump is earthquake vibration, and the earthquake of highest local efficiency is one that originates in a movement on the local fault plane.

SCARPS RELATED TO PIEDMONT SCARPS

Russell[37] has described a number of scarps in the Lahontan basin which are clearly due to dislocation but are not so related to mountain fronts that the title piedmont is appropriate. They traverse broad, smooth plains occupied by the Lake Lahontan depos-

[36] Emmons, S. F., U. S. Geol. Expl. 40th Par. Rept., vol. 2, pp. 440-441, 1877.

[37] Russell, I. C., U. S. Geol. Survey Mon. 11, pp. 278, 280-281, 1885.

its, and their faces expose the upper part of the deposits in section. At their bases are thermal springs, and in connection with one of them Russell notes a tilting of the plain. Two of them run parallel to mountain fronts at a distance of some miles; another, which crosses an embayed plain, falls in line with a piedmont scarp not far away. The thermal springs serve to show that the fractures penetrate to a great depth. The scarps are the surface expression of dislocations in the rock floor below the alluvial and lacustrine filling. Presumably they outline the outcrops of faults in the subterrane, copying at the surface the deformations of crustal blocks beneath. If this interpretation is correct they may properly be distinguished from piedmont scarps of the Wasatch type, which are caused by crevasses at the heads of alluvial bodies that have slid down sloping footwalls.

In the same connection should be mentioned the scarps created in the alluvium of Owens Valley at the time of the earthquake of 1872. On visiting the locality in 1883, I referred the scarps without question to the Wasatch type, but they have been differently interpreted by Hobbs,[38] who published an account of relatively extensive observations and surveys made in later years by W. D. Johnson. The principal scarps mapped by Johnson are parallel to the base of the Alabama Hills, a small range near the foot of the great Sierra Nevada escarpment. With them are many minor scarps, and the system of dislocations includes a number of large grabens. The displacements have horizontal components as well as vertical. As construed by Hobbs, the individual dislocations of the ground, instead of being incidental to the filling of an earth crevasse, are surface expressions of distinct dislocations of the subterrane. This view is supported by two special features which I failed to discover but which are clearly brought out by Johnson's maps and notes. Certain scarps created in 1872 not only traverse the alluvial fans between spurs of the Alabama Hills but are continued on the spurs, and the dislocation of the bedrock is similar in amount to the dislocation of the alluvium. Certain other scarps, which occur at some distance from bedrock, have zigzag courses, changing direction abruptly, repeatedly, and in a somewhat systematic manner. Scarps caused by earth crevasses would not be continued in the adjacent bedrock spurs, and the zigzagging of alluvial scarps suggests a fault line conditioned by peculiarities of structure in the faulted subterrane.

The Owens Valley scarps, as interpreted by Hobbs, show relationship to the scarps of the Lahontan lake plain. They are further related to scarps in alluvium that occur in places where the alluvial deposit is thin, constituting a veneer on a graded rock plain, and also to fault scarps in bare bedrock. As expressions of bedrock faulting they are more direct than piedmont scarps, and they have no necessary connection with the growth of existing mountain ranges.

[38] Hobbs, W. H., The earthquake of 1872 in Owens Valley, Calif.: Beitr. Geophysik, Band 10, Heft 3, pp. 352-385, 1910.

THE ESCARPMENT

TRUNCATION OF RIBS

To the geographer an escarpment is a face, more or less wall-like and more or less elongate, bounding an upland. The west face of the Wasatch Range is an escarpment. The sculpture of the escarpment has elements that are distinct from the sculptural features of the body or interior of the range, and those elements are connected with the origin of the escarpment.

A mountain range, considered in its entirety, is a ridge, and usually it is composed in large part of minor ridges. Some of the minor ridges end at the lateral margins of the range, and these, for want of a better name, I shall call ribs, thus extending the use of the anatomical figure under which an axial ridge is sometimes styled a backbone.

In a general way the western margin of the Wasatch Range is defined by the rock base, the line along which the bedrock of the mountain disappears beneath the alluvium and other discrete formations of the piedmont slope. The line of the rock base is essentially also the outcrop of the frontal fault and differs little from a contour of the fault surface, so that Figures 12 and 13, which are intended to represent the fault contour, serve also to portray the rock base. There are a few angles in the outline, but in the main it swings in free curves.

Along this line end the ribs of the range. The base line, or rock base, of the end of each rib runs somewhat directly from the mouth of a canyon to the mouth of the next canyon. It has indeed some curvature, but the curvature is part of the general curvature of the range base and has no relation to the character or size of the rib. It is concave toward the valley in as many places as convex. To express this character briefly, we may say that the rib ends are alined.

Above the base line the contours of rib ends tend toward alinement, but the tendency is not equally strong in all parts of the range front. It is favored by uniformity in the character of the rock and is especially favored by the power of the local rock to resist erosion. Under favorable conditions each higher contour of a rib end is parallel to the contour at the base line and is alined with the corresponding contours of neighboring rib ends. A row of rib ends in such a locality seem to be parts of a once continuous plane or gently flexed surface, the outer surface of an original great rock body out of which the canyons have been carved. Or, as an alternative conception, we may imagine that the ribs once ran farther valleyward but have been cut away—truncated—as by a single stroke of a gigantic blade. Ribs that end thus are appro-

A. WEST SIDE OF LONE PEAK SALIENT

The facets are part of a once continuous surface that has been dissected by the erosion of canyons. The principal rock is granite, but relatively weak schist and relatively strong quartzite occur in the lower parts of the face. The differences of rock strength find little expression in the configuration of the facets

B. VIEW SOUTH OF PROVO

At the left is Slate Canyon. The principal rock is limestone. The structure includes an anticline, with axis somewhat oblique to the range front. Of the strata truncated by the facets, some dip with the slope but more steeply, others dip with the slope but less steeply, and others dip away from the face

FACETS OF THE WASATCH ESCARPMENT, WASATCH RANGE, UTAH

A. GENERAL VIEW FROM PROVO

The faceted escarpment is the face of a subsidiary ridge of the Wasatch Range. The crest of the ridge descends northward toward Provo Canyon, at the left. At the right of the center is Rock Canyon. The principal rock is limestone, but there are small outcrops of quartzite and shale. The general dip is eastward and gentle, but an abrupt anticline is exposed near the bases of the nearer facets. (See figs. 4 and 5)

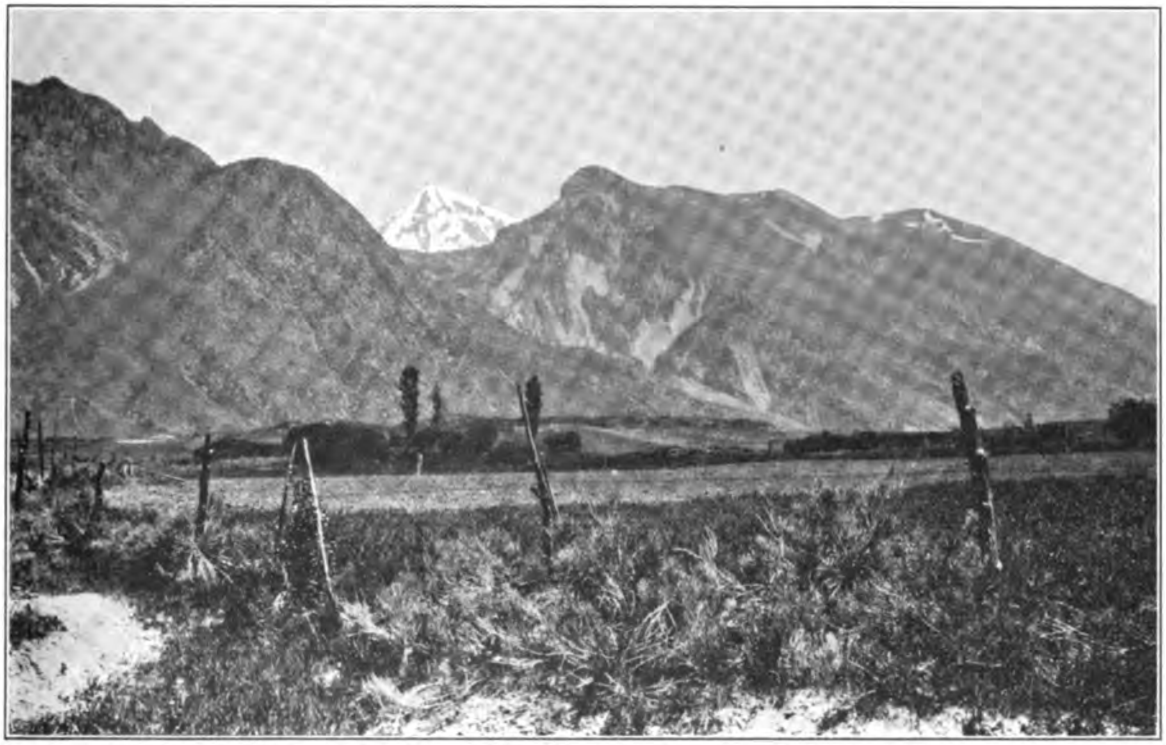
B. DETAILS AT ROCK CANYON

The structure at this point is shown by Figure 5. It is truncated by the smooth facet. In the distance is Timpanogos Peak

FACETS OF THE WASATCH ESCARPMENT NORTH OF PROVO, UTAH

A. NEAR BATTLE CREEK

Lower ridge runs parallel to the main ridge of the Wasatch Range, as shown in Figure 44, and streams cross this in V-section canyons. The facets of the escarpment meet the canyon walls in well-defined corners



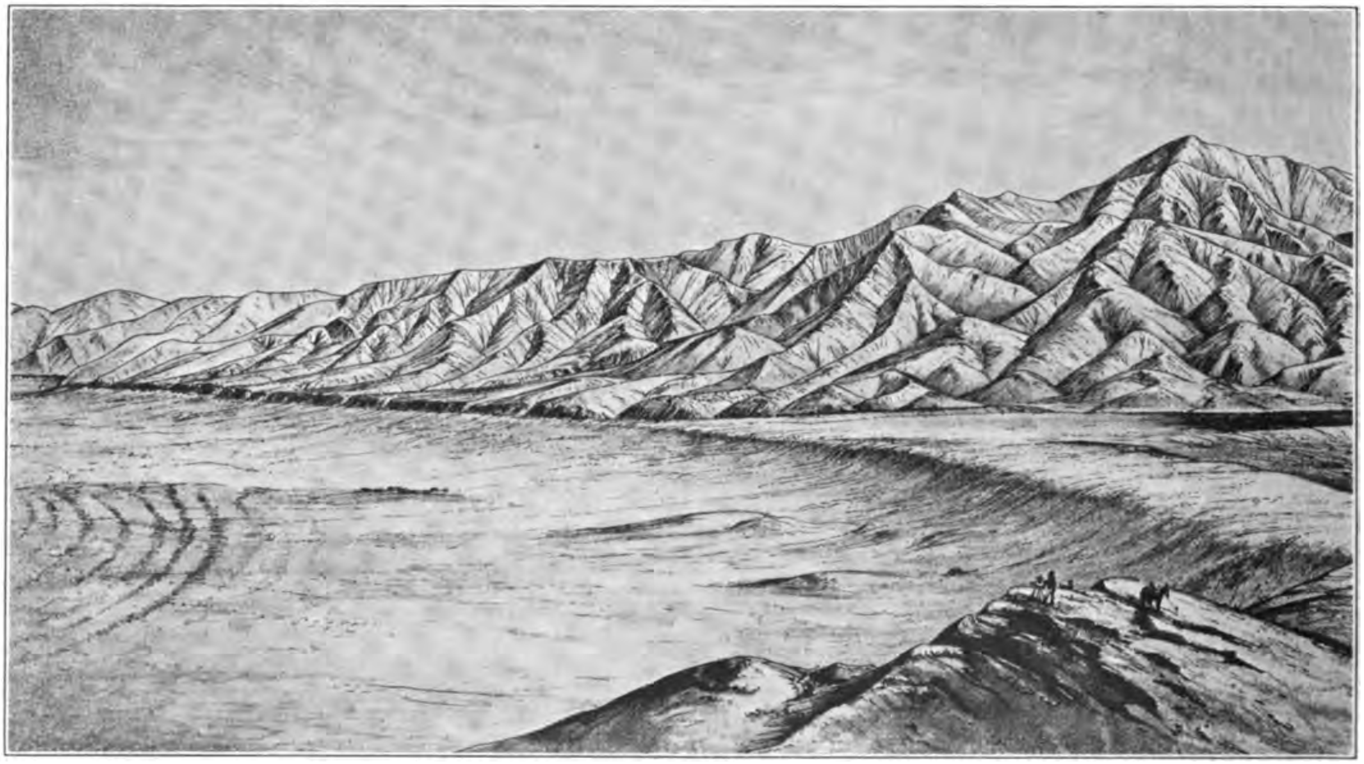
B. NEAR AMERICAN FORK

The lower ridge mentioned under *A* is divided by American Fork Canyon, the walls of which have a different sculpture from that of the faceted frontal face. The facet at the left of the canyon has lost its original surface by weathering, and the rock structure truncated by the frontal escarpment is thus revealed

FACETS OF THE TIMPANOGOS FRONT, WASATCH RANGE, UTAH

A. WASATCH ESCARPMENT OPPOSITE WILLARD, UTAH

The view illustrates the oblique truncation of structure by the plane of the range front. The broad pale band marks the outcrop of the Cambrian quartzite, which descends from right to left, reaching the base line of the front just outside the view. Below it is Archean gneiss, with tapering exposure. Plate 7, *B*, shows the same features from another direction

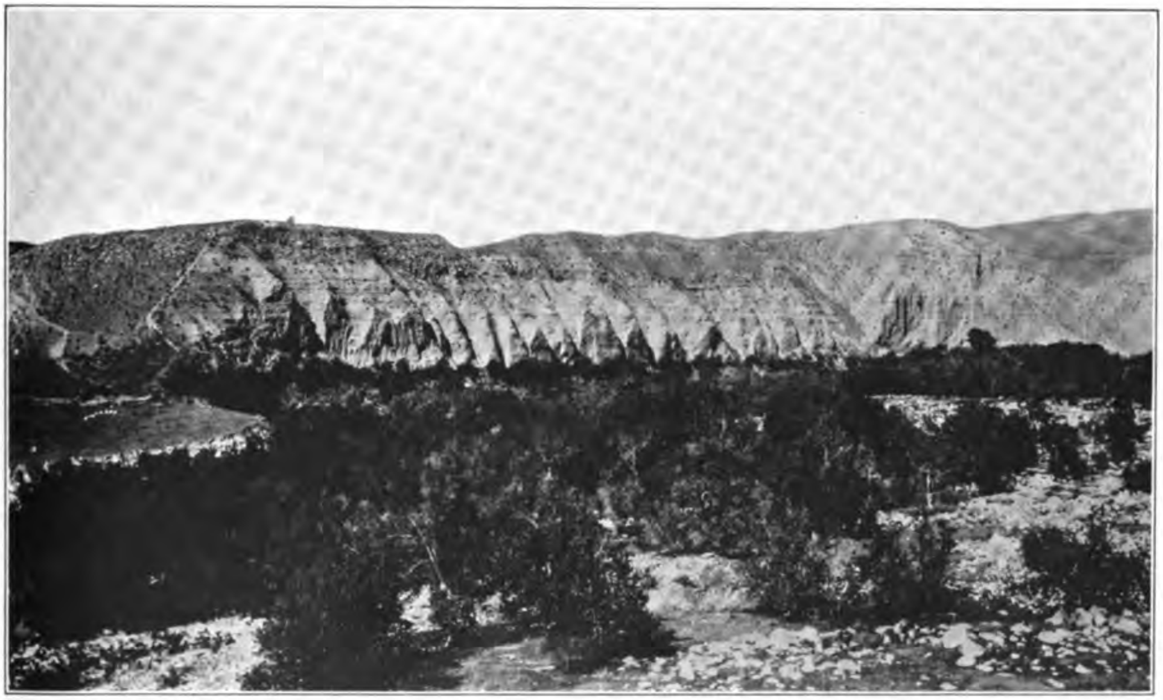


B. BONNEVILLE SHORE LINE NEAR TOOELE, UTAH

The escarpment produced by wave erosion truncates rock ribs of the Oquirrh Range, as well as the alluvial apron. Part of Plate 9, Monograph 1, from a drawing by F. D. Owen

A. ESCARPMENT ON SOUTH FORK OF OGDEN RIVER, UTAH

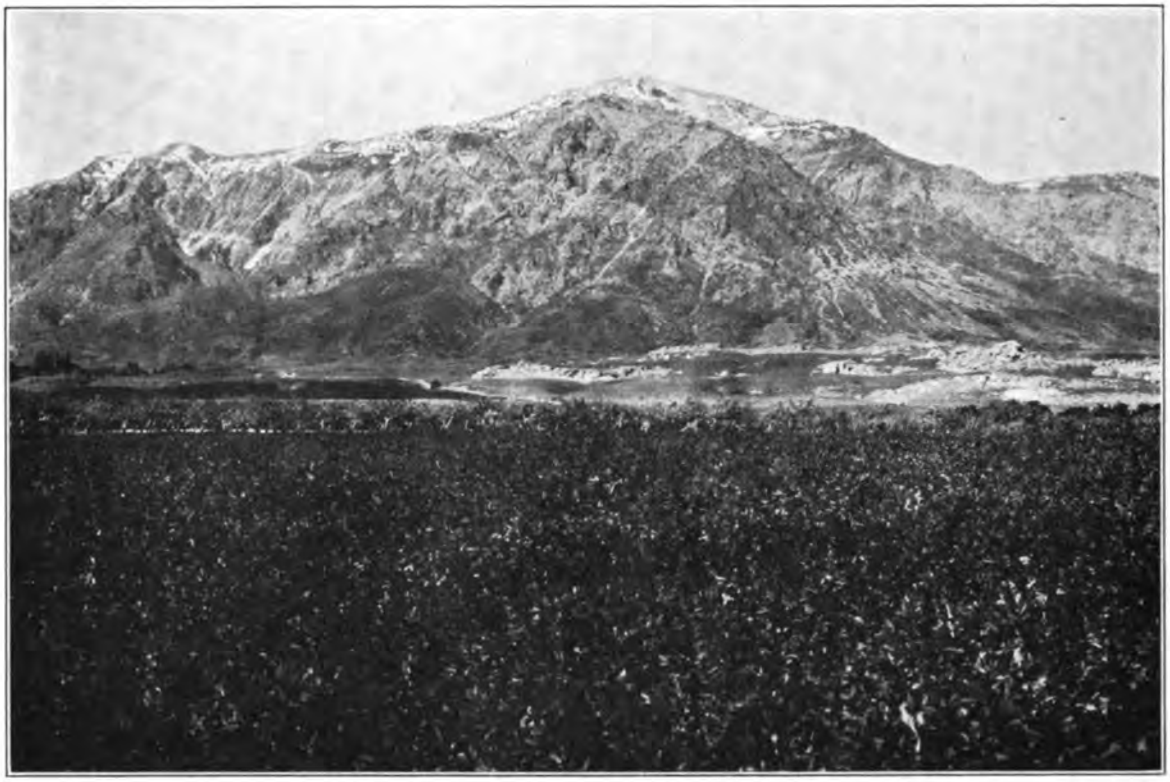
These triangular facets were developed by the migration of a stream valley down the dip of gently inclined strata. Photograph and description by Eliot Blackwelder



B. ESCARPMENT ON KERN RIVER, CALIFORNIA

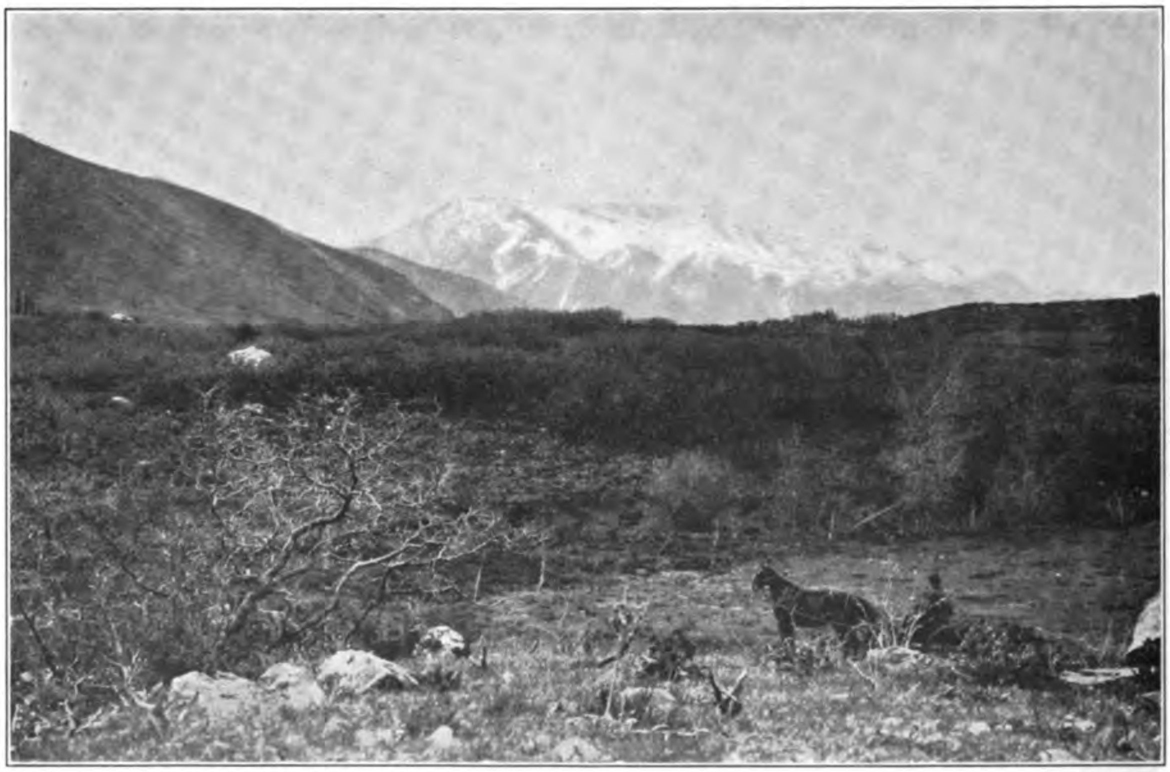
The facets are features of a bluff made by a meander of Kern River, which has developed a flood plain 1 mile wide

FACETED ESCARPMENTS MADE BY STREAM EROSION



A. WASATCH ESCARPMENT OPPOSITE PLEASANT VIEW SPUR

The peak, Ben Lomond, is made up of limestone, and the escarpment shows Cambrian quartzite above Archean gneiss



B. HIGH-LEVEL GRADE PLAINS

The grade plains slope from left to right in the region of the snowdrifts. The portion of the range on which they lie is just south of Weber Canyon

VIEWS IN WASATCH RANGE, UTAH

priately called truncate without any implication as to the origin of their forms, and a range front characterized by the terminal facets of truncate ribs is appropriately said to be faceted.

Examples of faceting are shown in Plates 19 and 20. Plate 19, *A*, presents the western side of the Lone Peak salient, where the rock is an exceptionally resistant granite. In the Provo division of the range, illustrated by the other views, the rocks are sedimentary and mainly calcareous. It will be noted that the facets are best preserved near the base and have suffered from erosion higher up. Plate 14, *A*, shows a large facet the erosion of which, in ways analyzed by Davis,[39] has resulted in the production of subsidiary facets that have a tendency toward triangular forms. Facets in more advanced stages of dissection and demolition are shown in Plates 7, *B*; 9, *A*; and 25, *A*, and the profile of a well-preserved facet appears in Plate 4, *B*. Quadrangular facets appear in Plate 21; and the nearer facet in Plate 21, *B*, shows a partial dissection that has been promoted by diversity of rock texture.

TRUNCATION OF CANYONS

The canyons of the range, except as modified by Pleistocene glaciers, have steep walls and narrow beds. Those that debouch on the western side hold these characters to the face of the escarpment. Where the rocks are strong the walls are specially steep and crags abound; where the rocks are weak the walls are steeply graded. The degree of narrowness of the beds also is related to rock characters. Whatever the nature of the rock the narrowness of bed continues to the rock base and there ends abruptly. Where the rocks are strong the canyon walls hold their character and direction to the range front and there meet the facets of the escarpment in well-defined angles. This feature is strikingly illustrated by Plates 4, *B*; 8, *B*; 19, *A*; and 21, *A* and *B*, and is shown also by Plates 19, *B*, and 20, *A* and *B*. Where the rocks are weak there is more or less blending of canyon walls and frontal facets, except at the rock base. Where the rocks are of unequal strength all other expression may be masked by differential weathering.

The general fact, which receives its full expression in strong rocks, is that the canyons hold their character to the plane of the facets and there lose them. In the same sense in which the ribs are truncate the canyons are truncate.

TRUNCATION OF STRUCTURAL FEATURES

Within the body of the range are folds and faults. The strikes of dipping strata and the strikes of faults are in general not parallel to neighboring parts of the western escarpment but meet it at some angle. For a few miles north of Brigham, for a few miles south of Willard, and for a few miles north and south of Provo Canyon the strike of the strata is approximately parallel to the rock base, but these localities are exceptional. Elsewhere, including not less than seven-eighths of the range front, the strike meets the rock base at a notable angle. The greatest fold of the range, a syncline that brings a great series of Paleozoic and Mesozoic formations in succession to the rock base, runs athwart the range in the latitude of Salt Lake City. As already described, the basal quartzite of the Cambrian comes obliquely to the rock base at a number of different points, its outcrops at the several localities belonging to distinct tectonic blocks. The outcrop of the Willard overthrust is intersected by the range front, and in the Ogden region normal faults of great displacement meet the rock base at right angles. All these elements of structure appear in section in the range front.

The obverse of these facts is that the line of the range base crosses the strike lines of the structure at all angles. The range front transects the range structure. The structural features that are exhibited in section in the range front are truncate, just as are the features of relief.

Davis [40] illustrates the transection of structural features by a sketch of the range front near Mona and points out that certain ridges and canyons developed on the outcrops of strong and weak strata are obliquely cut off at the line of the rock base. Plate 22, *A*, shows an outcrop of Cambrian quartzite as it obliquely descends the mountain face near Willard, and the same descent is portrayed in Plate 7, *B*. Plate 7, *A*, with its explanatory diagram, Figure 11, shows also the oblique outcrop of the Willard overthrust. In Plates 2, *A*, and 3, *B*, are seen strata on edge that meet the line of the front at right angles; and a similar relation is illustrated by the nearer facet of the view in Plate 21, *B*.

INTERPRETATION OF TRUNCATION

COMPARISON OF WASATCH ESCARPMENT WITH ESCARPMENTS NORTH OF THE GRAND CANYON

Men are prone to take the familiar as a matter of course and to ask the meaning of the strange only; and by our manifestation of this trait we geologists are assured of our humanity. To one who has lived solely in a glaciated region the forms of landscape peculiar to ice erosion suggest no mystery, and it is only through acquaintance with the dominant topography of aqueous origin that he is able to recognize the strongly marked characteristics of the work of ice. The illustration is drawn from personal experience, but its moral finds support in the circumstance that those who have undervalued the power and accomplishment of glaciers have been dwellers in lands once overrun by Pleistocene ice sheets. It has occurred to

[39] Davis, W. M., Harvard Coll. Mus. Comp. Zoology Bull., vol. 42, p. 151, 1903.

[40] Davis, W. M., Harvard Coll. Mus. Comp. Zoology Bull., vol 49, pp. 20-21, 1905.

me, as I wrote of the phenomena of truncation, and especially the truncation of canyons and of structural features, that such phenomena may be so familiar as features of mountain fronts that not all students of orogeny feel the need of their explanation, and I shall therefore preface a consideration of the meaning of truncation by a brief account of a group of escarpments whose characters stand in contrast.

From the brink of the Grand Canyon of the Colorado the general surface rises northward for 75 miles, but it does not rise in a simple, continuous slope. The ascent, as described by Powell [41] in one of the classics of physiography, is a stairway. The tread of each stair slopes gently northward, and the riser of each stair is an escarpment that faces toward the canyon. The rocks are stratified and dip northward at a low angle, and discriminative erosion has brought the stronger members of the series into topographic prominence. The northward slopes are on the bared tops of strong beds; the escarpments exhibit the edges of the same beds, sapped by the wasting of underlying weak beds. The general direction of drainage is southward to Colorado River. Each major stream traverses the strong beds in canyons, but between the canyons it has a wider valley. Minor streams, wet-weather streams, head in the escarpments and join the major streams. Each canyon broadens downstream, flaring widely as its stream leaves the strong bed. The head of each minor stream is in a reentrant angle of an escarpment. The outline or ground plan of each escarpment is a series of convex scallops, large and small, the larger scallops spaced by the major drainage and the smaller by the minor drainage. The canyons and gullies of the drainage correspond to the canyons of the Wasatch front, and instead of being truncated at the basal outlines of escarpments they determine reentrants of the escarpments. The ridges between lines of drainage correspond to the ribs of the Wasatch, and instead of being truncated along the bases of the escarpments they determine the salient scallops of the escarpments and their bases.

The district is crossed by faults and monoclinal folds, which trend in the direction of the general dip and are thus transverse to the general trend of the escarpments. In one place two monoclinal folds are so related as to constitute an anticline. The escarpments met by this anticline are deflected far to the north, swinging in great reentrants 25 miles from their normal courses. They are thus deflected because their positions are determined by the conditions affecting erosion and because the elevation of the cliff-making beds in the anticline exposes them to more active erosion. A cognate deflection is found wherever an escarpment is crossed by a fault or a monoclinal fold. The escarpment is advanced on the side of the downthrow and carried back on the side of the upthrow.[42] The Vermilion escarpment is offset by the Sevier fault through a space of 7 or 8 miles and by the East Kaibab fault and fold through about 32 miles. Thus such structural features as faults and folds, instead of being truncated by the escarpments, serve as important factors in the control of the courses of the escarpments.

The control of the forms of these escarpments by elements of structure and by elements of drainage pattern is effected mainly through processes of stream erosion, and it is a general fact that the forms of escarpments created by stream erosion are largely controlled by the structure of the eroded terrane and by the pattern of its drainage. Because flowing water is the dominant agency in the sculpture of the land, the form types it produces constitute the norm, and departures from its types call for explanation. When, therefore, so important a form element as the basal outline of an escarpment is found to be independent of the rock structure, independent of the drainage pattern, and independent of the distribution of intercanyon ridges (distribution which is of course a function of drainage pattern), so that the basal outline appears to cut off or truncate these features, the phenomenon is one requiring explanation.

For the Wasatch escarpment the explanation is at hand, because the base line of the escarpment is also the line of a great fault, characterized by an abundance of the phenomena created by fault friction and followed through long distances by piedmont scarps. The escarpment is evidently the face of an uplifted tectonic block, and the adjacent depressed block is buried under waste from the sculpturing of the uplifted block. The structural elements of the uplifted block end at the fault line because they were actually cut off by the faulting. The ribs end where the block from which they were carved ends. The canyons also end where the block ends, and they end without flaring because the upfaulting was too rapid to give their streams time for lateral corrasion.

If faulting affords the only admissible explanation of the phenomena of truncation, then all ranges whose fronts are truncate may be classed at once as fault-block mountains. If the phenomena of truncation may be produced also in other ways, then truncation alone, although suggesting fault-block structure, is not demonstrative. In considering the question thus arising attention should be given to the several natural agencies or processes, other than faulting, that are known or supposed to produce escarpments. These are volcanism, ice erosion, wave erosion, wind erosion, and stream erosion.

[41] Powell, J. W., Some remarks on the geologic structure of a district of country lying north of the Grand Canyon of the Colorado: Am. Jour. Sci., 3d ser., vol. 5, pp. 456–465, 1873.

[42] Idem. pp. 461–462.

VOLCANIC ESCARPMENTS

The inward-facing wall of an ordinary crater is an escarpment created by explosion. The Krakatoa explosion made an escarpment by blowing out the side of a volcanic cone. The inner walls of Hawaiian craters are escarpments due to engulfment. None of these types need be considered here because their forms do not resemble mountain ridges of the Great Basin. For a similar reason the mention of several minor types may be omitted.

The edge of a coulee, or stream of solidified lava, though ordinarily a very low escarpment, is exceptionally of such size as to deserve attention in the present connection. The eruptive plateau of the Mono craters, for example, is bounded by an escarpment 500 to 1,000 feet high; and the faces of the effusive portion of the Mount Elden dacite body, which Robinson [43] has shown to be part laccolith and part coulee, are 2,000 feet high.

A coulee is a single body of rock; it is a bed but is not composed of beds. So one character of its escarpment is the lack of such structural elements as are necessary to exhibit truncation of structural features. Initially the coulee lacks surface drainage because it is penetrated by a plexus of shrinkage cracks. By the time it has acquired surface drainage and canyons have been opened in it the original definition of its escarpment has been dimmed by weathering, but there is a stage of dissection in which canyons and residual ribs end along a line of rock base, so that the features of internal structure are truncate. It is therefore possible that an escarpment that is composed of unbedded lava and that exhibits truncation of sculptural features originated by a purely volcanic process.

Coulee-edge escarpments of the magnitude of mountain ranges are rare, but high escarpments composed wholly or mainly of volcanic rock are not rare. An escarpment that shows two or more lava beds can not generally be regarded as an original product of eruption, because of the improbability that a free-flowing lava stream in spreading over an earlier stream should stop at the same line. Superposed lava flows that are halted by a barrier, however, may have a common limit, and an escarpment may afterward be created by the erosion of the barrier. Lavas that rest on weaker beds may be brought into strong relief through the erosion of bordering lands and thus become the conspicuous elements of escarpments, and lavas, like other rocks, may compose fault scarps.

ICE-MADE ESCARPMENTS

The U valley of glacial sculpture is bounded by mural escarpments that truncate tributary valleys, intervalley ridges, and structural features of the terrane. Among the truncated valleys are many hanging valleys, whose mouths are high on the walls. The contours of the escarpments may be as simply curved as those of a fault surface but differ in that they are not wholly independent of truncated valleys and ribs. Other resemblances and differences might be pointed out, but it will suffice to say that the characteristics of ice sculpture are so well known that a hypothesis of glacial sculpture need not be considered in a discussion of frontal escarpments of Basin ranges. The intermont troughs were here and there invaded in the Pleistocene epoch by tongues of alpine glaciers, and in a few places piedmont glaciers may have been developed, but ice-sheet conditions were not approached, and none of the troughs were traversed by longitudinal ice currents.

WAVE-MADE ESCARPMENTS

Erosion of a coast by waves creates an escarpment with all the features of truncation. Structural features are truncated, ribs are pared away until their ends are truncate and alined, inter-rib valleys and canyons are made to debouch at the common line of truncation, and the resulting base line of the escarpment is simply curved. These are the results of long-continued wave attack, and they should perhaps be characterized as ideal because no example of a finished coastal escarpment can be cited. In the coasts, recent and fossil, of my acquaintance the work is unfinished. There are stretches, some of them long, of perfected escarpment, but there are bays whose shores are protected from wave attack by wave-built barriers, and there are obdurate ribs not yet reduced to the scheme of alinement.

All these characters are exemplified by the Bonneville shore line, and some of them by the illustrations of this paper. Plate 1, *A*, shows a piece of perfected coastal escarpment—perfected, that is, at the time of its making and still preserving its main features. The rib facets are alined, and they rise from a base line that is simply curved. The canyons, which once ended at the same base line, have been extended as gullies by recent work of their streams. The facets of the wave-made escarpment, which stand at the angle of earth slope, have been carved from the less steep facets of an older escarpment. The older escarpment, a fault scarp, is thousands of feet high, and the wave-made facets are a few hundred feet high. The perfection of the wave-wrought alinement depends in this case on the fact that it has been superposed on a perfect fault-made alinement. Plate 22, *B*, portrays another piece of perfected shore escarpment in which the facets of truncation are in part on rock ribs of a Basin range and in part on flat-topped ribs made by the dissection of alluvial fans. The higher facets and the lower, those on bedrock and those on alluvium, are alined in the same simple curve. The

[43] Robinson, H. H., The San Franciscan volcanic field, Arizona: U. S. Geol. Survey Prof. Paper 76, pp. 74–85, 1913.

map in Figure 33 shows a piece of protected and unscarped coast between two portions truncated by wave attack. Waves of efficient size reached this tract of coast from the northwest and from the southeast. The waves from the northwest carved out a westward-facing escarpment and drifted the débris southward; the waves from the southeast carved a southward-facing escarpment and drifted the débris westward; and their work produced embankments of coarse débris by which the intervening coast was sheltered. The embankments stand at different levels, corresponding to different positions of the lake surface.

FIGURE 33.—Map of Bonneville shore escarpment and shore terraces near Dove Creek, Utah. Scale, 1 inch=1,600 feet. Contour interval, 10 feet. (Part of pl. 22, U. S. Geol. Survey Mon. 1, 1890)

The protection of bay coasts is further illustrated by the sketch map in Figure 29. The waves of Lake Bonneville did not carry their work of erosion into the Corner Creek Bay but built a curving bar in front of it. The whole physiography of coasts shows that waves do not erode in angular reentrants of coast lines, and it follows that such reentrant angles of the Wasatch escarpment as that at Taylor Creek (fig. 14) could not be made by wave erosion.

The base line of the escarpment made by a frontal fault lies in the plane of the fault and may have any relation to a horizontal plane. It rises and falls with the upper edge of the alluvial apron, which is controlled by a number of conditions. The base line of a coastal escarpment lies initially in a horizontal plane but may afterward lose horizontality through deformation and dislocation.

The size and therefore the efficiency of waves are related to the width and depth of the water body on which they are generated. Lake waves are weaker than ocean waves, and the waves of a lake in the bottom of an intermont valley are feeble as compared to those of Lake Bonneville. The waves of Lake Bonneville have in places steepened the Wasatch escarpment at certain levels, but it is evident that the scarped front of a Basin range could not be created by lake waves, because intermont lake waves are inefficient at low levels.

Coordinate with erosion by lake waves is deposition on lake bottoms, and the volume of lake deposits is much greater than the volume of material moved by lake erosion because the deposits include also débris brought by tributary streams. Lakes are thus fillers of intermont valleys and can not either make them or aid in their making. They have had no part in the creation of the corrugation of the Great Basin.

Because wave erosion truncates structure and sculpture there may be examples of truncation in the Great Basin which are wholly attributable to waves. The great examples, however, have been created along with the corrugation of the province and are therefore independent of wave work. I find no reason to regard the modification of escarpments by lake waves as of quantitative importance. The relative magnitude of the work of Pleistocene waves is fairly expressed by the contrast shown in Plate 1, *A*, between wave-made facets and the preexistent facets from which they were carved. The work of Pliocene and Miocene waves can not be evaluated in the same way, because the Tertiary wave scarps have not been recognized and are probably worn beyond recognition.

WIND-MADE ESCARPMENTS

It is the opinion of Keyes that in the more arid parts of the Cordillera truncate escarpments are produced by wind erosion. His view is that although stream erosion dominates within the ranges, causing dissection, wind erosion dominates in the intermont valleys, causing planation; that the valley floors are being lowered and leveled by deflation; that the lowland plains encroach on the mountains by eolian lateral corrasion; and that by this lateral corrasion mountain fronts are sapped at the base, steepened, and straightened, so as to have a deceptive resemblance to fault scarps.

Such degradation of desert plains should produce tracts of planed rock, with little waste on the surface. Such lateral corrasion at mountain bases should produce piedmont slopes with rock floors. The eolian theory finds support not only in the existence of such rock floors but in the fact that they abound especially in a very arid belt across the southern parts of New Mexico, Arizona, and California and are comparatively rare in northern parts of the Great Basin, where the climate is less arid.

This support is qualified by another factor of distribution—that rock-cut plains occur chiefly in regions of exterior drainage and are rarely found in closed basins. Their rarity in closed basins may indicate that deflation does not there keep pace with the aqueous deposition of waste from surrounding uplands; their relative abundance in regions of exterior drainage points to aqueous transportation as the efficient means of removing waste.

Whatever the local conditions in our desert regions, it is evident that in a district of extreme aridity eolian agencies must dominate, and there is advantage, therefore, in considering the probable result of dominant wind work in the shaping of mountain fronts. A wind blowing against a mountain face and up its slope is somewhat checked against the rib ends and strengthened at the canyon mouths. Its erosive work has a corresponding distribution and tends to preserve features of aqueous sculpture instead of truncating them. A wind blowing down the slope finds tools for corrasion only in the hollows and corrades only there. A wind parallel to the front behaves somewhat like an ocean current parallel to a coast; it makes eddies of low velocity in the bays and is accelerated against the capes. It is strongest high on the capes but does not corrade there for lack of tools. Its most efficient attack is at and near the bases of rib ends, and it tends to truncate the ribs. The work of oblique winds and of variable winds shows intermediate characters. It is probable that a wind truncation comparable with truncation by faulting can be accomplished only by a wind of fixed direction and is not ordinarily possible to cyclonic winds.

The foregoing statements, although largely deductive, have been guided in part by observations of eolian corrasion in three localities where the direction of efficient winds is controlled by local configuration. The observations most in point were made along the base of the Shinarump cliff, near the head of Marble Canyon, in northern Arizona. The cliff exposes sandstone at the top and sandy shale below. The only strong winds that carry sand for corrasion blow from the southwest, parallel to the general trend of the cliff. The cliff base is not straightened but has reentrants and salients adjusted to the drainage system. The wind has blunted the salients and keeps their ends free from talus, but the shale slopes in the reentrants are covered by talus.

Unfortunately the mountains cited by Keyes as examples have not been adequately mapped, and he illustrates their characters only by diagrammatic sections.

Before the development of the eolian hypothesis McGee[44] wrote of the rock-cut plains of the Sonoran deserts and ascribed them to a special type of water action which he called sheet-flood erosion. After the development of McGee's hypothesis Paige[45] discussed the rock-cut piedmont plains of the Silver City quadrangle, in southwestern New Mexico, and ascribed them to normal stream erosion. Paige's study had the advantage of such comprehensive knowledge of local structure as is acquired in the preparation of a folio of the Geologic Atlas and a further advantage arising from the fact that one of the plains studied has been dissected in consequence of a recent local uplift. The dissection has revealed the fact that the alluvial mantle of the beveled rock surface, although a mere veneer near the mountain base, thickens valleyward; and this character indicates that the retreat of the mountain front and the concomitant development of

[44] McGee, W J, Sheet-flood erosion: Geol. Soc. America Bull., vol. 8, pp. 87-112, 1897.

[45] Paige, Sidney, Rock-cut surfaces in the desert ranges: Jour. Geology, vol. 20, pp. 442-450, 1912.

the rock-cut plain at its base had been accompanied by aggradation in the valley. More recently Lawson[46] has included the profiles of rock-cut piedmonts in a general analytic discussion of the profiles developed under desert conditions. His views are in accord with those of Paige, and he assigns only a minor part to the wind.

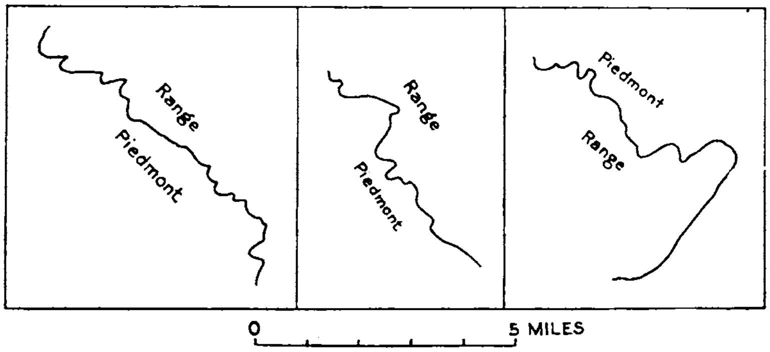


FIGURE 34.—Outlines of mountain escarpments where joined by rock-cut piedmont plains, Silver City quadrangle, N. Mex. (After Paige)

In three of Paige's illustrations the outline of mountain base resulting from the development of the rock-cut piedmont is charted, and I have reproduced these outlines in Figure 34. It will be observed that the outlines have not the general appearance of the basal outline of the Wasatch escarpment but are relatively indentate. Examination of the contour map on which these outlines were drawn shows that their reentrants and salients, instead of being independent of the mountain sculpture, are in close accord, severally, with the drainage lines and ribs of the mountain. So the escarpments, whatever their relation to the structure, do not truncate the sculptural features of the mountain. Moreover, the ends of salients have not such an alinement as would be expected if their positions were determined through lateral corrasion by currents parallel to the general trend of the escarpments.

In a fourth illustration, which I reproduce in Figure 35, Paige gives the complete outline of the rock base of a range that is bounded on one side by a fault. On the side of the fault the outline is direct and simple, despite complexity in the internal structure of the range; structure and sculpture are truncate. On the opposite side the outline is tortuous.

The question whether some escarpments of desert ranges are of eolian origin will be settled by future field studies but appears for the present to be open. The observations of McGee, Keyes, and Paige agree in indicating that the fronts of certain desert ranges have been steepened by some erosive process or processes, with the concomitant development of a rock-floored piedmont. The indentate escarpments described by Paige seem best explained as a product of erosion that is mainly aqueous. If it shall be found that some of the escarpments made by erosion truncate both structure and mountain sculpture I think the eolian hypothesis will find application, but its application has not yet been shown by the reports of adequate studies.

[46] Lawson, A. C., The epigene profiles of the desert: California Univ. Dept. Geology Bull., vol. 9, pp. 23–48, 1915.

It is proper to observe that the association of a truncating escarpment with a rock piedmont does not necessarily indicate eolian erosion unless the rocks of the escarpment are continuous with those of the piedmont. The association may be created by faulting and then the rocks are not continuous.

The production of an escarpment by sapping implies the preexistence of a mountain front. The sapping does not create the differentiation of upland from lowland but modifies the form and position of the sloping face by which they are separated. The question considered in this section is not that of range origin but only that of the value of the truncating escarpment as a character to be used in the nition of fault-block ranges.

STREAM-MADE ESCARPMENTS

Strike escarpments developed by streams from bodies of dipping beds, including cuesta escarpments and escarpments like those north of the Grand Canyon (p. 42), are not considered in the following paragraphs, but only escarpments that traverse the strike of strata, folds, and faults.

A rapidly corrading stream in carving its gorge creates two escarpments. Tributary gorges divide each escarpment into facets. The facets are parallel to the stream that establishes their base lines. Each escarpment truncates the tributary gorges and intergorge ridges. If the course of the stream is transverse or oblique to the strike of the structure, each escarpment truncates structural features. Thus an ordinary canyon wall is a truncating escarpment, with many of the characters of the frontal escarpment of the Wasatch. It may or may not have a simply curved basal outline. It differs primarily by having a counterpart close by. The carving of a gorge may be regarded as the initiation of a stream valley. Under stable conditions of base-level downward corrasion first slackens and then ceases, and it is gradually replaced by lateral

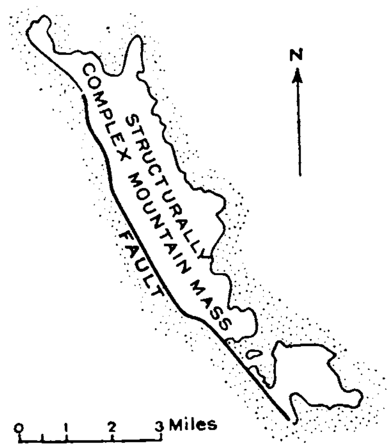


FIGURE 35.—Outline of the Little Burro Mountains, N. Mex., showing the boundary between the bedrock of the range and the surrounding alluvial apron. (After Paige)

corrasion. Flood plains are developed, and the canyon walls recede.

A conceivable method of producing the frontal escarpment of a Basin range begins with the carving of a canyon parallel to the range axis and continues with the broadening of the canyon until it becomes an intermont valley. Another conceivable method begins with a river meandering in a broad plain above the present site of an intermont valley and continues with a downward erosion by the river so slow as to involve no canyon phase.

The river work, by either hypothetic method, carries the valley floor below its present level and is followed by the work of minor streams, which partly fill the eroded valley with deposits of waste from the bordering ranges. Before the disappearance of the hypothetic intermont river the mountain streams were tributary to it, and while the river was eroding the main valley the mountain streams were eroding canyons and narrow valleys. When a sloping alluvial deposit is afterward built up along each edge of the main valley it necessarily occupies also the lower parts of the lateral valleys and canyons. The resulting line of the rock base of each range is therefore a zigzag, and its reentrants and salients correspond severally to the canyons and ribs of the range. So a frontal escarpment created by an intermont river and modified, after the disappearance of the river, by partial burial does not truncate the sculptural features of the range.

The erosive activity of a mountain stream is conditioned by a base-level outside the mountain. When a change in the relation to base-level checks its downward corrasion the influence is first felt in the lower course, so that lateral corrasion goes on near the canyon mouth while vertical corrasion still persists farther up. The result is a flaring of the canyon mouth. By the widening of a series of canyon mouths the intervening ribs are pared away and the canyon floors are made to coalesce in a piedmont plain of rock. This process is an influential factor in the sculpture of mountain fronts in arid districts, as analyzed by Lawson, and is essentially the process to which Paige ascribes the rock-cut piedmonts of the Silver City area. The escarpment thus produced is indentate.

SUMMARY AND CONCLUSIONS

The truncation of canyons and intercanyon ridges, so that the lower part of a range front consists of a row of facets with bases well alined, may result, as on the west face of the Wasatch, from faulting. Similar truncation may result from sapping by waves, but no available example shows the completed products. Because efficient waves imply breadth of water surface, the power of the waves diminishes downward on the slopes of intermont valleys, becoming zero at the bottom. So waves can not create the range fronts but only modify them. Wind erosion is theoretically able to cause similar truncation. The degree of similarity is unknown, because examples either have not been found or have not been adequately described. The conditions for eolian truncation are that the climate shall be so arid that wind work dominates stream work and that the direction of the winds efficient for corrasion shall be parallel to the escarpment. Stream erosion, if the stream runs parallel to the range front and if its work is followed by deposition of alluvium from the range, may produce an escarpment with indentate base, the canyon mouths being invaded by the alluvial apron. Stream erosion by the streams draining the range may produce an indentate escarpment that rises from a piedmont of planed rock.

The wave-made escarpment is distinguished from all others by the horizontality of its base line; the coulee-edge escarpment is distinguished by the fact that it presents a single bed of lava. Escarpments made by erosion, whether the agent be wave, wind, or stream, are initially characterized by a planed-rock piedmont, but an eroded escarpment may acquire an alluvial piedmont after the conditions under which it was made have ceased to exist. A fault-made escarpment is ordinarily accompanied by an alluvial apron, because base-level conditions rarely permit the entire body of waste from the lifted block to be washed from the adjacent part of the thrown block. For a truncating escarpment met at the base by an alluvial apron the presumptive origin is to be ascribed to faulting.

Because the waves of intermont lakes do not create mountain fronts, because wind-made escarpments that truncate range sculpture are possible only under rare conditions of aridity and wind direction, because ice rivers have not occupied the intermont troughs of the Great Basin region, because the base line of an escarpment created by the streams draining a range is indentate, and because the base line of an escarpment created in a past age by a river traversing an intermont valley and afterward partly buried by alluvium is also indentate—therefore a range front that is an escarpment which truncates both structure and sculpture has presumably originated by faulting. The presumption is specially strong if the piedmont plain is alluvial. If the piedmont plain is of rock and the piedmont rock is continuous with the rock of the range the escarpment was created or has been steepened by some erosive process.

FACETS

Davis [47] has shown deductively that truncate facets should be characteristic, as they are in reality, of youthful fronts of block mountains; and he has recognized also their occurrence in wave-made escarpments. As we have seen, they are found in canyon walls and belong theoretically to a type of wind-made escarpments. Plate 23 illustrates their origin by sapping where the agent of sapping is a stream and the process is lateral corrasion. They are, in fact, features of escarpments in general rather than of escarpments

[47] Davis, W. M., Harvard Coll. Mus. Comp. Zoology Bull., vol. 42, pp. 143–160, 1903.

of a particular type, and it is only through special characters that they become diagnostic of fault scarps. The alinement of facets has already received attention, but other characters also are illustrated by the Wasatch examples.

The base line of a facet due to sapping, and the base line only, is determined by the sapping agent. The side lines are given by the hollows, usually trenches formed by erosion, between which it stands. If the walls of those trenches meet upward in a tentlike crest the facet is triangular; otherwise the top line of the facet is determined by the form of the upland between the trenches.

The slope and the texture of the facet result from wasting, and the wasting is conditioned by the nature of the material and by climate. An omnipresent agent in the process of wasting is gravity. If the material is clastic and uncemented, gravity at once determines a slope at the angle of rest, 30° to 35°. Coherent material stands in a cliff until disintegrated, and as disintegration proceeds it is graded to the angle of rest. Under an arid climate the dominant cause of disintegration is disruptive strain from changes of temperature. Under a moist temperate climate rending by frost is important and chemical weathering also takes place.

The rate of disintegration is different for different rocks. If the terrane of the facet is heterogeneous the outcrops of its more stubborn rocks retain steep faces after the outcrops of more yielding rocks have been reduced to the angle of rest. Their positions may be marked, at least during the youth of the facet, by cliff lines or by crags that interrupt a slope otherwise well graded.

During the process of gravitational grading the facet may be washed by rains, but the rains accomplish little in the way of erosion. Their apparent impotence is specially noteworthy because the transporting and corrading power of flowing water increases rapidly with increase of slope, and the facet slope is steep. The explanation is probably to be found in absorption and retardation by porous talus and in conditions unfavorable to concentration of flow. The general uniformity of slope toward which gravitational grading tends does not encourage oblique flow but guides the water along the dip of the surface; and such runnels as may be formed are likely to become clogged by talus. For most rocks gravitational wasting is relatively rapid and wasting by rainwash relatively slow. This is peculiarly true where the climate is arid. After the slope of rest has been attained, the work of weathering and rainwash may be said to begin, and by these processes the slope is slowly reduced. Because the angle of rest is quickly acquired and slowly lost it has a certain critical importance and is characteristic of many facets. When the veneer of talus is replaced by a veneer of regolith runnels are more easily formed, and competition of runnels results eventually in concentration of drainage and the development of dissecting ravines. Through dissection the distinctive features of the facet are finally destroyed.

The facet produced by faulting has a somewhat different history. First, it has an initial slope—the dip of the fault. So far as we have definite knowledge frontal faults are normal and their dips range from 19° to 70°. The lower initial slopes, which are less than the angle of rest, admit of no gravitational grading; from facets that have higher initial slopes the gravitational wasting is less than from those due to sapping. Second, a facet made by faulting, or the footwall from which it is shaped, does not emerge all at once but is formed by a series of small movements separated by intervals of time. It is older, therefore, at the top than at the base, and the slope at the top may have been materially reduced by weathering while that at the base is unchanged. If the slope near the base is that of the fault plane it may be joined to the slope at the top by a continuous curve. It is possible that the convex profiles of certain fault scarps—for example, that illustrated by Plate 1, *A*—are due to progressive wasting of the rising footwall.

The same rising of a range block that develops frontal facets causes the deepening of dissecting canyons and thereby maintains steep canyon walls by sapping. Where frontal facets and canyon walls come together the types of scarp produced by faulting and by sapping are conveniently placed for comparison, and the scarps in juxtaposition usually contain the same formations. Plate 4, *B*, compares a sapped facet with a fault-made facet, shown in profile. The sapped facet is mainly graded to the talus slope, from which jut numerous crags. The fault-made facet is cragless, and its only cliff is a shore cliff of Lake Bonneville. The fault dip is here 29°, and the slope of the facet diminishes from 29° at the base to 23° at the top. As the entire slope of the facet is below the angle of rest there has been no gravitational wasting, and the curvature, if due to wasting, is a result of weathering. It is entirely possible, however, that the original fault surface is curved and that the wasting has been inappreciable. The profile of the next facet, faintly shown in the view, is nearly straight. Plate 21, *B*, compares two fault-made facets with a large canyon-wall facet. The sapped facet betrays details of rock structure by ledges and crags and is partly divided into minor facets. Its subdivision is probably due to bends in the course of the canyon stream, but other features of its sculpture are products of gravitational wasting. The faulted facet that adjoins it, of which the (unmeasured) slope differs little from the angle of rest, gives relatively little expression to elements of rock structure. The faulted facet on this side of the canyon reveals many details of structure. The weaker members of its steeply dipping sedimentary beds have segregated the drainage and thus initiated dissection.

The fault-made facets shown in Plate 20, *A*, which stand approximately at the angle of rest, have few crags at low levels and many at high levels but are smooth compared with adjacent canyon walls.

In general the frontal facets of the Wasatch are smoother than the parts of canyon walls immediately adjacent. Where they are not smoother they are equally smooth. The primary reason of the difference in surface character is that the frontal facets derived their slopes mainly from faulting, whereas the slopes of the canyon walls are produced by gravitational wasting under the incitement of continual sapping. If the frontal fault had been vertical its gradual development would have produced frontal facets through the same process of gravitational wasting, and the facet surfaces would have agreed in character with those of the canyon walls, but the dip of the fault corresponds so nearly with the angle of rest that adjustment to stability involves little or no wasting. The frontal facets have been initiated in a condition of approximate maturity, whereas the canyon walls are continually rejuvenated.

The facets shown in Plate 19, *B*, are distinctly convex, but I am not confident that the curvature should be ascribed to weathering. As the structure is far from simple and as the mass includes rocks of unequal strength, a more varied surface might be expected as a result of extensive wasting.

Convexity is further illustrated by the configuration of the Lone Peak salient, as portrayed in Plates 19, *A*, and 11, *A*, and Figures 22 and 23. A part of the western face is seen in Plate 19, *A*, to be deeply dissected, so as to display clearly differentiated basal facets, but farther south the pattern is less definite, and not all the intergorge facets are basal. High on the salient are bits of sloping plain that together with certain smooth rib crests indicate the surface of a convex mass from which the gorges have been carved. The simple sky line in Plate 19, *A*, is a composite of such elements, and so is the smooth profile from *a* to *j* in Figure 23. The highest of the detached facets is at *j*, about 4,400 feet above the rock base. The harmonious alinement of high facets and high ridge crests supports the inference from the stranded channels of Corner Creek (p. 28) that the original form of the granite body is fairly represented by the surviving outer slopes, so that its restoration requires only a moderate allowance for waste by normal weathering. Even with a large allowance for weathering the indicated form is strongly convex.

The general convexity of the facet profiles where such profiles are best preserved suggests that the fault surface as a whole is convex toward the west and that the rising movement of the Wasatch block was combined with a notable rotation toward the east. The alternative view is that the convexity of the profiles is due chiefly to the deeper weathering of the upper parts of the facets because of their longer exposure. The evidence at the Lone Peak salient might be regarded as decisive but for its association with an immense lump of granite, which retained its integrity despite the shearing stress to which it was subjected in common with the inclosing rock bodies. The convexity at the salient is essentially that of the oburate lump and should not be regarded as typical of the footwall. The question of the rotation of blocks will eventually be approached from another side, and for the present it is well to hold in abeyance the interpretation of the convexity of facets.

The frontal facets to which attention has thus far been directed are all, in a topographic sense, young. Because the Wasatch block is actively rising they have not been long exposed to wasting agencies, and because their rocks are strong they have wasted little. The Wasatch facets in weak rocks are comparatively worn and indefinite, and the original facets of block mountains now old and stagnant have been worn out and replaced by rib ends of a different type. The most decadent of the Wasatch facets are blunted and well-rounded rib ends, retaining of the typical characters only the simple base line, but these I am not able to illustrate by views. Facets of intermediate character appear in Plates 22, *A*, 24, *A*, and 25, *A*, which represent localities where the faceted rock is a gneiss that weathers more readily than the overlying quartzite.

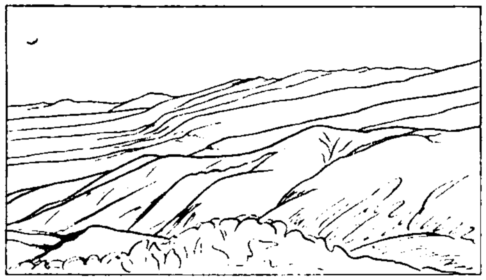


FIGURE 36.—View of west face of Wasatch Range, Utah, north of City Creek spur, illustrating the evenly graded crests of interfluve ridges. (From a photograph)

OLD GRADED SLOPES

In a division of the range between Salt Lake City and the canyon of Weber River, which may for brevity be called the Farmington division, lie remnants of graded plains at high levels. They head at or near the crest and slope westward. The best-defined group occurs a short distance south of Weber Canyon, and a second group occurs opposite and south of the village of Farmington. Associated with them are somewhat evenly dressed rib crests with similar westward slopes, and these run from points near the summit of the range to the tops of frontal facets. The graded plains near Weber Canyon are imperfectly shown in Plate 24, *B*. Two of the rib crests appear in Plate 25, *A*, but these examples are not so evenly dressed as some others of the series. Figure 36, based on a photograph made from the City Creek spur, is a general view of the rib crests and shows the definite change of slope from crest line to frontal facet. The general relations are further indicated by the diagram in Figure 37. The slopes of the facets are about 30°; those of the rib crests and high graded plains 11° to 15°. The steep slope just east of the crest is due to Pleistocene glaciation. In this part of the range the summit region and western face are composed of Archean gneisses, and on the eastern face the gneisses are overlain by eastward-dipping Eocene conglomerates.

The broad plain indicated by these features projects itself into the air in both directions. If it was piedmont to a range, the range has disappeared. Its extent suggests a peneplain, but its present slope is steeper than that of a peneplain in the making. Slopes of 11° to 15° are found in canyon beds. They are also found on some alluvial aprons for short distances near their heads but are not, to my knowledge, continued for miles. The great alluvial apron of the Sierra Nevada bordering Owens Valley has a slope near the top of 6° and a general slope of more than 4°. Tongues of alluvium that invade the Ivanpah Range have slopes as steep as 5°.

Lawson [48] has shown that the wasting of a range in an arid region may produce a planed rock slope

FIGURE 37.—Diagrammatic profile of west face of Wasatch Range, Utah, between City Creek spur and Weber Canyon

steeper than the slope of overlying alluvium, provided the waste is retained by a closed basin so that the base-level may rise as the work of grading progresses, and it is perhaps possible to produce in this way a graded rock slope as steep as that on the Wasatch. Such a result, however, could be attained only under exceptional conditions—for example, those afforded by a small closed basin that was being rapidly aggraded by the waste from a large upland—and it is much more probable that the features observed on the Wasatch are vestiges of an old peneplain, originally of gentle slope, which acquired its present attitude when it was uplifted. This interpretation implies that the Wasatch block, or at least a minor block of the Wasatch uplift, was tilted westward as it rose. The portion to which the inference is directly applicable is about 20 miles long, from Weber Canyon southward to the City Creek spur, and includes the western face and main crest line. In the latitude of Farmington there is a subsidiary crest line farther east, which appears to have been determined by the presence there of a distinct crustal block.

Graded plain remnants high on the range opposite the City Creek spur have already been mentioned. Their relation to those farther north was not determined, but presumably they belong to the same system; and if so, they promise considerable aid to future investigators, for they are associated with an aggraded plain on the spur.

In the same Farmington division of the range rock-floored terraces lie within the canyons. One of these terraces, dissected transversely by drainage from the canyon wall, is shown in Figure 17. A remnant that has escaped dissection and appears to retain its alluvial cover appears at the right in Plate 25, *B*. A closely related grade plain, dissected longitudinally, is shown in Figure 16. All these stand at lower levels than the rib-crest system and are necessarily younger. They record a period of orogenic rest, preceded and followed by periods of orogenic activity. The period of rest was long enough to enable the canyon streams to establish stable profiles and to begin the enlargement of their gorges by lateral corrasion.

There may have been more than one interval of rest. The possibility of a second is suggested by features at and near the City Creek spur, but the data are too fragmentary for profitable discussion.

The Farmington division appears to stand alone in its record of a high-level grade plain with marked westward slope. In some places the crest line of the range shows such evenness as to suggest that it has wasted by only a moderate amount from an earlier plain condition, and similar suggestion has come from photographs that show profiles of ribs, but if these obscure indications are of real significance they tell of peneplains with gentle slopes, and they are all associated with relatively high westward-facing escarpments.

THROW OF THE FRONTAL FAULT

The throw of a fault is the vertical element of the displacement between the dissevered bodies, provided the fault movement is translatory only. If the movement involves rotation, the throw is not the same for all parts of the bodies. For any pair of points, on opposite sides of the fault surface, that were in contact before the movement the right-line distance after the movement is the slip, and the vertical component of the slip is the throw. The horizontal component of the slip in the direction of the strike of the fault surface is the strike slip, and the horizontal component normal to the strike is the heave.[49]

Where the corresponding points are visible and identifiable, the measurement of throw is simple. Accurate computation of the throw is possible also where corresponding structure lines are recognized on opposite sides of the fault and the direction of the slip is shown by striation of the fault walls. There are other special relations that admit of definite determination. But where, as in the Wasatch frontal fault, only one of the dislocated blocks is visible, the throw

[48] Lawson, A. C., The epigene profiles of the desert: California Univ. Dept. Geology Bull., vol. 9, pp. 34–38, 1915.

[49] Report of the committee on the nomenclature of faults: Geol. Soc. America Bull., vol. 24, pp. 170–181, 1913.

can not be measured but only estimated. In some places, perhaps in most, it is possible to determine that the throw is not less than a certain amount.

Figure 38 gives a section of the Wasatch Range in the Cottonwood region and is extended to include Jordan Valley and the Oquirrh Range. AC represents the plane of the frontal fault, the attitude of which is known only at the rock base. Its profile is probably a curve and has been drawn as a straight line only because the nature of the curve is unknown. When the fault movement began the point A of the footwall and the point B of the hanging wall were in contact and at the surface. The distance AB is the slip of the fault, coincident here with the dip slip, and DB is the throw. Because the crest of the lifted block has disappeared through erosion, the position of A is unknown, and so is the true direction of the profile of the old land surface, but that profile should surely be drawn above the profile of Twin Peak, and it is highly probable that the true position of A is higher than Twin Peak. B is concealed by valley deposits. The throw of the fault is equal to the height of Twin Peak above the rock base, 7,000 feet, plus an amount representing erosion of the lifted block, plus an amount representing depth of valley deposits on the edge of the depressed block. It may be said with confidence that the throw is greater than 7,000 feet.

The canyons of the range front head in the neighborhood of Clayton Peak. Twin Peak is the culminating point of a residual ridge between canyons. It is sharply crested and gives no suggestion of the prefault surface. It is, however, one of a series of ridge culminations that suggest to Hintze [50] the probable position of the high edge of a tilted fault block, and the curved facets of the Lone Peak salient indicate that that peak, which is in line with the rib culminations, reaches nearly to the plane of the old surface. (See fig. 23.) Clayton Peak (fig. 38) is part of a relatively broad summit, a table of resistant diorite that has been reduced to a skeleton by the development of glacial cirques. With reference to its immediate surroundings the table is a monadnock,[51] and the tabular elements of its top may well have been graded as part of the prefault land surface. From these suggestions that the summit region retains details of form inherited from the old land surface I infer that in an estimate of the throw of the fault only a moderate allowance should be made for the reduction of Twin Peak by erosion—probably 1,000 or 2,000 feet is sufficient.

Jordan Valley, here 17 miles wide, is occupied to an unknown depth by alluvium from the two ranges and by lake beds. Borings near the river have explored the deposits for 1,300 feet without reaching their base. On the line of the section the surface deposits are alluvial, graded downward from the range bases to the river. The flood plain of the river is narrow, and the position of the river in the valley is determined by the alluvial aprons. It follows the line along which the aprons meet. That line is nearer to the Wasatch Range than to the Oquirrh. For a distance of 18 miles, from the Traverse spur to the head of the Jordan delta, the average width of the Wasatch apron is 6 miles and that of the Oquirrh apron is 10.5 miles. This relation is abnormal, for the streams from the greater range are much larger and carry the greater load of waste. Because of the greater annual volume of waste from the Wasatch its apron should be not only wider but much wider than the Oquirrh apron, and the position normally appropriate for the river course is near the base of the Oquirrh Range. The probable explanation of the river's abnormal position is that the bedrock support of the Wasatch apron is going down. The piedmont scarps show its descent in relation to the Wasatch block, and the narrowness of the apron shows that it is descending as compared with the bedrock support of the Oquirrh apron. Whether the rock floor of Jordan Valley consists of one tectonic block or of many, it is being tilted eastward; and as the piedmont plain of the Wasatch is built up by the addition of waste from the range, it is being lowered by the subsidence of its foundation, so that its position represents a balance between antagonistic influences. It is therefore probable that the valley fill is deeper on the east side than on the west. This consideration tends toward a large allowance for depth of valley deposits in estimating the throw of the fault.

If all the waste from the range were lodged in the piedmont deposit a computation based on the volume of excavation involved in the sculpture of the range would yield an estimate—or at least a minimum estimate—of the depth of the piedmont deposit, but as an unknown fraction of the waste escapes down Jordan River to Great Salt Lake, the data are too indefinite for profitable discussion.

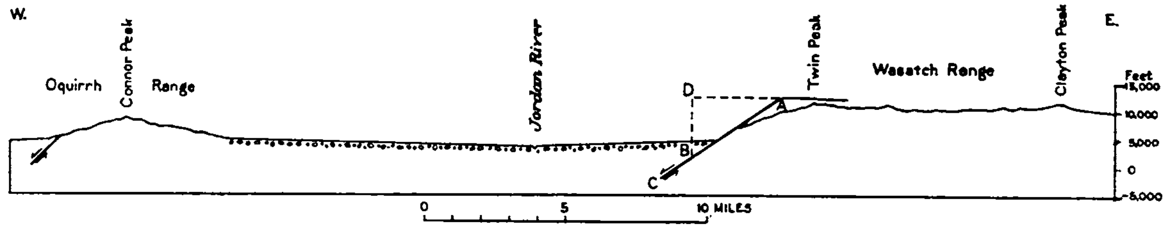


FIGURE 38.—Profile of Wasatch Range and Jordan Valley, Utah, illustrating data on throw of Wasatch frontal fault

[50] Hintze, F. F., A contribution to the geology of the Wasatch Mountains, Utah: New York Acad. Sci. Annals, vol. 23, pp. 88-91, 1913.

[51] Boutwell, J. M., Geology and ore deposits of the Park City district, Utah: U. S. Geol. Survey Prof. Paper 77, pls. 2 and 4, B, 1912.

Such attention as I have given to the question has left the impression that unless Twin Peak is far below the original surface of the Wasatch block the proper allowance for thickness of the apron may be 2,000 or 3,000 feet. The greater the original height of the point A in Figure 38, or the greater the volume of erosion, the greater the allowance for thickness of apron and the lower the depression of B.

In accepting 7,000 feet as an absolute minimum for estimates of the throw of the fault, I am disposed to regard 10,000 feet as a moderate and not improbable estimate of the throw. With the assumption that the fault surface has a uniform inclination of 34°, this yields a slip of 17,900 feet and a heave of 14,800 feet.

The only other estimate of the throw with which I am acquainted was made by King and is 40,000 feet. It applies to the same part of the range. His statement indicates a point of view so different from my own that I do not venture to paraphrase it but quote entire the paragraph in which it occurs:

> Fortunately, in the case of the Wahsatch fault we have, in the Cottonwood region of the Wahsatch, a magnificent exposure of folded stratified rocks through which the plane has cut, and from the direct, evident reading of the section it is clear that the fissure which traced itself throughout the axis of fold of the Wahsatch in this particular neighborhood caused the westward member to sink fully 40,000 feet. A relic of the eastern half of the great arch of Paleozoic and Mesozoic rocks still remains in position, its summit members deeply worn away by post-Cretaceous erosion, but all the details of the sequence of rocks are so clear and so perfectly exposed that there can be no doubt of the quantitative correctness of my reading of this tremendous dislocation. In passing northward we have less direct evidence of the amount of the fault, but through the northern part of the range it can not have have dropped less than 2 miles. The action is simply a vertical one by which the western half of the Wahsatch and the country lying west for some miles was, relatively to the eastern part of the range, dropped, and the dislocation took place on the axial line which cut the region of the extreme topographical heights of the Cottonwood group, where the maximum downfall was, as announced, 40,000 feet.[52]

In the Farmington region, 30 miles farther north, where the range is both lower and narrower than in the Cottonwood region, the high-level grade plains and graded ribs already described (p. 49) aid the estimate of throw by giving fairly definite indication of the position of the prefault surface of the lifted block. The generalized profile of grade plains and escarpment in Figure 37 may serve for the consideration of the throw. Neither the height of the escarpment nor the local dip of the fault has been measured. The height above the rock base of the rib ends, points corresponding to Twin Peak in the Cottonwood profile, is estimated at 1,500 feet, and the height of the range crest is about 4,000 feet. A point that corresponds to A in Figure 38 is about 1,500 feet above the rock base; and an estimate of the throw would add to this an allowance for the thickness of deposits resting on the valley block.

The frontal apron is here narrow, being only 2 or 3 miles wide in a tract at the south, where its development is not modified by deposits from Weber River. It does not meet, as in Jordan Valley, the frontal apron of another range, but its lower edge merges with a plain composed of lake sediments. As the level of Great Salt Lake rises and falls the boundary between areas of lacustrine and alluvial deposition shifts toward and from the range, and the two deposits are thus interleaved. The annual output of waste from the range is here much less than in the Cottonwood region, and so is the total volume, per unit of frontage, that has been excavated in the dissection of the range. These considerations tend toward a low estimate for the depth of burial of the valley block. On the other hand, the present width of the zone of alluvial deposition is small, and it has been still smaller whenever the lake has stood at higher levels. Bonneville sediments are interlarded with the alluvial deposits, and there is also a question of Pliocene lake beds.

Here also there is reason to believe that the depth of deposition on the valley block has been affected by subsidence, but the most significant evidence of subsidence pertains to a tract much broader than Jordan Valley.[53] Great Salt Lake does not lie in a bowl but is spread over a plain. Its mean depth is less than 15 feet. The plain extends from the base of the Wasatch Range westward for 120 miles to the base of the Gosiute Range. West of the lake it is the Salt Lake Desert and is so nearly level that the flow of water on its surface does not wash the salt from its soil. The plain has been produced by deposition, not by erosion, as is shown by its relation to the Great Basin corrugation. It lies within the province of corrugation, but its ridges are low and discontinuous. They are crests and peaks of mountain ranges whose bases are deeply buried by sediments. Toward the north and toward the south the corrugated system rises, until at the limits of the plain the ranges have normal heights and the valley troughs are of normal type. The plain occupies an epeirogenic hollow in a region of orogenic corrugation.

The principal rivers that bring detritus for the building of the plain are the Jordan, Weber, and Bear, all rising in the uplands east of the Wasatch Range. Their contribution of débris must be several times greater than that brought to the plain by all other streams. All the coarser part of their débris is deposited near their mouths, and at all times they must have deposited more débris, coarse and fine, on the eastern part of the plain than on the western part. Neverthe-

[52] King, Clarence, U. S. Geol. Expl. 40th Par. Rept., vol. 1, pp. 745-746, 1878.

[53] The discussion contained in this paragraph is in part the restatement of an earlier discussion. See Gilbert, G. K., U. S. Geol. Survey Mon. 1, pp. 384-386, pl. 48, 1890.

less the position of the lake shows that the plain is lower at the east than at the west. The western shore of the lake is 75 miles from the western edge of the plain. The eastern shore in two of its bays lies close to the base of the Wasatch Range. At the south edge of the Weber River delta the strip of land between lake and mountain is 2 miles wide, and at the north edge it is only 1 mile wide. Had the rock foundation of the region been stable during the building of the plain the surface would now slope westward and Great Salt Lake would lie along the base of the Gosiute Range. The actual position of the lake testifies to subsidence of the eastern part of the plain. Because the total volume of débris accumulated in building the plain is large, and because the contribution from the east has been relatively large during at least the later part of the period of plain building, and because during the same later part of the period the greater part of the débris from the east has been deposited near the eastern edge of the plain, it is inferred that the depth of the deposit close to the Wasatch fault is large. Because the epeirogenic sag, as indicated by the relation of the aggraded plain to orogenic corrugation, is greater where the lake lies than toward the north or south, it is inferred that the depth of deposit is specially great under that part of the Wasatch foreland that is opposite the lake. Therefore, for the Farmington division, the portion of the range between Weber Canyon and Salt Lake City, the estimate of the throw of the fault should include a very large allowance for depth of deposit on the concealed block, a much larger allowance than should be made for the Cottonwood division. A quantitative statement of the difference is not warranted by the facts at command, but it is evident that a mistake would be made if great disparity of fault magnitude between the two localities were inferred because at one locality the fault scarp is 7,000 feet high and at the other only 1,500 feet.

The preceding discussion leads to two suggestions for the explanation of apparent anomalies. As already noted (p. 50), the attitude of high-level grade plains of the Farmington region indicates that the great fault block of the range is there tilted westward through an angle of more than 10°. Evidence of similar tilting has not been discovered in other parts of the range, but for the Cottonwood division of the Wasatch Range Hintze has plausibly suggested tilting in the opposite direction, and many range blocks in the Great Basin have been thought to be tilted away from their bolder escarpments. It is now suggested that the apparently exceptional tilting of the Farmington division of the Wasatch Range is connected with its relation to the epeirogenic sag that is marked by the position of Great Salt Lake, that the steepest slope toward that depression is not from the north or south but from the east, and that the attitude of the range block is due less to its own rotation than to epeirogenic warping.

In no other part of the range have well-preserved high-level grade plains been found. The exceptionally good indication in this tract of the attitude of the fault block has occasioned surprise, because the Archean rocks on which the grade plains are preserved are neither homogeneous nor highly durable. For the preservation of fault facets along the escarpment they are inferior to the quartzites and granites. At one time I suspected that this part of the range was relatively young, but it now seems to me more probable that its dissection has been retarded by its peculiar attitude and its moderate altitude. Because the fault scarp is here relatively low the canyons that dissect the range block are relatively shallow and narrow and their development has not wholly obliterated the original profiles of the intercanyon ridges. Also because the range crest is here less lofty than in some other divisions it has been less consumed by Pleistocene glaciers. In the Cottonwood region, where névé buried the whole crest tract and ice tongues reached the western base of the range, the upper reaches of the canyons were enlarged and remodeled by glacial head erosion. In the Farmington region, where the summit tract is 3,000 feet lower, most of the accumulation of névé was on the east side—the lee side—of the crest, and, although the east side shows to distant view a complete cornice of high cirques, the west side betrays little evidence of glaciation.

CROSS DRAINAGE AND BACK VALLEYS

CROSS DRAINAGE

A tract of country east of the range is drained by streams that cross the range to the lowlands at the west, their waters ultimately reaching Great Salt Lake. It is characteristic of this system of cross drainage that it follows many lines instead of one or two. Its streams are Box Elder Creek, Ogden River, Weber River, Provo River, Hobble Creek, Spanish Fork, and Santaquin Creek, and the list should perhaps include also Payson Creek. Bear River, which runs westward past the north end of the range, cuts through a low, uplifted ridge that may properly be called a continuation of the Wasatch, and a similar statement would apply to Salt Creek at the south. Were the canyons of cross drainage to be filled up, the basins of Box Elder Creek, Ogden River, and Weber River would drain northward to Bear River in Cache Valley, and those of Provo River, Hobble Creek, and Spanish Fork would drain southward through San Pete Valley to Sevier River and Sevier Lake.

The main crest line of the range is in part the summit of a continuous ridge and in part a line through high points separated by canyons, and there are several subordinate crest lines. At points where the eastern face is most definitely shown its base is bordered by small valleys sunk in the general upland. These valleys, which are described in the next section, I find it convenient to speak of as back valleys. As defined by them and by the courses of certain creeks, the range has an average width of 8 or 9 miles, but the width runs from about 2 miles opposite Mantua Valley to 15 or 20 miles in the region of the Lone Peak and Clayton Peak granite bodies.

The uplifting of a mountain ridge tends to create a water parting. If the uplift of the Wasatch ridge had been the only factor in the development of Wasatch drainage no streams would cross the axis of uplift. The cross drainage has been caused by some other factor, and the determination of its mode of origin should contribute to our knowledge of the history of the range. The first writer to consider this subject was Howell, whose observations included the southern part of the range as well as adjacent regions on the east, west, and south. In common with the geologists of the Fortieth Parallel Survey he recognized that the Great Basin had been a dry-land area at a time when Tertiary lakes covered much country on the east and regarded it as a source of material for Tertiary lake beds. The general direction of the local drainage was at that time eastward, and it was afterward reversed. Howell's idea was that the notches in the Wasatch ridge were made before the reversal of the drainage and that these notches controlled the courses of streams when the elevation of the area occupied by the Tertiary lakes turned the drainage toward the Great Basin.[54] It is implied that a ridge existed on the present site of the Wasatch before the great change in relative altitudes of the districts east and west of it. The positions of crossing streams having been thus determined, the present canyons were developed during the uplift of the range.

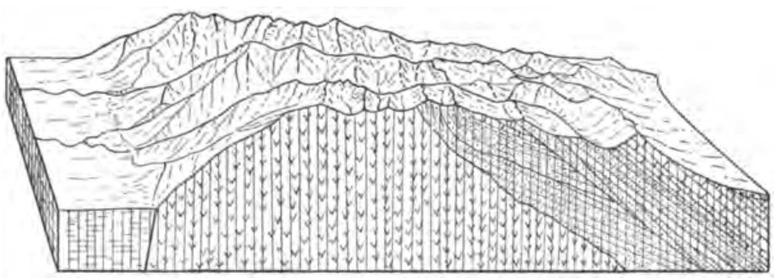


FIGURE 39.—Stereogram of a portion of the central Wasatch Mountains, Utah. The main gorges are Big Cottonwood and Little Cottonwood Canyons. (After Hintze)

Hintze,[55] whose treatment of the subject is comparatively full, made his principal studies in the Cottonwood district, where the range is exceptionally high and broad. It is his idea that as the range block rose its western face was relatively steep and high, that the relative power thus given to westward-flowing mountain streams enabled them to lengthen their courses by headwater erosion, and that the water parting was thereby made to migrate eastward. In the Cottonwood district the divide is now near the eastern edge of the range and its earlier position is indicated by a line of high points on intercanyon ridges farther west. To illustrate these relations Hintze constructed a bird's-eye view, which I reproduce in Figure 39. We now know that the dip of the frontal fault is much less than his diagram indicates, and it may be noted also that the vertical dimensions of the diagram are unduly large in relation to the horizontal, but the truthfulness of the construction as a general expression of the local structure and topography is not vitiated by these minor defects. I see no reason to question his conclusion that the water parting has migrated eastward and that the migration has been determined by the superior vigor of westward-flowing streams. In a tentative way Hintze extends this explanation to other parts of the range, suggesting that Weber and Provo Rivers began their careers as streams of the fault face and, having eaten headward across the range, succeeded in capturing other drainage and thus acquired their present broad development.

A contribution to the same general theory of the development of the river basins by head erosion has been made by Anderson,[56] who points out that one of the principal branches of Weber River has recently been diverted to the Provo drainage basin, ascribes the diversion to headwater erosion by the Provo, and states with confidence that the Weber drainage was fully developed before Provo River pierced the range. Two of the back valleys he ascribes to lateral erosion by the rivers—Rhodes Valley, which was carved out by Weber River while the deepening of its channel was delayed by a strong sill a few miles below, and Heber Valley, which was similarly opened by Provo River in consequence of resistance in its near-by canyon through the range. I shall have occasion to consider these conclusions in discussing the back valleys.

In describing the geology of the belt of country traversed by the Union Pacific Railroad Lee [57] mentions the cross drainage of Weber and Ogden Rivers and briefly considers its cause. He states that the river courses were established in Tertiary time on an aggraded plain and held these courses during the growth of the range. As the rivers sank their channels into terranes of complicated structure beneath the original plain they produced canyons in the stronger rocks and valleys in the weaker. His view is perhaps consistent with Howell's but not with the views of Hintze and Anderson.

The primary question as to which opinions differ is that of the antiquity of the range-crossing watercourses. Were they established before the growth of the range, or were they developed by headwater

[54] Howell, E.E., Report on the geology of portions of Utah, Nevada, Arizona, and New Mexico examined in the years 1872 and 1873: U. S. Geog. and Geol. Surveys W. 100th Mer., vol. 3, pp. 227–301, 1875. (See especially pp. 251–252.)

[55] Hintze, F. F., A contribution to the geology of the Wasatch Mountains, Utah: New York Acad. Sci. Annals, vol. 23, pp. 88–91, 1913.

[56] Anderson, G. E., Stream piracy of the Provo and Weber Rivers, Utah: Am. Jour. Sci., 4th ser., vol. 40, pp. 314–316, 1915.

[57] Lee, W. T., Guidebook of the western United States, Part B, The Overland Route: U. S. Geol. Survey Bull. 612, footnotes to pp. 97 and 102, 1915.

erosion from short courses on the western flank? With reference to the movements that created the range, are they antecedent or subsequent?

Howell notes that two streams cross the range on lines of structural weakness. He says: "Provo River marks the axis of a synclinal, and at Spanish Fork there is probably a fault," but he adds that "this only illustrates the tendency of eroding water to attack the weakest points, and while it serves to explain the selection of these particular lines for crossing, it leaves untouched the question why the streams crossed the range at all instead of escaping eastward over the lower barriers which in that direction limit their basins." It is true also that Box Elder Creek crosses at a point where the structure of the range changes, where the line of the front makes a sudden turn, and where the range is exceptionally narrow and exceptionally low.

On the other hand, I know no reason to infer guidance by structural weakness at the canyons of Weber River and Hobble Creek, and there is no cross drainage opposite Salt Lake City, where a great syncline not only brings weak rocks to the surface but arranges their outcrops in lines athwart the range. On the axis of the syncline the divide is forced far to the east of the main crest line but not farther than in the neighboring Cottonwood district (fig. 39), where the rocks are exceptionally strong.

Ogden Canyon is near a cross fault of pre-Tertiary date, but it is not probable that this occasioned weakness at the time when the range was lifted. Little light is thrown by these facts of position on the origin of the drainage. Because headwater extension is promoted by weak rocks the fact that some of the courses follow faults is favorable to the theory of subsequent drainage, but its influence seems to be offset by the failure of cross drainage to occupy the outcrop of weakest strata near Salt Lake City. Because a rising ridge tends to pond the cross drainage and thereby divert it to low passes, the positions of two courses on sags of the range favor the theory of antecedent drainage. Such other evidence as is available is connected with the phenomena of the back valleys, and the consideration of cross drainage will be resumed after the back valleys have been described.

BACK VALLEYS

HEBER VALLEY

The southernmost of the back valleys, Heber, has no pronounced trend; its main part is 8 or 10 miles across in any direction. Provo River enters it from the north and leaves it toward the southwest, passing quickly into Provo Canyon, by which the river crosses the Wasatch Range. Several creeks that rise in the surrounding hills join the river within the valley. The valley surface is a smooth alluvial plain, evidently built by the streams that traverse it. The stream channels are little below the plain, and the deepest incision is that made by the river near its point of exit. The boundaries of the plain are irregular in outline and in places are indefinite. There is no alinement of hill fronts to suggest faulting. The hill slopes meet the plain in such a way as to suggest that their sculpture is related to a base-level lower than the present and that the alluvial fill is deep in the lower part of the valley. As illustrated by Plate 26, *A*, the aspect is that of a "drowned" valley, except that the invading flood is alluvial instead of aqueous. The surrounding uplands are hilly rather than mountainous except on the side toward the Wasatch Range, and there the valley and mountain are separated by irregular foothills.

Confluent with Heber Valley is a smaller pocket among the hills called Round Valley. A narrow arm of Heber Valley follows down Provo River and is joined by a narrow arm of Round Valley just above the head of Provo Canyon. At the point of junction is a graded plain of local origin (pl. 27, *B*), coordinate with the plains of the two valleys but standing about 75 feet above the flood plain of the river. The condition that determined aggradation in the valley system has ceased to exist, and the erosion of the deposits is in progress. The terrace that is so conspicuous at the junction of the valleys is not traceable downstream. The upper part of Provo Canyon, although carved in the weak rocks of the eastern foothills, is a narrow V gorge, as shown by Plate 27, *A*.

The probable history of Heber and Round Valleys is as follows: A period of rest in the growth of the range permitted Provo Canyon to be cut so deeply and maintained with low grade for so long a time that Heber and Round Valleys were excavated, their sites having been occupied by weak rocks. Renewed or accelerated uplift of the range then raised the local base-level and caused the valleys to be aggraded. Finally, slackening uplift has permitted the river, by deepening its canyon, to lower the sill that is base-level for the valleys, and the filling of alluvium has now begun to be trenched by the river.

Consideration was given to two alternative explanations of the deposition and trenching of alluvium in the valley. The lower part of Provo Canyon contains elevated grade plains that are supposed to be related to temporary base-levels created by Lake Bonneville. None were seen in the upper part of the canyon. As the river bed at the head of the canyon is about 300 feet higher than the Bonneville shore line, it is thought that the Bonneville high water did not appreciably affect gradation in Heber Valley.

When Provo River captured the south branch of Weber River (see p. 56), a body of alluvium was swept down the Provo from Rhodes Valley. This alluvium would tend toward temporary aggradation in Heber Valley but is thought not to have caused the principal changes there—first, because it is inferior in volume to the deposit in Heber Valley and, second, because the time of its movement, as judged from the phenomena in Rhodes Valley, is later than the time of maximum deposition in Heber Valley. Provo River was probably able, after enlargement by the discharge of the captured branch, to transport its enlarged load without noteworthy temporary lodgment in Heber Valley. It is possible, however, that the débris from Rhodes Valley is responsible for the fact that the Provo channel, although well incised just above the head of Provo Canyon, shows little incision in the upper part of Heber Valley.

RHODES VALLEY

The Uinta Range, which trends westward, approaches the Wasatch Range at the point where the Wasatch is widest. Between them lies a belt of trachyte that obscures the structural relations of the ranges. Between the trachyte and the core rocks of the Uinta lies Rhodes Valley—formerly known as Kamas Prairie—which has a length north and south of 11 miles and a width of 2 to 4 miles. The general structure of the Uinta Range is anticlinal, with westerly strike, and the rocks near Rhodes Valley are Paleozoic. The drainage from the western 20 miles of the crest region is caught by Provo River at the south and Weber River at the north, and these streams flow westward, in the general direction of the strike. The Provo crosses the south end of Rhodes Valley on its way to Heber Valley, Provo Canyon, and Utah Lake. The Weber crosses the north end of Rhodes Valley on its way to Morgan Valley, Weber Canyon, and Great Salt Lake. Thus two streams that rise in the Uinta Range cross the same little hill-girt open valley and eventually cut through the Wasatch Range at points 56 miles apart.

The floor of the valley is alluvial and smooth, with gentle slopes toward the north and west. Except for a narrow strip along Provo River it is drained by Weber River, and, as pointed out by Anderson,[58] the floor was evidently shaped in chief part by the south branch of the Weber before that branch was captured by the Provo. Since the capture the Provo has intrenched itself to a depth of about 150 feet and in so doing has exposed a partial section of the floor material, showing that it is river gravel and sand with stratification parallel to the surface. The present plain is not a veneered rock floor but has been built up by alluvial deposition in a preexistent valley. The principal depositing stream was the south fork of the Weber, and its work of deposition was probably continued up to the time of its diversion to the Provo Basin, after which it began to erode what it had before deposited. The moderate width of the excavated trench indicates that the date of the diversion was not remote.

My only visit to the locality was made in 1877, and I gave only casual attention to the drainage system. My notes ascribe the diversion to the upbuilding of the alluvial plain until it reached the level of a col between the Weber and Provo drainage basins. Anderson has since ascribed it, as already mentioned, to headwater erosion by a branch of the early Provo. At the time of my visit only reconnaissance maps were available, but the region has now been more accurately delineated, so that many details of relief are expressed by contours. A study of the contours has led to the suggestion that neither of the two proposed explanations of the diversion is adequate without modification and has indicated the desirability of additional field study.

There is need also of further investigation to determine the origin of the valley. Anderson notes the existence of a strong rock sill over which the Weber runs after leaving the valley and thinks the resistance at that point so delayed vertical corrasion that the river was enabled to carve out the valley by lateral corrasion; but this hypothesis does not account for the excavation of the valley below the surface of its present alluvial plain. As an alternative hypothesis I suggest a fault, with westward throw, along the eastern edge of the valley. The Fortieth Parallel Survey geologic map indicates truncation of structural features by the escarpment on that side of the valley, and the contours of the Coalville topographic map suggest truncation of sculpture.

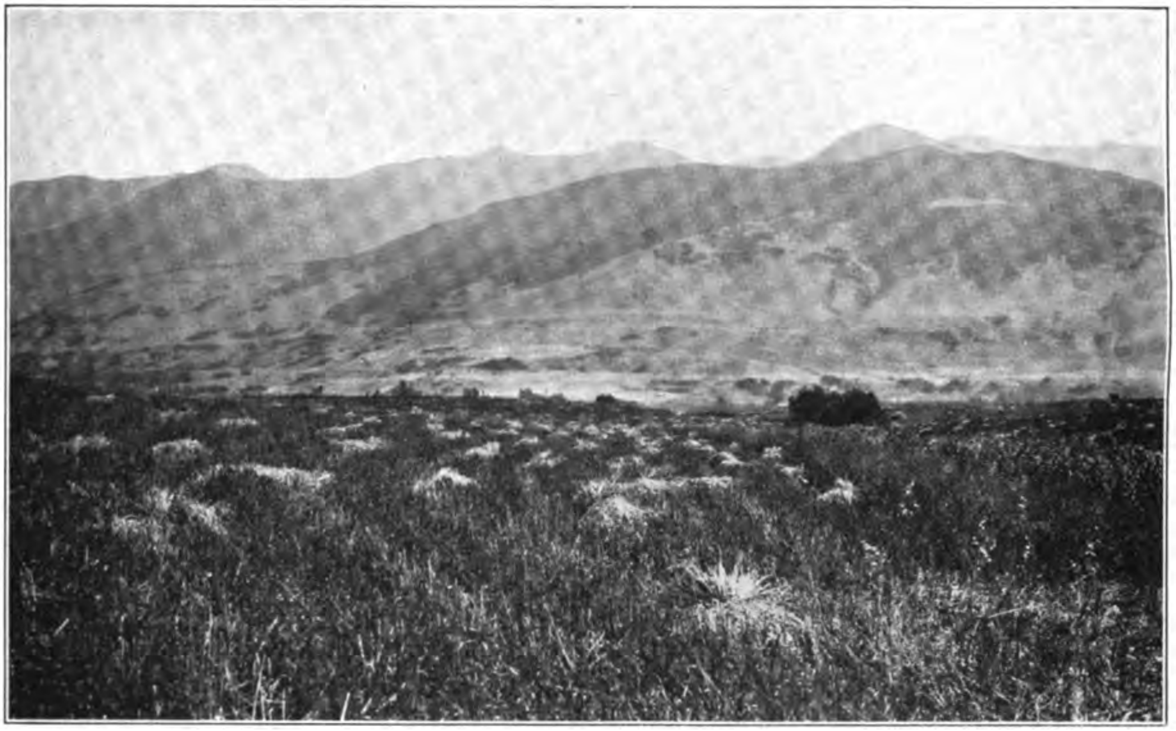
MORGAN VALLEY

From Rhodes Valley to Morgan Valley Weber River runs for 35 miles through an upland of varied rock, and the width of the passage it has opened is everywhere adjusted to the erosibility of the rocks. Close to Morgan Valley there is a small opening, one of the many to receive the title of Round Valley, which well illustrates the adjustment. Above it the river is held in a close canyon by walls of strong Paleozoic limestone. Below it lies a narrow passage across a spur of similar limestone. Between the two is a circular opening in weaker rocks, which are in part arenaceous shales of Carboniferous age and in part Eocene sands.

Morgan Valley, which is much broader than the other openings, is plausibly interpreted by Lee [59] as equally a product of erosion, its width being correlated with the weakness of a local Pliocene formation. It differs from the others, however, in that its recent development by erosion has been but the clearing out of a preexistent structural valley, and there is also the possibility of renewed movement on an old line of dislocation. The Paleozoic rocks about Round Valley are part of a large mass that projects through and rises above the prevalent Eocene terrane, culminating in Morgan Peak, 4,000 feet above Morgan Valley.

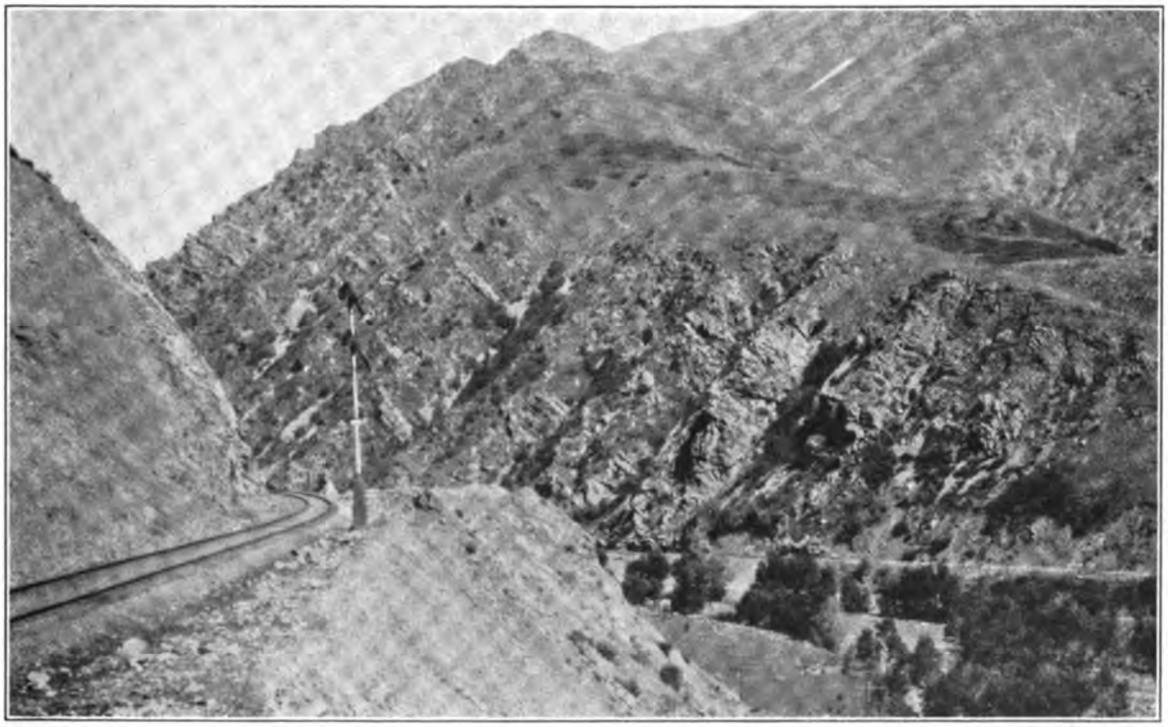
[58] Anderson, G. E., Stream piracy of the Provo and Weber Rivers, Utah: Am. Jour. Sci., 4th ser., vol. 40, pp. 314–316, 1915.

[59] Lee, W. T., Guidebook of the western United States, Part B, The Overland Route: U. S. Geol. Survey Bull. 612, p. 89, 1915.



A. THE RANGE SEEN FROM THE WEST NEAR KAYSVILLE

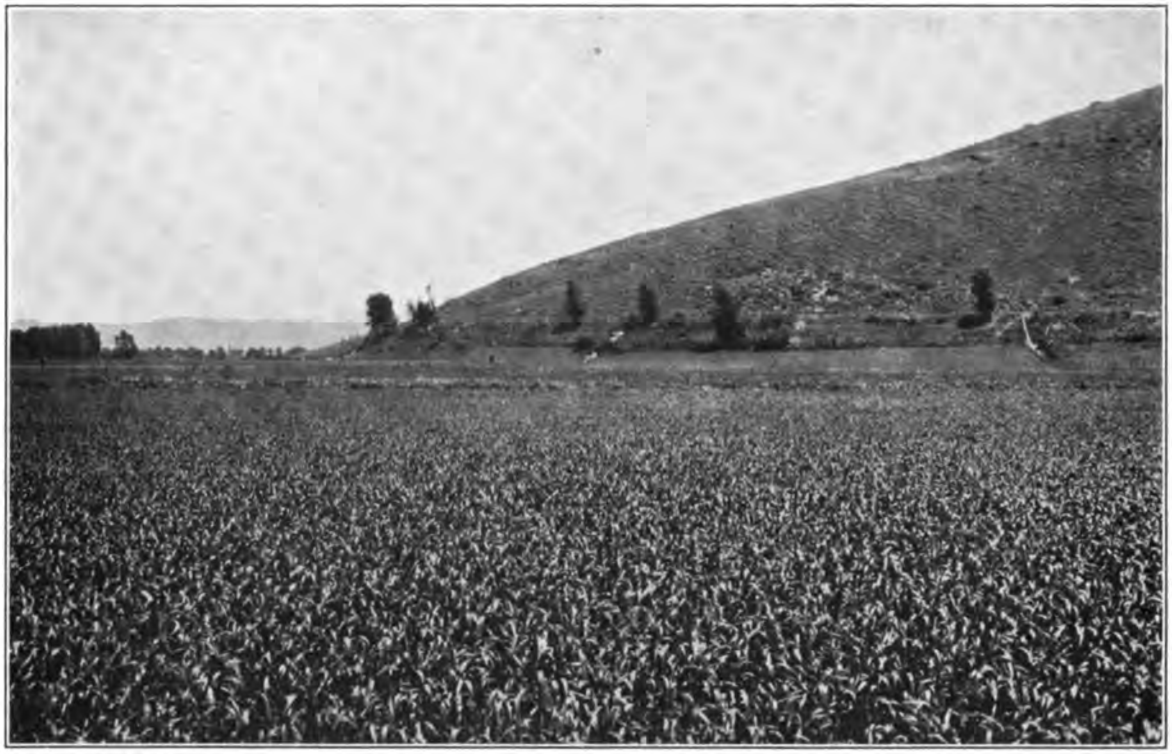
The crests of intercanyon ridges have inherited evenness of profile from an old peneplain, of which fragments are shown in Plate 24, *B*. The truncate ends of the ridges are facets of the frontal escarpment. Across them run horizontal terraces shaped by Lake Bonneville



B. MOUTH OF WEBER CANYON

The walls consist of Archean gneiss. The walls of the smaller canyon at the right are relatively mature in sculpture, and so is the alluvium-capped bench between the canyons. The end of that bench is notched (at the extreme right) by the Bonneville shore line

VIEWS IN WASATCH RANGE, UTAH



A. MARGIN OF HEBER VALLEY, NEAR CHARLESTON

The valley, once deeper, has received a flood of alluvium. The level surface of the alluvium is here contrasted with slopes of the older topography

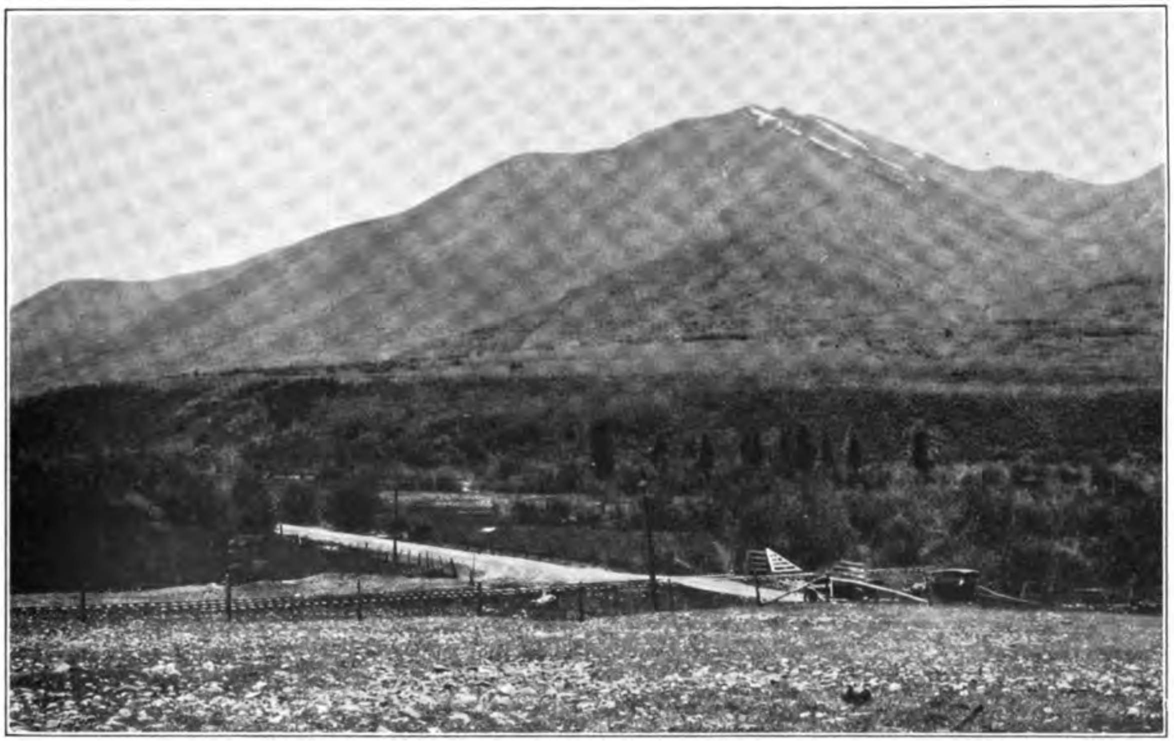
B. SOUTH END OF MORGAN VALLEY

The view is southward from a point near Morgan. The smooth plain has been produced by alluvial deposition in a valley previously deep

BACK VALLEYS OF THE WASATCH RANGE, UTAH

A. THE CANYON NEAR ITS HEAD

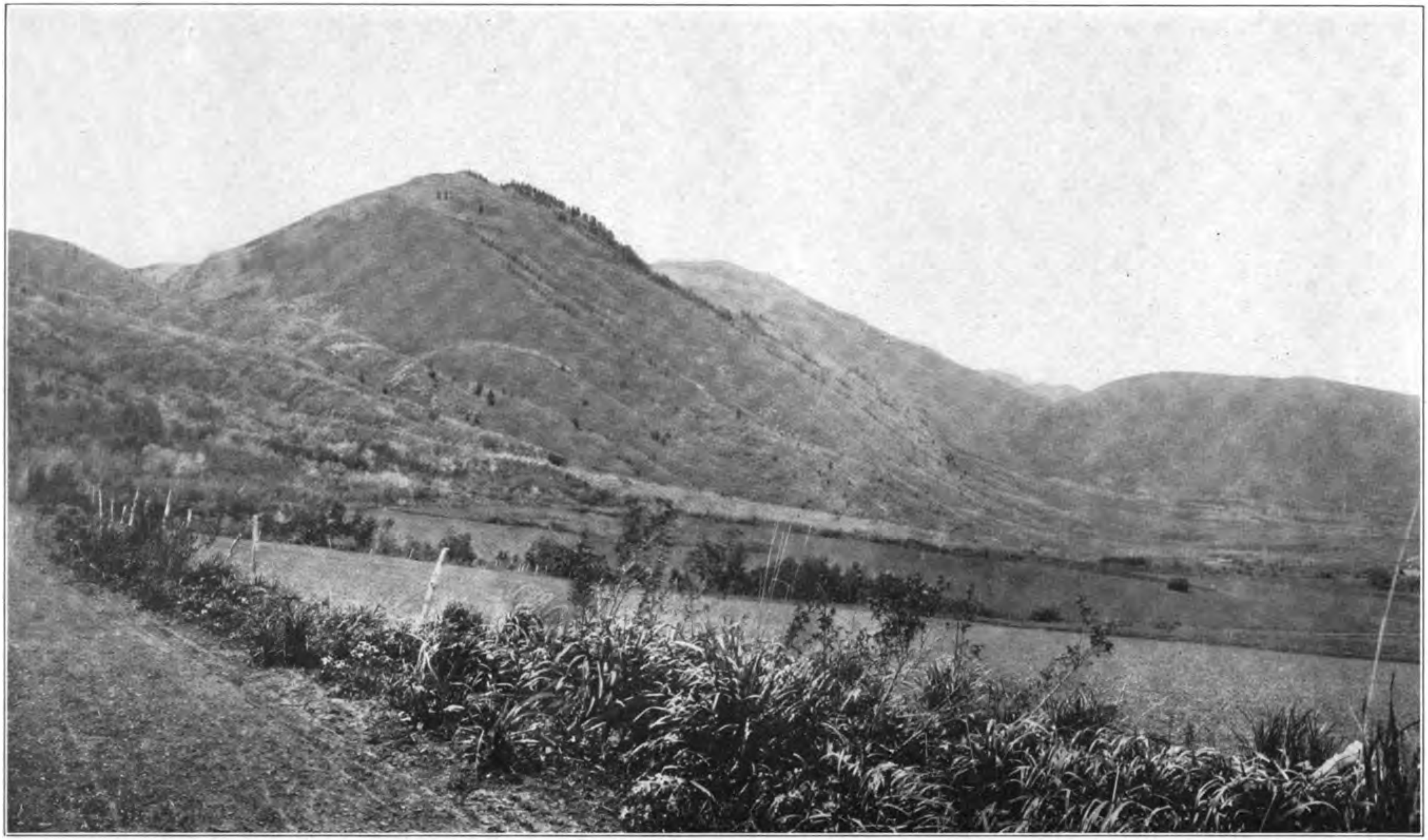
Provo River crosses the Wasatch Range from east to west by this canyon. The view is downstream. In this part the canyon is narrow and without a flood plain



B. AN OPENING ABOVE THE CANYON

The opening is a back valley, communicating with Heber Valley and Circle Valley, and was aggraded at the same time with those valleys. (See pl. 26, *A.*) The aggradation is ascribed to an uplift of the range. The subsequent deepening of the canyon has enabled the river to scour a channel through this part of the deposit

PROVO CANYON, UTAH



EAST FACE OF WASATCH RANGE NEAR EDEN PASS, UTAH

The pass is seen at the left. The lowland is part of Ogden Valley, now drained by Ogden River, which crosses the range farther south. The pass is interpreted as the channel of a stream that once drained part of the Ogden Valley area but was finally decapitated by a branch of Ogden River

This body of older rock appears to belong to an orogenic block distinct from the Wasatch and coordinate with if not continuous with the block that constitutes the Bear River Range east of Cache Valley. The same tentative correlation makes Morgan Valley a structural trough, like Cache Valley, and separates the Morgan block from the Morgan Peak block by a fault. The Pliocene formation is not known to extend beyond Morgan Valley but appears to have been deposited in a lake, or perhaps a bay, bounded by the valley walls.[60] Since deposition it has been broken into blocks, the blocks have been tilted, and the resulting disturbed surface has been graded, but this history, so far as known, has been enacted within the Morgan trough and has not affected its topographic or tectonic unity.

The present Morgan Valley has a flat alluvial floor about 13 miles long and from 2 to 3 miles wide. Its trend is west of north and is not quite parallel to that of the adjacent part of the Wasatch Range, being more westerly. Weber River does not run through the entire length of the floor but enters it a few miles north of the south end.

For several miles along the western side of the plain the steep fronts of the bounding hills, which are composed of Tertiary rocks, form a nearly straight escarpment and have been modified by recent slumping. The scarps made by the slumping fall nearly in line, and it is possible that they constitute a fault scarp, indicating a very recent movement on the plane of the old fault at the edge of the structural trough.

The walls of the valley bear terraces at several levels, and the study of these can not fail to throw light on the valley's later history, but such scattered observations as I have been able to make have opened more questions than they have answered. At about 1,000 feet above the Bonneville plain is a grade plain, now dissected, that truncates the inclined Pliocene strata. It was most clearly seen at the north end of the valley and probably corresponds to the upper of two undissected terraces east of the north end. Less definite high terraces appear farther south on the east side and in Round Valley. The fact that corresponding terraces were not discovered on the west side of the valley suggests the possibility of an extensive late Pliocene deformation or dislocation that involved the adjacent part of the Wasatch Range.

The principal part of the alluvial floor of the valley was laid during the Provo stage of Lake Bonneville. At that time a large delta was built by Weber River against the west face of the Wasatch Range, and the floor of the valley was graded in relation to the delta as a base-level. The material was brought not only by the river but by many of its local tributaries, and a large contribution was furnished by East Canyon Creek, which traverses the south end of the valley beyond the point at which the river enters. (See pl. 26, *B*.) At the earlier and higher stage of the Pleistocene lake the valley contained a bay, the shore lines of which are readily recognized at a number of points. Since the fall of the lake waters from the Provo level the Weber and some of its tributaries have intrenched themselves in the Provo plain, but the amount of erosion has been small. The depth of the incised channels is greatest at the outlet of the valley and diminishes upstream until it ceases to be appreciable at Morgan, where the Weber enters the valley. East Canyon Creek still flows at the level of the plain it built in the Provo epoch.

[60] By the geologists of the Fortieth Parallel Survey the Pliocene beds of Morgan and Cache Valleys were called Humboldt, but this name implies a correlation and classification that have since been questioned. Until the Morgan Valley Pliocene beds shall be restudied it seems best to leave them without a formation name.

PARLEYS PARK

Rhodes Valley, which lies against the end of the Uinta Range, is not so closely related to the Wasatch Range as Morgan and Heber Valleys. Between Rhodes Valley and the Wasatch crest is a smaller opening known as Parleys Park. As this park lies at the base of the range and falls in line with Heber, Morgan, and Ogden Valleys, it is topographically one of the back valleys of the Wasatch, but I am not able to describe it from direct observation. It is the highest of the series, lying 2,200 feet above Heber Valley, 1,300 feet above Rhodes Valley, and 2,800 feet above Morgan Valley, to which its drainage is carried by East Canyon Creek.

OGDEN VALLEY AND EDEN PASS

The valley in which the branches of Ogden River unite before crossing the range has the general form of an acute triangle with one side at the base of the range and the greater width at the south. In several features it resembles Morgan Valley. It contained a bay of Lake Bonneville and retains some of the higher shore traces. Its lower part was aggraded during the Provo epoch of the lake, and the grade plain was continuous with that of a delta built against the west face of the range. Since the Provo epoch the streams have opened narrow, terraced valleys in the alluvium of the plain. Hague[61] has recorded Pliocene lake beds in the valley, and though I have not visited their outcrops I have noted from a distance that they exhibit such dips as to indicate dislocation since their formation and that the dislocated blocks have been truncated by grade plains of more recent construction. On the eastern margin of the valley there is a fault with throw to the southwest, and the northwesterly strike of this fault is not parallel to the local trend of the Wasatch Range, but if projected the fault would meet the range at the north.

[61] Hague, Arnold, and Emmons, S. F., Descriptive geology: U. S. Geol. Expl. 40th Par. Rept., vol. 2, p. 418, 1877.

The fault is indicated by a straight boundary between rock hills on the east (mapped by Blackwelder as "Algonkian?") and the alluvium of the valley. In part the hill face is steep and the alluvium at its base has a gentle slope, but farther north the hill slope is low, differing little from that of the alluvium, which is banked high against it. In the last-mentioned tract the alluvium has slumped toward the valley in great waves, leaving a scarp that is well defined for about 2 miles. These features are best shown a short distance south of Wolf Creek.

The portion of the Wasatch Range opposite Ogden Valley has two members distinguished by their physiographic habit. The western member has rugged summits, with many crags of resistant rock. The eastern member has rounded summits, and its entire sculpture is of a mature or subdued type. At the south, near Ogden Canyon, and again at the extreme north the western member is much the higher and the eastern ranks as a belt of large foothills, the relations being as indicated in Figure 40 and the diagram on Plate 28, *A*. A little north of Ogden Canyon the eastern member climbs high on the western, and it is there evident that the plane which separates the two rock bodies inclines toward the east. Farther

FIGURE 40.—Diagram of two members of Wasatch Range, Utah, opposite Ogden Valley. Compare with diagram on Plate 28, *A*

north, beyond the village of Liberty, a break occurs in the eastern member and the face of the western has a slope of 30° or 35°. In a general way the eastern member corresponds to the Algonkian body described by Blackwelder[62] and the western to the body of Paleozoic rocks over which the Algonkian has been thrust by a reverse fault, the Willard overthrust, but north of Liberty the correlation breaks down. From that point the outcrop of the overthrust surface turns westward and crosses the range obliquely, but the line between the two members distinguished by physiographic characters continues northward, parallel to the main axis of the range. The working hypothesis yielded by the physiographic relations is that a normal fault separates the eastern body from the western, the plane of the fault dipping eastward at about 35° and probably coinciding in part with the plane of the much older overthrust, which is undulatory.

Five miles north of Ogden Canyon the range is deeply grooved by a cross valley, Eden Pass. The summit of the pass is about 800 feet above the eastern base, 1,500 feet above the western, and 2,000 feet below neighboring parts of the range crest.[63] The pioneer trail and the first wagon road from the Salt Lake plain to Ogden Valley followed this route. The summit lies close to the eastern face of the range, as illustrated by Figures 41 and 42, and the pass, as seen from the east (pl. 28, *A*), has the appearance of a hanging valley. The material at the summit (see pl. 28, *B*) is hill wash with smooth slopes, and this occupies a space of about 1,500 feet between rock walls at the north and south. The eastward descent from the summit is steeper than the westward. The branches of the main draining streams are adjusted in direction to the position of the divide, as indicated diagrammatically in Figure 42. All these characters

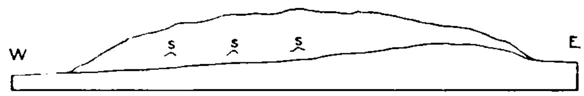


FIGURE 41.—Diagrammatic profiles of Wasatch Range at Eden Pass, Utah. The middle line is the profile in the pass. s, s, Shoulders on side wall of pass

indicate that the pass is an "air gap" which marks the course of a stream that once crossed the range from east to west. The alternative hypothesis—that the pass has been created through headwater erosion by the stream flowing westward from the summit—is negatived by the relative steepness of the westward descent from the pass and by the trends of the subordinate drainage. It is further negatived by the fact that the rocks traversed by the westward-flowing stream are stronger than those traversed by the eastward-flowing stream. Acceptance of the air-gap hypothesis makes it possible to utilize also certain details of sculpture that might otherwise be regarded

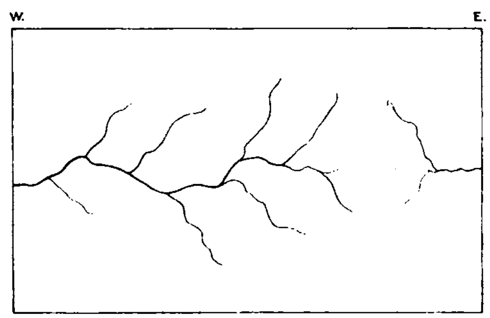


FIGURE 42.—Diagram to illustrate directions of drainage lines at Eden Pass, Utah

as accidental. On the south side of the cross trench and west of the pass there are several shoulders on side spurs (see fig. 41) that suggest an ancient terrace of gentle slope, descending westward from the summit. They are not sufficiently definite to be independently demonstrative, but in connection with an accepted air-gap hypothesis they indicate the direction of slope of the ancient cross channel.

To put the accepted hypothesis in other words: At a stage in the history of the range when the difference in height between the range block and the valley block was 1,000 to 1,500 feet less than now a part of the tract that now drains westward through Ogden

[62] Blackwelder, Eliot, New light on the geology of the Wasatch Mountains, Utah: Geol. Soc. America Bull., vol. 21, pp. 520-526, 533-536, 1910.

[63] Accuracy is not claimed for the figures here given and the dimensions implied by the diagrams. The available maps are crude, and I undertook no measurements.

Canyon was drained in the same direction through Eden Pass, and afterward the Eden Pass drainage was diverted to Ogden River. The diversion presumably occurred by capture, although the capture may have been induced by warping or faulting. Whatever the circumstances of capture, the channel of Ogden River must have been lower than a corresponding part of the channel of the Eden Pass stream; and thus the interpretation of the air gap leads to the conclusion that Ogden Canyon was in existence long before the completion of the uplift of the range.

MANTUA VALLEY AND DRY LAKE TROUGH

The small settlement long known as Copenhagen has been rechristened Mantua, and its post office, once styled Geneva, is now known as Mantua. This name is therefore selected to designate the little back valley that contains it. The valley floor, about 2 miles wide and nearly twice as long, is surrounded by hills that rise rather abruptly. On the west is the Wasatch Range, a definite high wall that extends visibly beyond the valley in both directions. It is flanked by a narrow belt of foothills, which in part have the character of a sloping terrace. On the east stands a bold, undissected, and rather even escarpment, 1,500 feet high, the steep face of a ridge that falls off more gradually on the opposite side. This escarpment is parallel to that of the range, and the two serve to give to the valley an appearance of definite trend a little west of north. In the eastern ridge there are rock croppings that show strike and dip, and it is evident that the rock structure is not parallel to the trend of the ridge. The escarpment truncates the structure and is presumably the fault face of an orogenic block that is tilted eastward. The valley thus resembles Morgan and Ogden Valleys in that its eastern edge coincides with a normal fault so recent that its topographic expression has not been effaced. The fault and fault block are evidently features of the post-Eocene diastrophism, and the discordant dips of strata within the block are assumed to be features of pre-Eocene diastrophism.

The floor of the valley is alluvial and smooth. Streams that reach it from the south and north run near the western edge and unite midway to constitute Box Elder Creek, which immediately enters the canyon by which it crosses the range. The floor is graded in slopes that converge toward the canyon, and a related gradation is indicated by terraces in the canyon. My observations did not suffice to establish a general correlation, but presumably the slopes are adjusted to those of a delta that was built at the mouth of Box Elder Canyon during the Provo stage of Lake Bonneville. The stronger streams of the valley have sunk their channels below the general floor, exposing its constitution of gravel and sand, and the trench of the main or south branch of Box Elder Creek is about 100 feet deep where it turns to enter the canyon. Just beyond the point where rock appears in its banks it is joined by a branch from the north, and between them at the fork stands a little rock hill that does not rise so high as the valley plain. It is inferred from the local details that at some earlier time the canyon was single at its head, then it was flooded by alluvium to the terrace level, and when deposition was followed by erosion the stream courses were superposed on the bedrock of the range in such a way as to isolate a small tract of rock.

Hague [64] mentions Pliocene beds in the valley, local gravel of pale color, but says nothing of their structure. I did not examine them and have only noted that outcrops of suggestive pale color appear at a number of points within 300 feet of the alluvial floor.

On the northwest Mantua Valley is joined by a higher valley which may conveniently be called the Dry Lake trough. On the line along which they meet the trough is 300 to 400 feet higher than Mantua Valley. The upper floor is not so even as the lower and is dissected by its drainage. The escarpment that separates the two valleys is irregular in outline but may nevertheless be due to faulting; the presence of a fault is suggested by copious springs along its base.

For the greater part of the Wasatch Range the only available maps are of reconnaissance grade, but the Dry Lake trough and the northern half of Mantua Valley, which are included in the Logan quadrangle, have been surveyed with the accuracy appropriate to publication on a scale of 1:125,000. Contours from the Logan map are reproduced in Plate 29, to which the reader's attention is directed in connection with the following description.

The Dry Lake trough follows the eastern base of the Wasatch Range for 16 miles northward from Mantua Valley. At the south it is nearly 4 miles wide, at the north less than 2 miles, and its outlines, though they indicate a general trend, are somewhat irregular. On the east it is separated from Cache Valley by a ridge to which the same descriptive terms apply. Although this ridge has a well-marked general trend it is irregular in details of outline and form. As its culminating point bears the name Mount Pisgah, the name Pisgah may conveniently be applied to the entire ridge. At the south the Pisgah Ridge overlaps the ridge east of Mantua Valley; and the two constitute a compound upland that separates the Dry Lake-Mantua compound trough from the Cache Valley trough. The rocks of the ridge are Paleozoic, they are inclined at high angles, and their directions of strike are independent of the general trend of the ridge. A few strikes measured by E. H. Finch [65] are northwesterly and make angles of 30° to 40 ° with the general trend. The ridge evidently owes much of its irregularity to structural features, but its eastern slope is also diversified by erosion, being deeply scored along lines of easterly drainage.

[64] Hague, Arnold, op. cit., p. 418, 1877.

[65] Mr. Finch's data were communicated by letter and at the time of writing are unpublished.

The drainage system of the Dry Lake trough has three divisions. The southern third is drained along two lines southward to Mantua Valley and thence westward across the Wasatch uplift. The northern two-fifths is drained eastward to Cache Valley by a stream that crosses the Pisgah Ridge in Wellsville Canyon. An intermediate division drains to Dry Lake, which has no outlet. The southern boundary of the Dry Lake Basin is a low rock ridge; the northern boundary an alluvial fan from the Wasatch.

The Pisgah Ridge, which is cleft to its base by Wellsville Canyon, is also cleft within a few hundred feet of the floor of Dry Lake trough by three other canyons. The Wasatch Range, which is cleft to its base by Box Elder Canyon, is deeply cleft also at two other points, one 2 miles north of Box Elder Canyon, the other so related to the canyon as to partly merge with it.

The floor of the trough is diversified by a system of small ridges, all of which make wide angles with the general trend of the trough. The trough trends about N. 20° W., the ridges about N. 40° E. A conspicuous character of the ridges is that the Paleozoic strata which compose them do not strike with their trend. In some ridges the dominant strike is at right angles to the trend. Because of this peculiarity of structure, and as a result of weathering, some ridges and parts of ridges are cross-ribbed, and the crests of all the ridges show a series of humps.

The Wasatch face that overlooks the trough is composed, either wholly or in chief part, of Paleozoic strata, and it is evident to distant inspection that their structure, instead of determining the trend of the face, is truncated by the face. So both side walls of the trough, as well as its floor, have forms that are independent of that element of structure which is represented by the strike of inclined sedimentary rocks. The trough is not a strike valley, developed by erosion along the outcrop of a weak formation. Its situation as a sort of shelf on the slope from the range crest to Cache Valley precludes the suggestion that it originated as a stream valley. The only alternative hypothesis worthy of consideration is that it is a graben and that its floor has gone down between fault-determined walls at so recent a date that the disturbed drainage has not yet been fully readjusted. If there shall be no further tectonic changes the closed basin of Dry Lake will eventually be filled by waste from the range and its waters will find outlet to the north or east.

The cross ridges of the trough floor may be the crests of interstream ridges produced by erosion before the faulting that created the eastern wall, but their parallelism and their close order suggest rather that they are edges of minor tectonic blocks that were dislocated with reference to one another at the same time that collectively they were dislocated with reference to the range and the Pisgah Ridge.

The interpretation that correlates the floor of the Dry Lake trough with the rock floor of Mantua Valley and ascribes their present difference in height to a fault serves to explain a feature of the Mantua Valley that was not mentioned in the general description. The smooth alluvial blanket by which the rock floor of the valley is concealed is interrupted at two points by short rock ridges, which run parallel to the ridges of the Dry Lake trough and have the same peculiar topographic habit. They are on opposite sides of the valley and appear on the map (pl. 29) close to its lower edge. It is easy to surmise that when their rocks shall be examined the strikes will be found to diverge widely from the trends of the ridges.

The deep clefts in the Pisgah Ridge are all of one type. They may be described as canyons leading from Cache Valley up to low saddles that are close to the west face of the ridge. In each cleft the contours represent the descent from the saddle as steeper on the eastern side than on the western. So unless the difference in slope is determined by rock texture, the indication is that the divides are migrating westward and the canyons are lengthening at the head. This condition favors the view that the clefts have been developed by headwater erosion. It is not, however, necessarily inconsistent with the view that the erosion of the canyons was begun before the dislocation of the ridge and graben and that the development of the clefts kept pace with the rising, or rising and tilting, of the ridge.

The deep clefts of the ridge west of the Dry Lake trough open similar questions of interpretation, and these can not be fully answered without local examinations, which have not been made, but approximate answers are indicated by the contours of the map. In the cleft 2 miles north of Box Elder Canyon (see fig. 43) the saddle lies a little east of the crest line of the range, and the passage at the saddle is wide. Eastward from the saddle the passage is also wide and the descent is gradual; westward the descent is accomplished by a steep, narrow canyon. The steeper descent, as well as the narrower way, indicates more rapid corrasion, and it is probable that the canyon of the western slope is being lengthened by headward erosion, that the divide is migrating eastward, and that a continuance of the process will move the divide beyond the eastern base of the range and thus establish a new line of cross drainage. But it is not to be assumed that headward erosion has developed the entire cleft. The broad passage from the summit eastward requires a different explanation. Two explanations may be suggested—first, that the passage is an air gap, a disused valley of cross drainage; second, that it was occupied by a local body of weak rock that has been washed out.

The other streamless cleft in the ridge west of the Dry Lake trough does not cross the entire ridge but runs obliquely from Mantua Valley to the cross canyon of Box Elder Creek. This cleft is narrow throughout. On the north wall of the canyon it appears as a hanging valley 500 feet above the base, and the saddle within the cleft is not far back from the canyon wall. The hypothesis that the cleft is determined by a zone of weakness is not tenable here, because the presence of the zone is not indicated by the contours of the canyon wall. It seems clear that the cleft existed before the development of the canyon and was truncated by that development; and the probable history involves the hypothesis that the cleft was eroded by a branch of Box Elder Creek when the main creek ran at the same level. Afterward the headwaters of the north branch were captured by the south branch, and then, with the growth of the range, the south branch and trunk stream deepened the canyon, and the notch in the mountain carved by the north branch was left as an air gap.

As the clefts are but 2 miles apart and have similar relations to Mantua Valley, it is probable that their general histories are similar. So the exclusion at one locality of the hypothesis of headward erosion along a zone of weak rock practically negatives that hypothesis for the other locality and leads to the acceptance of the air-gap explanation for both.

DISCUSSION OF BACK VALLEYS

The evidence that the eastern margins of Mantua Valley and the Dry Lake trough are determined by faults is strong; evidence of similar tenor as to the eastern margin of Ogden Valley is perhaps less cogent, and evidence as to Morgan Valley is relatively weak. In view of the fact that the three valleys are similarly related to the Wasatch Range it seems proper to consider the data collectively instead of in three independent parcels, and the mutual support that comes with collective consideration makes a strong case for determination by faults. With recognition of the lines of dislocation comes the recognition of an additional character of similarity—each of the three lines is oblique to the Wasatch axis, trending more to the west than the adjacent part of the range.

The westward canting of old grade plains on the Wasatch Range opposite Morgan Valley suggests, by indicating rotation of the range block, that the eastern face was determined by a fault, but the suggestion has not yet been tested by a study of structure on the eastern slope. Opposite Ogden Valley the physiographic evidence of a fault between the main range and the eastern foothill belt appeals strongly to the eye. It is possibly supplemented by the observation of an extensive shear zone on the plane of the inferred normal fault, but at the point of observation, near Eden Pass, the plane of that fault either coincides with or approaches closely the plane of the Willard overthrust, so that the crushing of rock might be referred, with perhaps equal propriety, to the more ancient dislocation. The floor of the Dry Lake trench is a feature so distinct in attitude and type from the adjacent lofty range face as to suggest separation by dislocation. Despite the knobs by which its surface is diversified, that part of the floor south of Dry Lake is essentially horizontal in its east-west profile, and north of the lake the rock floor is concealed by a great bank of alluvium that has been washed from the steep face of the range. Once more it appears proper to consider data for the three valleys collectively instead of separately, and if taken all together the evidence of dislocation on the west side is strong.

It is probable, therefore, that the range is bordered on the east, for at least 40 miles, by a series of grabens—that the depressions just east of the range, instead of representing the lower edge of a broad range block tilted eastward, really represent local subsidence between faults.

It is worthy of remark that the structural classification, which coordinates Morgan and Ogden Valleys with the Mantua-Dry Lake depression, is not the classification of the geographer. The Pisgah Ridge is so small and lies so near the main Wasatch crest that it has properly been regarded as a subsidiary feature of the Wasatch Range. The upland east of Ogden Valley is both high and broad; and its front, although much broken by dissecting streams, falls in line with the fronts of Morgan Peak at the south and the Bear River Range at the north. Parallel to the line of fronts, and overlooked by them, lie Morgan, Ogden, and Cache Valleys, also in line and separated by hilly tracts of moderate height, and these mark the eastern boundary, albeit indefinite, of the northern part of the Wasatch upland. The upland east of the valleys has not yet been satisfactorily named, and the settlement of its nomenclature, now confused, may perhaps await the completion of adequate maps. In a vague way it has been called the Bear River Plateau; its western part has been included under the title Wasatch Mountains; a crested portion opposite Cache Valley has been named the Bear River Range, and the same title has been applied also to the Morgan Peak mass.

Pliocene lake beds have been found in Morgan, Ogden, and Mantua Valleys as well as in Cache Valley, but not in the Dry Lake trough. As the beds show many outcrops at low levels but are not known to occur high on the valley sides, it is inferred that the valleys were already in existence in that lacustrine epoch. Because the beds show strong dips, with other evidences of dislocation, in at least two of the valleys, it is inferred not only that the sunken tract has suffered diastrophic change since the lake epoch but also that the rock floors of the valleys are composed, like that of the Dry Lake trough, of groups of minor blocks instead of single large blocks.

The same three back valleys received bays of Lake Bonneville and were aggraded to the condition of smooth plains during the Provo stage of that lake. Subsequent trenching of the Provo plains has not uncovered the base of the alluvial deposits. Slopes of bordering uplands that appear to be erosional meet the aggraded plains in such way as to indicate that the base-level to which they were adjusted lay not only below the present stream channels but below the rock sills across which the valleys drain westward; and this inference is sustained in Ogden Valley by borings that penetrate below the level of the rock sill without reaching the base of the alluvial fill. It is inferred that at some late epoch in the history of the valleys the erosion of their floors was checked and aggradation was determined by a diastrophic change that increased the amount of displacement between the range and the valleys.

This particular differential movement occurred in pre-Bonneville time, and it was subsequent to the principal disturbance and principal erosion of the Pliocene lake beds. It may be assumed to have been but one of many movements involved in the growth of the range and the subsidence of the back-valley grabens. An earlier movement of similar character may have determined the capture of the Eden Pass stream by Ogden River.

There is a certain analogy of position between the back-valley grabens and the little grabens of earth in the zone of the piedmont scarps; and this analogy suggests that the back-valley grabens may be subsidiary features of a fault by which the Wasatch Range rose in relation to the crust blocks east of it—that the movements connected with the formation of the eastern Wasatch fault tended toward the creation of a crevasse, and that the potential crevasse was filled by the subsidence of wedging crust fragments.

Parleys Park lies at the eastern base of the range at a place where the range is exceptionally broad. Investigation may perhaps find it to be a site of local subsidence. The deep alluvial deposit in Rhodes Valley tells of a preexistent hollow, and local subsidence is a possible cause of the hollow. A southward extension of the disturbed belt that includes the recognized back-valley grabens is thus suggested.

Heber Valley, although outside the influence of the Bonneville changes of base-level, has a broad alluvial floor, the result of aggradation in a preexistent hollow. The sill of the outflowing stream appears to have been raised by an upward movement of the range that was not shared by the crust block beneath the valley. To that extent its history resembles the history of the northern back valleys.

THE WASATCH A HORST

The study of the back valleys has served to modify considerably my conception of the dislocations involved in the production of the Wasatch Range. The eastern fault and associated grabens evidently belong to the later or post-Eocene period of diastrophism and are companions in origin with the western or frontal fault. The range, instead of being the higher edge of a tilted fault block, is essentially a horst. The western fault has much the greater throw, and it is probable also that the two faults, although both normal, differ notably in type. Fragments broken from the descending block on the west side have lodged on the slope of the horst, where they constitute spurs of the range. Fragments broken from the descending block on the east side have dropped below the level of the block, as if slipping into a crevasse. These characters are doubtless significant of the nature and directions of subterranean forces, and they constitute data for the use of the future student of the dynamics of the Great Basin corrugation.

In this connection it is to be noted that the Wasatch Range is on the common border of two tectonic units or provinces whose areas are large as compared to those of individual mountain ranges. The eastern province once stood lower than the western, so as to receive waste from it, and these relations were afterward reversed. In a general way the period during which the eastern province was lifted corresponds to the period of range creation, although exact correlation can not, from present knowledge, be asserted. So the uplift of the Wasatch, occurring at the edge of the rising broad province, may owe to that fact the peculiar asymmetry of its development.

THE THROUGH CANYONS

Four of the canyons of cross drainage have received critical attention, and as these have common characters they may be assumed to be representative. Their walls are steep and consist in considerable part of cliffs. They are narrow at the bottom; in places the stream channels occupy the entire space, but elsewhere they are bordered by strips of flood plain. Bedrock is not visible in the channels; the streams flow over beds of boulders. The side slopes indicate that the deposit of boulders is not deep. Outside each canyon mouth is a large body of gravel and sand accumulated as a delta in Lake Bonneville during the Provo epoch, and through this material the modern stream has opened a valley. Scattered alluvial terraces within the canyon show that during the making of the delta it was filled with similar material up to a grade plane conformable with that of the delta. Each canyon holds its characters to the mouth. There is no flaring, but the stream passes abruptly from its narrow strait between rock walls to its wide terraced valley through the delta. As shown in Plate 8, *B*, the canyon is sharply truncated by the plane of the frontal fault.

Ogden Canyon is exceptional in that it contains a flood plain of some width, a plain that affords space for a group of summer cottages, and for this special feature there is a special explanation. Some of the gravel that occupied the canyon during the Provo epoch was cemented by a calcareous deposit from thermal springs, and the resulting conglomerate has resisted erosion and retarded the river in its work of clearing out the accumulation of detritus.

There is an exception also to the rule that the canyon streams flow over boulder beds instead of solid rock, and the exceptional locality has special features that serve to explain the anomaly. Brief mention of these features has been made by Lee,[66] but a fuller account is warranted by the value of the locality as an object lesson in superimposed drainage. Midway in its canyon Weber River is joined by a mountain creek coming from the south, and that stream delivers a large load of coarse débris. While Lake Bonneville stood at its highest level the canyon was occupied by a strait, and into this strait the creek dumped its débris, building a steep conical delta that projected as a cape and approached the opposite shore. Afterward, when the water fell to the Provo level and the strait was replaced by a narrow river valley with gravelly flood plain, the creek cut away most of its earlier delta but shaped another at a lower level, and the new delta was extended so far as to crowd the river against the north side of its valley. The river attacked the valley wall and carved a notch in it, so that later, when the lake fell and the river began its final work of erosion, the river rested at this one point on a shelf of rock. So soon as it had corraded a channel in the rock shelf its course became fixed, and the old course was never resumed. On this bit of new course the river has cut a narrow gorge. From other parts of the canyon the greater part of the deposit of the Provo stage has been washed away, but here a large body of it remains, and opposite thé body of gravel is the narrow defile—the Devil's Gate—in which both walls and bed are of solid gneiss. The Union Pacific Railroad follows the line of the old channel, and its grade makes a deep cut through the gravel deposit.

The mouths of three of the canyons are crossed by piedmont scarps which demonstrate fault movements since the Lake Bonneville epoch. The steep and rugged canyon walls (see pl. 25, *B*) testify to recent active corrasion of the beds and support the view that the block is rising and is being sawed into sections by the streams as it rises. Nevertheless the streams are now separated from the rock of the canyon beds by layers of boulders. This incongruity is probably a result of the Bonneville episode. Time is needed for the removal of the Bonneville detrital deposits, and that work is still unfinished.

DISCUSSION OF CROSS DRAINAGE

Eden Pass and the air gaps at and near Box Elder Canyon testify to the former existence of streams crossing the Wasatch Range where now the waters are parted by the range. Those streams were decapitated by Ogden River and Box Elder Creek, which therefore must have been their contemporaries. Thus lines of drainage are shown to have crossed the northern part of the range at a time when the range was less developed than now. As indicated by the present heights of the passes, the subsequent uplift of the range in their vicinity has been 800 to 1,200 feet. In this way the history of cross drainage is carried back through a fraction, probably a minor fraction, of the life of the range.

The air gap associated with Box Elder Canyon shows a bifurcation of cross drainage that is peculiarly significant. In Figure 43 the shaded area represents the bedrock of the range, separating the alluvium of Mantua Valley at the east from the alluvium of the Salt Lake plain at the west. Box Elder Creek, which runs from B to E, crosses the range in a canyon, the bed of which is about 1,800 feet below peaks on either side. At D it is joined by a minor branch, FD, and in the fork is a small triangle of rock. As explained on page 59, the Y-form plan of the drainage was superimposed during the Lake Bonneville epoch by an alluvial fill that spread over Mantua Valley and extended through the canyon. The gravel of that fill

FIGURE 43.—Plan of drainage across Wasatch Range, Utah, at and near Box Elder Canyon

still rests on and against the triangle of rock in the fork. With future lifting of the range and deepening of the canyon and the upstream channels, the basin of the stronger branch will grow larger at the expense of the weaker, and when the smaller branch is at last decapitated its course in the rock will be stranded as an air gap.

The air gap that exists at the present time has the position indicated at A. The summit within the gap is 800 feet above the canyon bed. The approximate course of the stream that once flowed through it is represented in the figure by a broken line. That stream joined the Box Elder Creek of its time at some point, C, in the heart of the range and west of the axis. The Y-form plan of the ancient drainage may have originated, like the smaller Y of the modern drainage, by superimposition, but it is also possible that the streams of the Y had acquired their courses before the uplift of the range and were strictly antecedent. The triangular tract of rock embraced by the arms of the ancient Y is much wider than that of the modern Y, and its crest presumably rode higher above the stream beds. Much of its volume has been eaten away in the development of the modern canyon, and

[66] Lee, W. T., Guidebook of the western United States, Part B, The Overland Route: U. S. Geol. Survey Bull. 612, p. 91, 1915.

the crest of the remnant stands now only about 100 feet above the saddle at A, but when the main branch of the creek ran at the same level with the A branch, the intervening crest line was probably 500 feet above either channel. The hypothesis of superimposition thus seems to imply a deep burial of the range after the growth of the range had begun, and it thereby encounters difficulties that are escaped by the hypothesis of antecedence. More probably the branching cross drainage was established before the uplift of the range.

Unfortunately this air gap was not discovered during my field examination, so that inferences from it depend wholly on the form features expressed by the contours on the map, but the evidence as it stands points decidedly toward antecedence as the explanation of the cross drainage.

If the tract drained by streams crossing the range acquired its present drainage system through retrogressive development by streams that began on the western face of the range, then during the early history of the range the tract was drained in other directions. And if the tendency to form grabens along the east base of the range was early manifested, the sag valleys would be likely to assemble the water falling on the adjacent face of the range and guide it northward and southward to the ends of the range. Such a drainage system, if once established, would not be easily broken up. This suggestion is not regarded as of special importance, for the reason that the graben development most clearly determined is associated with the later history of the range. It is worthy of note, however, that the dislocations which produce grabens have not diverted either Weber River or Ogden River. Both streams rise far east of the graben belt and cross the tectonic sags as independently as they cross the tectonic ridge.

Whenever the problem of Wasatch cross drainage shall be comprehensively investigated its study will necessarily include a study of the drainage problems of the western part of the Uinta Range. The fact that the upper Weber and upper Provo, which rise near the summit of the broad Uinta anticline, flow for many miles with the strike instead of the dip requires explanation, and the explanation, when attained, will contribute to an understanding of the history of the two ranges in the region of their near approach.

The history of the Wasatch drainage interlocks also with the history of the Pliocene lakes. Despite the dislocations that the lake beds have suffered, they are still confined to rather low parts of the three lowest back valleys, and their general relations are identical with those of the Pliocene lake beds in Cache Valley. The present passes from valley to valley are so high that the valley lakes can not be supposed to have been directly connected as a chain, but their association is readily explained on the assumption that preexistent canyons through the Wasatch joined their waters to those of a lake west of the range. It is true that the vestiges of the western lake have not been identified along the west front of the range in the vicinity of the through canyons, but they were noted farther north by Hague,[67] and their southward extension may fairly be assumed. The belt of country in which they should exist was occupied by Lake Bonneville, whose sediments bury the sediments of earlier lakes and whose littoral records make difficult the recognition of earlier littoral records. If the Pliocene lake waters were connected across the range the cross canyons antedate them, and some of the main lines of cross drainage must have been established before that lake epoch.

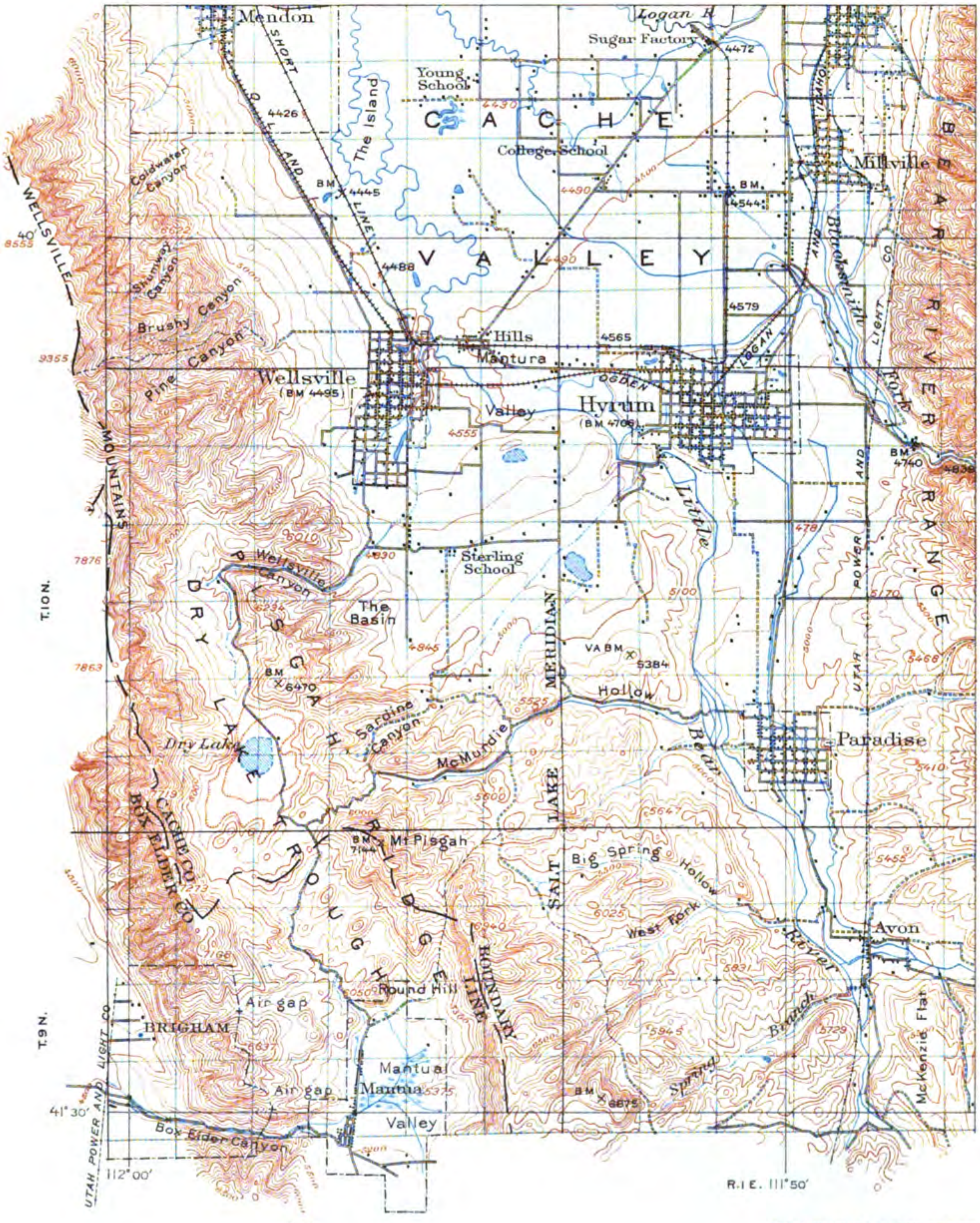
At some time between the deposition periods of the Eocene conglomerates and the Pliocene lake beds the uplift of a broad region east of the Wasatch changed the general direction of descent in the Wasatch district from eastward to westward. Between the same time limits began the uprising of the Wasatch Range. With the data now available the sequence of these events is not evident. Probably neither of the changes was of simple character, and through their diverse factors the local drainage may have been rearranged more than once. It may never be possible to determine whether the present cross drainage antedates the entire life of the range or was consequent on some stage of its growth—such a question is perhaps academic—but with reference to the Pliocene and later growth of the range there need be little doubt that the cross drainage is mainly antecedent.

FAULTS WITHIN THE RANGE

Periods of diastrophism are usually distinguished by means of unconformities, but in considering the disturbances of the Wasatch region I find it more convenient to use the frontal fault of the range as a basis of classification. So far as we know, the growth of the range has been coincident with the development of the frontal fault. The frontal fault transects folds and faults older than itself. The diastrophism that produced those folds and faults will here be spoken of as the earlier and the diastrophism contemporaneous with the frontal fault as the later.

The normal fault that borders the range, for at least a part of its length, on the east may be referred with confidence to the later period, and so may the associated grabens. The grabens are not simple blocks but composites. On the west side of the range are the fault-block spurs and also the fault-block ridges near Santaquin, both indicating that the crust block that went down on that side did not go down as a simple unit. Thus the crustal members that fell away from the two sides of the Wasatch horst were each more or less broken as they descended; and it is of interest to inquire whether the horst itself was broken at the same time. As the horst contains the

[67] Hague, Arnold, and Emmons, S. F., Descriptive geology: U. S. Geol. Expl. 40th Par. Rept., vol. 2, p. 406, 1877.



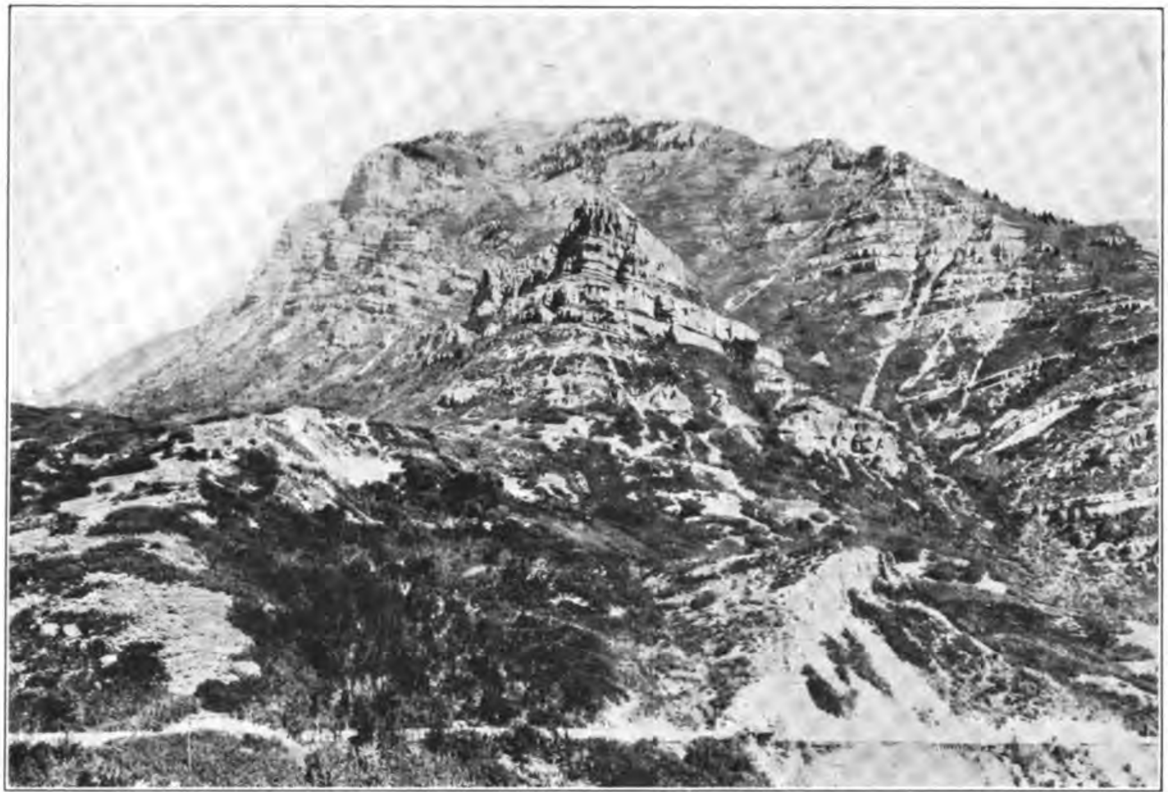
MAP OF DRY LAKE TROUGH AND PART OF MANTUA VALLEY, UTAH

Scale $\frac{1}{125000}$

1 ½ 0 1 2 3 4 5 Miles

Contour interval 100 feet.

Datum is mean sea level.



A. NORTH WALL OF PROVO CANYON

North of the canyon is the Timpanogos ridge, trending northward. Part of its western face, a fault scarp, appears in the view at the left of the central crag. The ravine at the right of the crag follows the line of a minor fault. The strata are Paleozoic and chiefly limestones

B. VIEW EASTWARD IN EDEN PASS

At the left is Cambrian quartzite. Beyond Ogden Valley is the Bear River Range

VIEWS IN WASATCH RANGE, UTAH

ancient structural features that have been truncated by the western and eastern faults, it is evident that the inquiry involves the discrimination of products of the later from products of the earlier diastrophism.

An evident criterion for discrimination pertains to form. Just as marginal faults of the later period are expressed in the present topography, so may be interior faults of the same period; but the initial topographic expression of the older faults has been lost, and such expression as they now have has been wrought by erosion and depends wholly on the distribution they gave to strong and weak rocks.

A second criterion involving form is connected with grade plains and may conveniently be stated in terms of the features observed in the Farmington region. The Farmington grade plain, which was carved in a period of rest that preceded the formation of the frontal fault, transects the structural features of the earlier diastrophism. Whatever dislocation or deformation it exhibits—for example, its tilting—is referable to the later diastrophism.

A third criterion pertains to deformation and depth. One of the conditions that determines folding, instead of fracture, as a result of strain is superincumbent load. Because this is not the sole condition its application is somewhat indefinite, but it is true in a general way that folds are not made in strong rocks near the surface. Because denudation occurred between the two periods of diastrophism it is evident that the rocks now visible at the surface were in general more deeply buried and more heavily loaded during the earlier diastrophism than during the later, and the folds of strong rocks are therefore as a rule to be referred to the earlier period.

A fourth criterion is connected with cementation. Those parts of the earlier shear zones that are now visible have become visible through denudation, and before they were exhumed they were in general in the zone of cementation and there acquired continuity and strength. Some of the shear zones of the later diastrophism have probably escaped cementation—in their visible parts—and are for that reason easily eroded. Therefore faults of the later period are more likely than faults of the earlier period to receive through erosion the topographic expression of weak formations.

In a description of the Timpanogos and Provo divisions of the range Emmons [68] says:

It will be seen by reference to the map that the general shape of the western slope of the ridge is that of a pair of steps, the first rise being of about 3,000 feet to an outlying shoulder, from which the main ridge rises, about 2 miles farther back, in a steep, almost perpendicular wall. Here again, as so frequently in the Rocky Mountain region, the physical structure gives the clue to the geological. Timpanogos Peak is formed of horizontally bedded limestones having at the most an inclination of 3° east and 1° or 2° to the south. * * * The topography suggests that the line of junction of this lower shoulder with the face of the upper wall is that of a line of fault, and this idea is confirmed, as will be seen later, by the finding of faultings in the canyons of the Provo and American Fork, at either end of the ridge, in corresponding position.

In the ridge of Provo Peaks the continuance of this line of fault is shown also in the topography, as well as rendered necessary by the thickness of the strata observed.

Plate 21, *A*, shows the lower and upper escarpments of Mount Timpanogos, with suggestion of the shoulder between them; and an oblique view of the upper escarpment appears in Plate 30. The faulting is here connected with the later period by the fact that the dislocation between the shoulder and the high crest still finds direct expression in the topography. Plate 30 shows also that the upper block is itself divided into two parts, the strata of which dip toward their common boundary, and that the boundary is a groove or ravine which runs parallel to the upper escarpment and is traceable upward to the sky line. The fault thus indicated has not been investigated, and the direction of its throw is unknown, but the topography indicates that its outcrop has proved a line of weakness to which the local drainage is adjusted and thus suggests an uncemented shear zone of the later diastrophism. Just outside the field of view, at the right, is a second ravine which separates blocks that do not agree in the direction of dips. Thus the section of the range shown in the north wall of Provo Canyon includes at least three internal faults that were probably made during the uplift of the range. All dip more steeply than the frontal fault. One is known to involve a downthrow, on the west side, of several thousand feet.

The last-mentioned fault, the one described by Emmons, is at least 20 miles long and is parallel to the frontal fault. Its throw is probably greatest near Provo Canyon but diminishes slowly northward and more rapidly southward. The two blocks separated by it are shown in longitudinal profile in Figure 44, which is not a perspective view but a right projection, plotted from data of maps and photographs. The lower and nearer block, gashed at a few points by cross drainage, is otherwise so little eroded that its topographic profile indicates clearly the original form

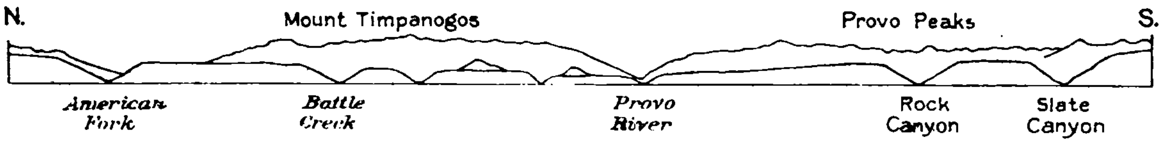


FIGURE 44.—Profile elevation of a portion of the Wasatch Range near Utah Lake, showing the main crest and a shoulder or terrace of the western face

[68] Hague, Arnold, and Emmons, S. F., op. cit., p. 345.

of the block. The higher block, wasted from the opposite side as well as from the nearer, has lost its original form and acquired an acute, serrate crest. The general dips in both are eastward and gentle, but to this rule there are notable exceptions. The lower block contains north of American Fork Canyon the steep dips shown in Plate 21, *B*, and includes in the neighborhood of Rock and Slate Canyons the anticline illustrated by Figures 4 and 5. Those deformations clearly belong to the earlier diastrophism, for they have no expression in the profile and are truncated by the frontal fault.

Between Battle and Provo Canyons are two large, steep-sided hills that seem, as seen from Utah Valley, to stand on the shoulder or terrace of the lower fault block. Their position, which is imperfectly shown in Plate 20, *B*, is well back from the front of the terrace and near the escarpment of the higher fault block. They are composed of strata that dip at a high angle to the north and are thereby contrasted with neighboring parts of the two greater blocks of the range, where only gentle dips are shown. They are tentatively explained as corners of two minor blocks, separated by faults from the greater blocks and rotated northward—or, perhaps more properly, as huge horses held in the fault zone between the greater blocks. If the suggested explanation is correct, their dislocation is a product of the later diastrophism. It is surmised that the curved ridges seen in the foreground of Plate 30 are in some way related to them.

The fault scarp above the terrace, best shown in Plate 30, differs notably from the scarp below the terrace, shown in Plates 19, *B*, 20, *A*, and 21. It has no smooth facets but is a rugged cliff buried at the base by talus. As the slope of the terrace corresponds in angle to the dip of the frontal fault, whereas the cliff is steeper, it is evident that the fault which produced the cliff has a dip steeper than the angle of rest. This steepness permits gravitational wasting and probably suffices to explain the ruggedness of the cliff.

The evenness of profile of the terrace constituted by the long western block may have been somewhat exaggerated in drawing Figure 44 but is nevertheless a strongly marked character. It indicates that a portion of the prefault surface is here preserved with little loss from postfault wasting and thus gives support to the inference from grade plains of the Farmington district that the Wasatch region was reduced to a condition of low relief before the period of range development. The fact that the drainage of the upper surface of the block issues through a small number of canyons shows that the surface slopes eastward (see also pl. 21, *A*) and thus indicates that the uplifting of the block was accompanied by a tilting toward the east.

In the Cottonwood region the later studies of structure, studies more or less connected with the mining industry, have discovered many faults, but nearly all of them have been referred to the earlier diastrophism, and those that might possibly have later origin are all of small displacement.[69] The interior faults in the Ogden-Willard region, described by Blackwelder, are regarded by him as older than the range. The small cross fault observed at the reservoir locality (p.17) is a contemporary of the frontal fault. Two other interior faults, known to me only from distant views, may prove on investigation to belong to the later period. One of them, seen in the face of the range between North Ogden Canyon and Pleasant View, has a high dip with a throw to the west. The other, near the crest of the range opposite Richville, has a throw to the east.

This review of interior faults of the later period covers, very imperfectly, less than half the area of the range. It leaves the impression that the rising block of the range was less subject to interior fracture than the adjoining descending blocks, though at the same time it shows that the horst is not to be regarded as an immovable mass from which other masses slumped away but rather as a free crustal unit strained along with its neighbors by the orogenic forces.

REVIEW OF RANGE STRUCTURE AND RANGE HISTORY

The subjects treated in this chapter are so interlocked that an orderly presentation was found impracticable, and the results of the inquiry are consequently scattered through the preceding pages. In the following paragraphs the more significant results are assembled and rearranged.

The range is a structural ridge, uplifted between two faults. The western or frontal fault is the greater. It is determined as a fault by structural and physiographic evidence. The structural evidence consists of products of friction observed on and in the footwall, including fault gouge, breccias, horses, and slickensides. The physiographic evidence includes (1) an escarpment, with alined base and alined facets, which truncates the sculpture and antecedent structure of the range and which is bordered by a wide alluvial plain, and (2) piedmont scarps.

The ground plan of the fault is neither straight nor approximately straight but includes notable flexures and some angular turns. Its bends are explained as features of the original fracture determined by preexisting structure. Some, but not all, of the controlling structural features are visible. The greatest of the visible controlling structural features is a body of granite, in passing which the fault is deflected several miles. The average dip of the fault is 34°. The direction of slip was with the dip. A conservative estimate of the throw, made in the region of Cottonwood Creek and Jordan Valley, is 10,000 feet.

[69] See especially Butler, B. S., and Loughlin, G. F., A reconnaissance of the Cottonwood-American Fork mining region, Utah: U. S. Geol. Survey Bull. 620, pp. 178-182, 1915.

The east-side fault was determined wholly from physiographic characters, but the determination may be checked by study of structural characters, for the thrown block is not everywhere concealed by alluvium, as is the thrown block on the west side. One physiographic character is an escarpment, well alined for about one-fourth of the length of the range. This escarpment truncates the internal structure of the range and is in part buttressed by hills of contrasted constitution. In another place differential movement at the supposed position of the fault is shown by the aggradation of a valley (Heber Valley) that had previously been excavated by a stream that flowed from the valley westward across the range. The line of the fault was examined at a few localities only.

In the northern third of the range the eastern fault is characterized by large grabens, and the dropped blocks are themselves broken by cross faults. The frontal fault scarp is buttressed by several spurs, each consisting of a fault block separated from the descending valley block and lodged at an intermediate height. The range block is locally divided by faults made during the period of uplift. These structural features created during the growth of the range are superposed on structural features of earlier origin.

Before the range arose its site—or at least a part of its site—was a tract of land of low relief, as is shown by remnants and other vestiges of a peneplain. The record is spread over a large area of the range between Salt Lake City and Weber Canyon and includes the top of a long, narrow subsidiary block of the range opposite Utah Lake. At the north the peneplain was developed on Archean and Paleozoic rocks; at the south, on Carboniferous rocks. Between the two localities lies a great syncline which brings Jurassic rocks below the general level of the peneplain, and by inference the period of peneplanation is later than post-Jurassic diastrophism. On the eastern borders of the range Emmons found the older rocks, Archean to Jurassic, overlain by a fresh-water formation—now regarded as largely terrestrial—referred to the Eocene, but the relation of the peneplain to the Eocene has not yet been established. One of the fault-block spurs on the west side of the range, the City Creek spur, is composed of Tertiary conglomerate resting unconformably on deformed Paleozoic strata. This conglomerate, which Emmons tentatively and plausibly correlated with the Eocene formation of the eastern flank, has been itself warped and faulted, and after its dislocation a plain was graded above it. The relation of that graded plain to the peneplain on the range has not been established; it may be of the same age or it may be more recent.

These imperfectly correlated data, although they fail to fix the date of the birth of the range, serve to show that the period of diastrophism to which its growth belongs is distinct from the period of the great post-Jurassic revolution, being separated by the period of quiet in which the peneplain was developed. The period of the peneplain, which immediately preceded the birth of the range, may have coincided with that of Eocene deposition a few miles farther east, or it may have followed not only Eocene deposition but the dislocation of the Eocene strata.

After the range had achieved the greater part of its growth a row of valleys along its eastern base was occupied for a time by lakes; and the lake beds, which are correlated with similar beds in Cache Valley that carry fossils, have been referred to the Pliocene. Still later the flanks of the range were washed by the waters of the Pleistocene Lake Bonneville, and the beaches of that lake were afterward dislocated by movements on the frontal fault. The same movements made piedmont scarps in Pleistocene moraines. By these phenomena the period of range growth, begun at some earlier Tertiary date, is shown to include Pliocene, Pleistocene, and Recent time.

The land east of the range is higher than the land west of it. At the time of the Eocene deposition the western region was the higher. The change in relative altitude affected large areas and should be classed as epeirogenic. Its period and the time of its beginning are only indefinitely known. One effect of the change was the reversal of the general direction of drainage in the Wasatch region. At the present time a number of streams from the eastern upland to the western lowland cross the Wasatch axis. The canyons by which they cross were already in existence at the time of the Pliocene lakes. The relations of an air gap to one of the canyons seem most easily explained by assuming that the lines of cross drainage were established before the beginning of the range uplift. There is need, however, of further investigation, and it is probable that when the questions as to the origin of the cross drainage shall have received full attention light will be thrown on the relation between epeirogenic and orogenic changes in the Wasatch region.

REVIEW OF PHYSIOGRAPHIC CHARACTERS OF MARGINAL FAULTS

The great fault of the Wasatch was originally recognized by the escarpment it has created. Afterward the piedmont scarps were discovered, and their evidence was regarded as confirmatory. Further confirmation has now been found in the structure created by fault friction. Because the physiographic characters of the Wasatch escarpment did not prove misleading, it seems proper to infer that similar characters may be used as criteria for the recognition of faults at the margins of other ranges. Among the characters of the Wasatch escarpment are these: (1) Its base line, although making many turns, follows a course that is independent of the sculptural features (canyons and ribs) of the range; (2) wherever the rock of the range is strong the ends of the ribs are faceted; (3) the facets are alined as if parts of the same warped surface;

(4) the base line, although somewhat adjusted to the distribution of strong and weak rocks, is largely independent of that distribution and is wholly independent of the strike of strata, folds, and faults within the range. The more noteworthy of these characters are summarized by saying that the escarpment truncates the sculpture and structure of the range.

If a truncating escarpment can be produced only by faulting its presence on the face of a range is demonstrative of a marginal fault; if it can be produced in other ways its presence is less than demonstrative. The other possible agencies of production are all erosive—ice erosion, wave erosion, wind erosion, stream erosion. Ice erosion need not be discussed, for the intermont valleys have not been occupied by glaciers. Wave erosion may be dismissed with a word, for the conditions require its application at the bottoms of intermont valleys, where efficient waves can not be generated.

Theoretically, in a land so arid that the wind is the dominant agent of erosion, a range that borders a plain and that is attacked by prevailing winds parallel to its base may be sapped at the base by eolian lateral corrasion and may thus acquire a truncating escarpment. Because I have not seen such a wind-made escarpment and have looked in vain for photographs or contour maps representing one, I am skeptical as to their existence in the United States, but the possibility remains that they will yet be discovered. An earmark for the recognition of a wind-made truncating escarpment is the presence at its base of a piedmont plain of rock, continuous with the rock of the escarpment, but this mark of identification might fail in consequence of a conceivable climatic change. Should the extreme aridity necessary to give the wind dominance in the piedmont belt be followed by moderate aridity, the rock platform might be buried by alluvium.

Stream erosion unquestionably produces truncating escarpments, for a pair of them are made by every mountain creek that digs a canyon athwart the strike of formations and faults; but canyon-wall escarpments are not marginal to ranges. It is true also that as the down cutting of a canyon bed approaches base-level, side cutting begins to sap the walls and thereby makes them retreat; and the question thus arises whether intermont valleys of the Great Basin may have been developed from medial canyons by the retreat of the canyon walls and thus have come to be bordered by escarpments that truncate sculpture and structure. The question can be treated only in a deductive way, because no streams through intermont valleys are now sapping the side walls. It is necessary to postulate a humid period with large rivers, followed by a less humid period in which have grown the alluvial aprons that now keep the intermont streams away from the valley walls. We may here ignore the difficulty of providing competent rivers for all the valleys that would need them and restrict attention to the type of mountain front that would result from such a process of valley formation. During the long time required for the development of one of the valleys through lateral corrasion by its trunk stream, the streams rising in the bordering uplands would not only adjust their grades to base-level but near their mouths would develop flood plains. They would, moreover, work selectively, opening wider flood plains in weak rocks than in strong. Then when changes of climate, by inducing deposition in the main valley, led to the building of alluvial aprons along its sides, those aprons would extend up every tributary valley and give to the rock base of each bordering upland an indentate outline. If the face of the upland retained such a slope that it might be called an escarpment, the escarpment would not truncate the sculpture of the upland but would be adjusted to it. It would still traverse the structure, but in an irregular manner, with much adjustment of its basal outline to the distribution of strong and weak rocks.

Thus it appears that a wind-made truncating escarpment rising above an alluvial apron, although conceivable, depends on an improbable combination of climatic sequences and local direction of wind, and that a stream-made escarpment that faces a wide valley may truncate structure but not sculpture. An escarpment that truncates both sculpture and structure and that overlooks a wide alluvial valley floor may therefore be assumed to have originated by faulting.

The Wasatch escarpment is characterized by topographic youth. The fault that has produced it is an active fault, and the fault's activity is vigorous. With every recurrent slip on the fault plane the facets of the escarpment are freshly extended at the base, and each slip gives fresh stimulus to the sculpturing streams of the range. The youth and strength of the escarpment give it special distinction as the representative of a type, but it represents a high development of the type rather than the average development. If the activity of the Wasatch fault should cease the processes of erosion would gradually mutilate and eventually obliterate the characteristic features of the escarpment.

The sequence of changes by which a fault scarp passes from youth to senility has received some attention from Davis,[70] and his discussion might be amplified by taking account of the control of this sequence by base-level and climate, but in the present connection it will suffice to point out certain general tendencies. The mountain streams, stimulated no longer by progressive uplift, lose power to corrade downward near the mouths of their canyons, and their energy is diverted to the widening of the canyon floors. The intercanyon ridges, or ribs, of the range are thus narrowed near their ends, and the terminal parts are

[70] Davis, W. M., An excursion to the plateau province of Utah and Arizona: Harvard Coll. Mus. Comp. Zoology Bull., vol. 42, pp. 151–152, 1903; Nomenclature of surface forms on faulted structure: Geol. Soc. America Bull., vol. 24, pp. 198–204, 1913.

at last wholly removed. As the grades of the canyon floors are continuous with those of the alluvial plain outside the fault, the change may be otherwise expressed by saying that the piedmont plain invades the range, extending tongues up the canyon and gradually consuming the ribs. In this process the larger streams work more rapidly than the smaller, the narrower ribs lose their terminal facets sooner than the wider, and the weaker rocks yield more readily than the stronger—with the result that the alinement of rib ends is destroyed. The line of the rock base, which was originally simple in form and independent of structure and sculpture, is now complex in form, and its complexity is a function of the distribution of strong and weak rocks, dependent on structure, and of the drainage system that conditioned sculpture. The escarpment, if it still deserves the title, no longer indicates the position of the fault, and the fault-block mountain is no longer distinguished by details of sculpture from mountains of other origin. If the line of the fault is still traceable its recognition depends on other characters.

The piedmont scarps of the Wasatch Range resemble landslide scarps in that they mark dislocations of unconsolidated formations. They are distinguished by their greater length and their simpler inflections and by the fact that they run parallel to the rock base. Landslide scarps are comparatively irregular, with a tendency toward lunate outlines. The simplicity of the outlines of the piedmont scarps is ascribed to the smoothness of the fault surfaces on which the slumping took place, and the irregularity of many landslide scarps is ascribed to the unevenness of the associated rock surfaces. In some localities the relations of the Wasatch piedmont scarps to other features demonstrate that they were caused by recent movements on the frontal fault. In some localities, also, they are associated with hummocky corrugations, such as are caused by strong earthquake shocks, and it is inferred that the corrugations are secondary products of the same fault movements. It is possible that a piedmont scarp might be caused by the passage of earthquake waves from a distant focus, but such a cause is in most places improbable because waves that arrive from a distance are weaker than waves of local origin, and waves of local origin imply a local fault movement competent for the direct production of the scarp. It is, however, conceivable that the alluvium resting against the smooth footwall of a range-margin fault that has been inactive for a long period might be caused to slump by a passing earthquake, which would thereby create a piedmont scarp with characteristic form; and any such piedmont scarp, although it resulted from no recent movement on the local fault, would nevertheless depend for its existence on the presence of that fault. Therefore, wherever a piedmont scarp is found, the presence of a fault may be inferred with confidence.

CHAPTER III. FISH SPRINGS AND HOUSE RANGES, UTAH

GENERAL FEATURES

The Fish Springs and House Ranges stand 80 miles west of the south end of the Wasatch Range. Other ranges intervene, and a geographic order of treatment would give them prior attention, but it happens that of them I have but a passing knowledge, whereas the remoter ranges have received some weeks of study, and for present purposes the preferable order gives first place to the better known. In 1872, while traveling with topographic parties of the Wheeler Survey, I twice touched the ranges and was able to give about three days to their examination. The information thus gained[1] was supplemented in the winter of 1879–80 by a few observations made during the mapping of shore lines of Lake Bonneville,[2] and in 1901 the ranges were the subject of systematic study for eight weeks. In 1901 I was accompanied by Mr. W. D. Johnson, who covered the field of geologic work with a topographic survey. Unfortunately his map was never completed, the field notes being destroyed by fire, but before that accident he had compiled a draft representing the middle portion of the House Range, and that has been published by Walcott. The Fish Springs quadrangle has since been mapped by the United States Geological Survey.

The House Range was visited in 1904 by Davis,[3] who devoted a week to its study, with special attention to physiographic features, and in the following year by Walcott,[4] who made an elaborate study of Cambrian stratigraphy and faunas in the vicinity of Antelope and Marjum Passes.

What is now called the Fish Springs Range was earlier mapped and described as part of the House Range. Either usage is defensible, for the two ridges, although separated by a pass and not standing absolutely in line, are bounded on the east and west by intermont plains that serve to differentiate them from other mountain ridges. Structurally they present a notable contrast in that the Fish Springs Range, which is composed of westward-dipping strata, presents a steep scarp toward the east, whereas the House Range, which is built of eastward-dipping strata, is steeply scarped on the west. Figure 45, which illustrates some of these features, is copied, with change of title, from the report of my reconnaissance of 1872.[5]

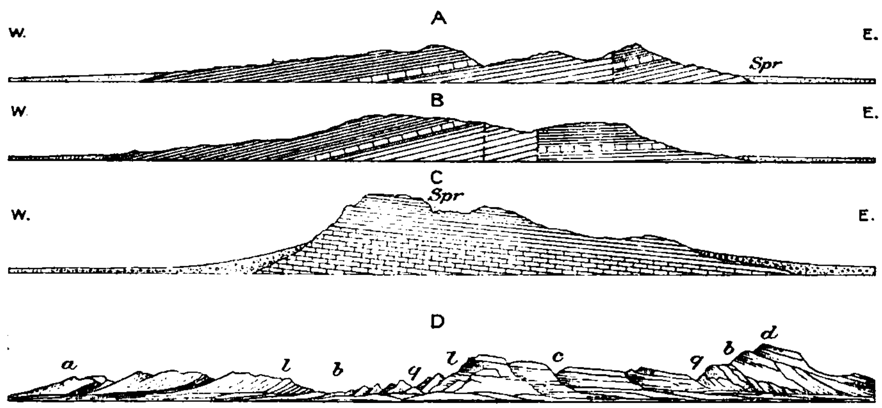


FIGURE 45.—The broad structural features of the Fish Springs and House Ranges, Utah. A, B, C, Sections of the House Range at Fish Springs, 2 miles south of Fish Springs, and at Dome Canyon; scale 1:98,000; base line level of Great Salt Lake. D, Section of House Range as seen from the west: *a*, Fish Springs; *b*, Dry Pass; *c*, Dome Canyon and Antelope Spring; *d*, Notch Mountain; *l*, Silurian limestone; *q*, Silurian quartzite

FISH SPRINGS RANGE

The Fish Springs Range is nearly 20 miles long and from 3 to 4 miles wide, as shown in Plate 31. Its trend is with the meridian and is nearly straight but has a slight westward convexity. The higher parts of its crest line are from 2,000 to 2,500 feet above either base. The valley that borders it on the east is broad and flat and merges northward with the saline plain of the Great Salt Lake Desert. On the west and southwest the range is separated from a range of hills by a narrower valley which drains both northward and southward. The lake plain of the desert wraps about its north end, concealing all but a narrow belt of its alluvial piedmont.

The eastern face is the steeper and is at most points strikingly bold. Because of its boldness it was early ascribed to faulting, and the diagnosis has since been verified by the discovery of a piedmont scarp and by the recognition of truncation. The outline of the rock base is by no means simple, but there is reason to believe that its principal bendings follow the courses of faults. From the north end of the range to a point beyond Cane Spring (see fig. 46) the course of the rock base is direct, except in one place, and through the greater part of this distance the base is paralleled by a piedmont scarp. The exceptional place is just south of Fish Springs, where a broad salient projects

[1] Gilbert, G. K., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, pp. 27–28, 167, 1876.

[2] Gilbert, G. K., U. S. Geol. Survey Mon. 1, p. 353, 1890.

[3] Davis, W. M., Harvard Coll. Mus. Comp. Zoology Bull., vol. 49, pp. 34–56, 1905.

[4] Walcott, C. D., Cambrian sections of the Cordilleran area: Smithsonian Misc. Coll., vol. 53, pp. 168, 173–185, 1908.

[5] Gilbert, G. K., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, p. 27, 1876.

eastward. The base of the salient is followed by the piedmont scarp for more than half its circuit. The principal body of strata in the salient dips gently toward the north and is separated by a fault from a greater body at the west in which the dip is strongly westward, but I am not able to say whether the entire block is coextensive with the salient. Where I crossed the fault (*c*, fig. 46) its position is represented by a shear zone, and the downthrow is to the west. The attitude of the fault plane was not determined. On the whole it is probable that the fault belongs wholly to an older period of diastrophism, and that there has been no separate movement of the salient block in connection with the uplift of the range.

South of Cane Spring is a broad compound salient, the principal points of which are both topographically and structurally distinct. Each of the parts indicated by Figure 46 is separated from its neighbors by such stratigraphic discontinuity as to demonstrate the existence of faults, although the faults themselves were seen at a few points only and were not traced out. The indicated east-west faults could be placed somewhat definitely because they coincide approximately with lines of drainage, but they are by no means the only faults of the tract. In the study of the stratigraphy many other breaks were found, and shear zones were seen at several points. The fault that falls in line with the frontal escarpment farther north is of greater throw than the east-west faults and is evidently a master fault of the system. At the point where I crossed it (*a*, fig. 46) the displacement is about 4,000 feet, with downthrow to the east, and its plane dips eastward at an angle that approaches 45°. Its course is readily traceable because marked by a distinct sulcus which falls and rises in crossing lines of eastward drainage. As shown on Plate 31 it is overlooked on the west by a fairly continuous escarpment, which is continuous with the frontal escarpment of the range farther north. At *a* (fig. 46) it is characterized by a wide shear zone, which is specially remarkable because uncemented. That part of the fault has not been within the subterranean zone of cementation since the occurrence of a large part of the fault movement; and this fact accords with the preservation of the footwall escarpment in indicating recency. On the other hand the shear zone includes at that point a large block of sandstone, a rock not now represented in adjacent parts of either wall. The probable stratigraphic position of the block is in the formation next above the adjacent formation of the hanging wall, and I infer that the hanging wall has been somewhat degraded since its detachment.

A still greater fault runs from *d* to *e*. (See fig. 46.) The block east of it shows only formations high in the Silurian, whereas the western block or blocks contain limestones near the base of the Cambrian rocks of the range. The estimated throw is 5,000 to 6,000 feet. The outer edge of the eastern block carries a small ridge that tapers southward, and a broad, low saddle separates this ridge from the high fronts of the western blocks. Those fronts fall in line as a discontinuous escarpment, the breaks being occupied by lines of eastward drainage. The same eastward drainage interrupts both the saddle and the eastern ridge.

At no point were two piedmont scarps seen on the same slope. The highest scarps seen, between Cane Spring and the Fish Springs salient, were estimated at 6 to 8 feet. At the apex of the salient the height is 1 foot; and in the northern division, between Fish Springs and Big Spring, the height is little greater. In a tract south of the Fish Springs salient the scarp appears only in the spaces between alluvial fans, having apparently been obliterated on the fans by fresh alluvial deposits. Here, as elsewhere, the scarp interrupts a slope that had been exposed to efficient waves of Lake Bonneville, so that its preservation proves a post-Bonneville origin.

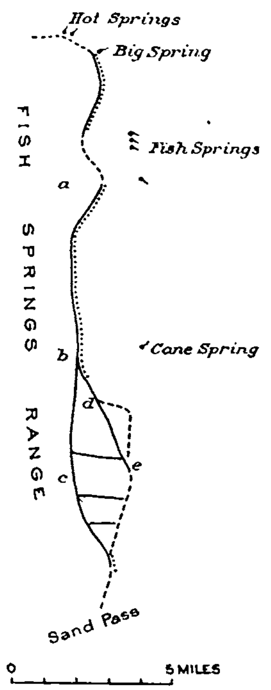


FIGURE 46.—Fault system of the eastern base of the Fish Springs Range, Utah

At *b* (fig. 46) the piedmont scarp that for miles has followed the mountain base southward is deflected and instead of continuing toward *c* takes a direction toward *d–e*, the escarpment of the salient. It then ceases to be traceable, but its turning helps to connect the fault *d–e* with the marginal fault of the range. The marginal fault north of *b* apparently represents the confluence of faults *b–c* and *b–e*; and the group of fault blocks between those two lines are related to the body of the range in somewhat the same way as the blocks that constitute spurs of the Wasatch Range are related to the body of that range. There is, however, a noteworthy difference. The spurs of the Wasatch are distinctly outside the frontal fault and are masses plucked from the valley block as it descended, but the compound unit between the two great faults of the Cane Spring salient is better described as intermediate between the mountain block and the valley block, belonging to neither but coordinate, except in size, with both.

Near Fish Springs is a compound landslide, a feature of magnitude compared with the piedmont scarp and so different in configuration that the two can not be confused. The landslide also is of post-Bonneville origin, for the plane of its slipping is in a Lake Bonneville deposit, and its mass is composed of a Lake

Bonneville shore formation. It is possibly an exact contemporary of the piedmont scarp.

No thoroughly satisfactory record was found of the dip of the frontal fault. The escarpment has no rock sufficiently durable to preserve a tract of footwall with slickensides. Opposite Cane Spring, at a height of 150 feet above the rock base, a fragment of a shear zone was seen, and the average slope from that to the rock base and piedmont scarp was measured. As there is much evidence of step faulting in some parts of the face, I was not sure that the sheared rock belongs to the main frontal fault. If it does, the local dip of the fault is 45°; otherwise the dip is steeper The general slope of the escarpment at points where its rocks are fairly resistant is 30° to 35° and may be ascribed to gravitational grading. It is safe to say that the general dip of the fault plane is not less steep.

The truncation of sculpture is less striking than on some parts of the Wasatch escarpment but is comparable with the face north of Pleasant View (pl. 9, *A*) and with the upper face of the Timpanogos front (pl. 30, *A*). The limestone of the stronger beds is a less durable rock than those that preserve the remarkable facets of the Wasatch; the stronger limestones are interlarded with sectile limestones and shales; and the relatively slow rate of uplift, revealed by the scant piedmont scarps, gives time for much weathering.

The truncation of structure is comparable with that shown in the Wasatch Range but is not equally illustrated by available photographic views. One who follows the rock base for a few miles finds his geologic horizon gradually rising or falling as the dip carries one formation after another below or above the base line, and here and there, as he passes a fault, the sequence is abruptly broken. The changes are expressed diagrammatically by Figure 47, in which the changing stratigraphic interval between the bed at the rock base and a reference horizon is plotted as a curve. The reference horizon is the top of the Cambrian. The stratigraphic range of rocks that occur at the eastern rock base is about 7,000 feet and includes nearly all the formations recognized in the mountain. Although the line thus plotted involves elements of deformation, it is not a profile of deformation. The line of the rock base in relation to which the Cambrian horizon is plotted is not straight in nature but has a vertical range of about 1,000 feet and a still greater horizontal range, as illustrated by Figure 47. It is by the combination of these irregularities with the dips of strata that the upward and downward flexures in the diagram are produced, and not by anticlines and synclines of the mountain structure.

The springs of the Fish Springs group are thermal. Their temperatures were noted December 15, 1879, as follows:

Spring walled in for house use at the old stage station, 78° F. Associated springs, 74°–77°. First spring south with large basin, 74°. Three springs, three-quarters of a mile south of station, 84.5°, 84.5°, 83°. Two springs with a common pond, 1.5 miles south of station, 80.2°, 81°.

The highest temperature, 84.5°, is 32° above the mean annual temperature at Salt Lake City. As no igneous rocks are associated with the range it is probable that the water comes in part from a deep source, but the points of issue are more than 1 mile from the frontal fault.

North of the end of the range hot springs rise on the plain within a mile of the rock base. I transcribe my notes, written December 17, 1879. The springs were approached from the east.

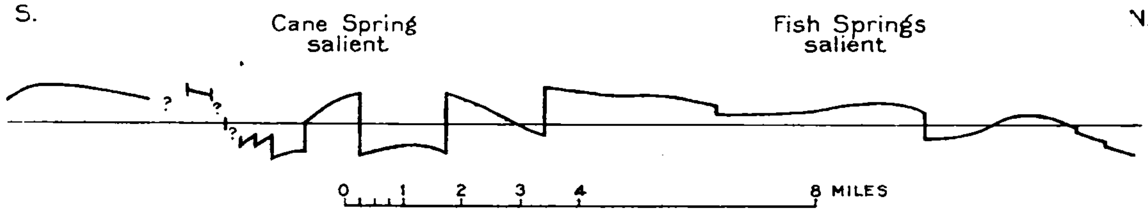


FIGURE 47.—Diagram illustrating truncation of structure by the eastern escarpment of the Fish Springs Range, Utah. Horizontal line shows rock base. Vertical lines show faults. Curve shows position and distance of summit of Cambrian above or below the formation at the rock base. Vertical and horizontal scales the same

The first has a temperature of 104.5° F. It has built a mound probably 12 feet high. The basin at the top is 12 feet across. Within it are stalagmites, built from the bottom nearly to the surface. Most of the deposit is yellow with iron, but some is white. I taste salt in the water.

The next has a lower mound, flat-topped and lying at the base of the first. Its pool is 8 feet across and lined with green; 136.5°. Bubbles rise continually. Deposit soft at surface, red.

The third has a mound higher and broader than the first. Too miry to approach.

The fourth has a mound 20 feet high and with a base of an acre; 139°. Basin 20 feet across; green lining; red or orange deposit. On the flank of the fourth is a small spring, nearly extinct.

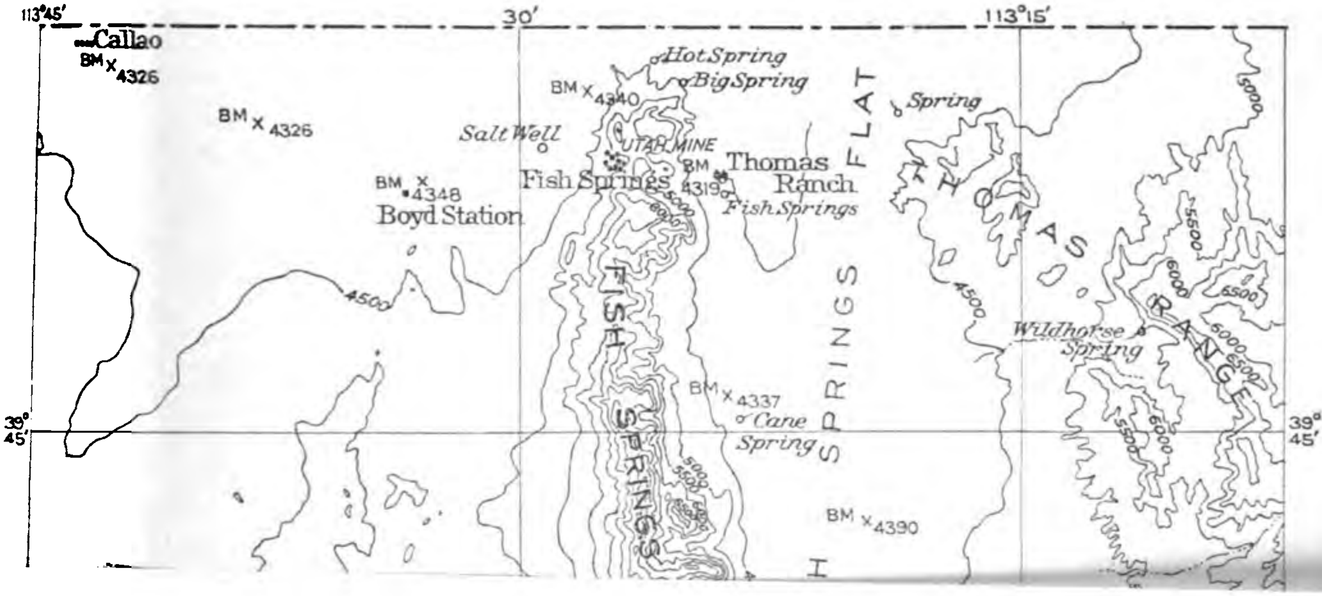
The fifth has a temperature of 99°. Basin 6 feet. Outflow small.

The sixth is 4 rods southeast of the fifth and a little lower. Pool 18 feet, green-lined; 137°.

There are two more. One I could not approach. It has a small basin, but a large mound. The other has no mound and receives water from the sixth.

The group have common characters; all are brackish. All have red to orange deposits where the water is hot and white where it is cool. The orange deposit is largely on Confervae, which grow in all the springs. The white deposits (salt and calcium carbonate?) form partly on *Salicornia* and salt grass and partly in fungoid forms. Gas rises in several springs, but I did not detect its odor.

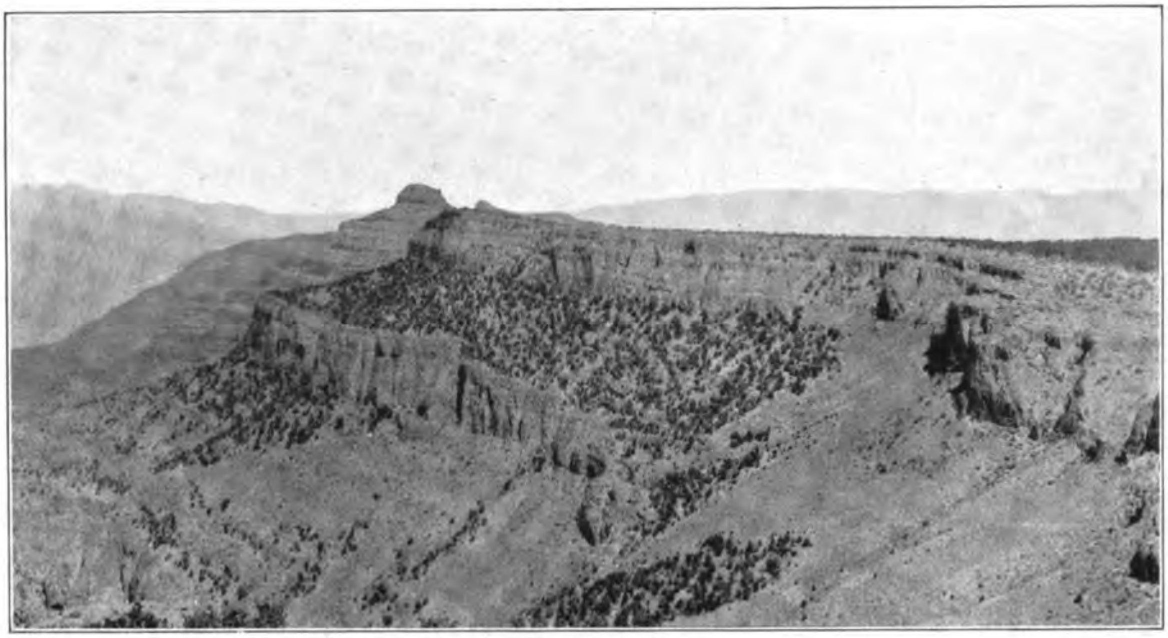
I was told in 1901 that a spring of this group, then used for bathing, was at times unbearably hot and at other times cool. These facts indicate that water


113°45'
30'
113°15'
Callao
BM x 4326
BM x 4326
Hot Spring
Big Spring
BM x 4340
Salt Well
UTAH MINE
Fish Springs
BM 4319
Thomas Ranch
Fish Springs
BM x 4348
Boyd Station
FISH SPRINGS
FISH SPRINGS FLAT
Spring
THOMAS RANGE
Wildhorse Spring
BM x 4337
Cane Spring
BM x 4390
4500
5000
5500
6000
39° 45'

A. WEST FRONT OF THE RANGE, NORTH OF THE FISH SPRINGS MINES

B. FAULT CLIFF AND SHEAR ZONE ON THE WEST FRONT OF THE RANGE, 5 MILES SOUTH OF THE FISH SPRINGS MINES

VIEWS IN FISH SPRINGS RANGE, UTAH



A. WEST FRONT OF HOUSE RANGE, UTAH, FROM A SUMMIT AT THE SOUTH

The prominent point is Tatow Knob. Fish Springs Range in the distance

B. GENERAL VIEW LOOKING NORTH

Photograph by John P. Buwalda

C. VIEW NORMAL TO THE FACE, SHOWING VERTICAL STRIAE AND TEXTURE OF FAULT ROCK

B, C. SLICKENSIDES ASSOCIATED WITH FAULT SCARPS IN PLUM RIDGE, NEAR ALGOMA, OREG.

The exposure is in a road cut, about 1¼ miles south of Algoma and 100 feet above the base of the scarp. The material bearing the polish is crushed rock, without cement and very friable. A thin layer of this veneers the footwall of the fault, which consists of basalt. The hanging wall, so far as visible, consists of basaltic talus. Dip of fault plane 49°

rising from a deep source, with a temperature higher than 139° F., mingles near the surface with water circulating in saliferous deposists of the lake plain. Taken in connection with the absence of volcanic rocks they indicate a deep fault; and the position of the springs suggests an east-west fault that limits the range at the end just as it is limited by another fault at the side. The suggestion finds support in the fact that in the north end of the range the strata dip toward the north instead of in the prevailing westerly direction. It is worthy of note, in this connection, that four other ranges—the Dugway, Simpson, Stansbury, and Oquirrh—somewhat similarly related to the Great Salt Lake plain, are also characterized by northerly dips at their northern ends. In the Oquirrh Range the northerly dip is steep and is strongly contrasted with the dips in the adjoining part of the mountains.

The rocks of the Fish Springs Range are sedimentary, and their dominant dip is westward, at angles that probably average 30° or 35°. The early characterization of the range as essentially a faulted monocline might with present fuller knowledge be repeated as a generalization. The internal structure, however, is by no means simple, and the generalization as to external structure admits of qualification.

The western face, although in detail quite as complicated as the eastern, received less attention in the field and can not be described in a comprehensive way. In preparing the following account of special features I have found much occasion to regret the incompleteness of my examination.

About 2 miles from the north end the face is bold and high, as shown in Plate 32, *A*, and there is probably a fault with downthrow to the west, between the cliff and a rocky foothill at the left in the view. The dip in the foothill is westward. The stratigraphic position of the foothill rock was not learned, and for that reason the demonstration of faulting is for the particular locality incomplete. Farther south, however, and for several miles the front presents a similarly bold face, overlooking similar foothills, where certain beds were correlated with beds that occur high in the cliff. The throw was roughly estimated at 1,000 to 2,000 feet.

South of this point and farther west rises a second scarp which contains fault features of a different type. The scarp bounds a rock-cut piedmont plain or peneplain, in which the general dip of strata is westerly. At the scarp the strata end against a wide and complicated shear zone, in which are included large blocks of similar strata.

Planes of shearing have dips that range from 50° to 70°, and a sheet of limestone so broad that its attitude is presumably that of the footwall of the fault dips westward at 50°. With a height of several hundred feet the scarp trends east of south for half a mile or more, and the base gradually rises. Its trend then changes to southeast and afterward to south. In the southeasterly portion the scarp base continues to ascend the piedmont slope, but the height of the scarp diminishes. Beyond the turn toward the south the base becomes level and coincides with the Bonneville shore line. At the same place the material of the scarp surface changes from sheared rock and bedrock to alluvium. Where the scarp is highest it marks the lower edge of a rock-cut piedmont plain, and this relation continues to the southward turn. Beyond that turn the piedmont plain has two parts—the upper cut in rock, the lower alluvial—and the surface grade passes from one to the other with interruption. The shear zone for a space marks the limit between rock and alluvium and then disappears in post-Bonneville arroyos that cross the piedmont slope. As I interpret them these features were thus developed: Long after the beginning of range growth a fault occurred with throw to the west. The fault was marginal and created a westward-facing escarpment, against which was gathered detritus from the rising block. Afterward, in a long period of diastrophic rest the escarpment retreated by erosion, with the development of a piedmont slope that was partly carved from rock and partly built up by alluvial deposition. There has been no later faulting on this plane, but the existing scarp has been created by erosion, the chief or only agent of erosion being the Bonneville waves, which have cleared away the alluvium and thus exhumed the ancient fault scarp.

Near the middle of the western face lies a tract several miles long in which the range rises rather steeply from a well-graded and somewhat definitely limited piedmont slope. The appearance of the piedmont as seen from a peak led me to suspect that it was a graded rock slope with a veneer of alluvium, but the suspicion was not confirmed by an inspection of one of the arroyos of the slope.

Farther south the head of the piedmont slope lies farther from the axis of the range, and the lower parts of the intercanyon ribs have a certain regularity of crest height that suggested the former existence of a rock-cut piedmont plain, about 300 feet above the grades of present canyons. The ends of the same ribs show an alinement that is partly independent of the internal structure and thus suggest the existence of a fault scarp. The evidence is vague and incomplete, but so far as it goes it indicates that a minor fault-bounded block, after resting so long as to have become graded to the piedmont slope, had been lifted a few hundred feet, with resulting dissection. The fragments of tectonic history gathered along the western front and base serve to qualify the simple conception of the range as a tilted fault block by showing that the process of its growth has included minor faulting on

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the side toward which the block inclines. At least a part of the range, like a part of the Wasatch, might properly be characterized as an unsymmetric horst.

The formations that constitute the range are Paleozoic and so far as known are conformable. More than half the section is Cambrian; the highest member is possibly Devonian, but its age was not learned. The section was studied only as a means of investigating the structure. Special attention was given to peculiarities of formations by means of which they could be recognized without close inspection, and paleontologic correlation was not attempted.

The following tabular statement shows the general sequence of formations and gives rough estimates of thickness; its notation will serve to correlate the members represented in structure sections.

Stratigraphic column of the Fish Springs Range

Symbol	Rock	Period	Thickness
			Feet
L	Limestone	(?)	600
K	do	(?)	600
J	do	Silurian	1,000
I	Sandstone	do	100
H	Limestone and shale	(?)	1,000
G	Massive limestone	Cambrian (?)	1,000
F	Limestone and shale	do	300
E	Limestone	do	200
D	do	do	1,200
C	Shale, with limestone	do	800
B	Shale, with sandstone	do	500
A	Sandstone, with conglomerate.	do	200
			7,500

With minor exceptions the beds dip toward the west, and with some exceptions the angle of westerly dip falls between 20° and 40°. At the extreme north the dips are northerly, and less steep. In the Fish Springs salient is a block that is nearly level but is thought to dip northward. The only recognized fold is a local syncline west of the axis and within a few miles of the north end. In the main body of the range there is a general slow descent of the formations toward the north, so that younger members predominate in northern districts and older in southern.

The range contains a number of strike faults. At 3 miles from the north end the position of a notable cross fault is marked by a pass. The throw of this cross fault is not the same in all parts, but the average throw is perhaps 2,000 feet and on the north side. Farther south occurs a cross fault that has a northward throw of about 500 feet.

The range is fairly riddled by minor faults. There are surely hundreds of them and probably thousands. They have many directions, but the strike faults appear to be most numerous. Some are seen in cliff faces as simple lines of division; others are marked by shear zones. They served to confuse every stratigraphic section of more than 100 feet that I attempted to measure, and my field notes characterize them as "disconcerting" and "exasperating." They are partly responsible for the fact that the thickness of the formation is indicated in the table only in round numbers.

In the axial region and along the eastern face the great majority of minor strike faults are normal and cut the bedding approximately at right angles. On the western face they are more nearly vertical. In both regions they cause both duplication and widening of outcrops.

Some of the faults belong to the movements that created the range. They may be styled "later," to distinguish them from faults "earlier" than the beginning of the present range. The fault of the eastern escarpment and all the faults of the Cane Spring salient may be classed with little question as later, and so, too, may those normal faults of the western face that are associated with the uplift of the axial horst. To the earlier class may be assigned with some confidence a fault that crosses the Fish Springs salient and a strike fault farther north. These faults are out of harmony with their neighbors on both sides and have a throw to the west. The strike fault contains a quartzose or quartzitic sheet which weathers into prominence and marks its course for some distance. The minor faults are thought to belong largely to the later class, because they are similar in dip and in direction of throw to the greater marginal faults.

HOUSE RANGE

The House Range is about 40 miles long and is from 5 to 10 miles wide. Its axis, which has a general trend a little west of south, is slightly concave toward the west. The west face is an escarpment that rises 3,000 to 4,000 feet from the rock base. The eastward slope descends to a base of irregular outline and is diversified by acute dissection. The rocks are almost wholly sedimentary, and their general dip is eastward at low angles. The attitude of the strata and the character of the westward-facing escarpment are illustrated by the foreground of Plate 33, *A*. The Fish Springs Range, with its westward-dipping rocks and steeper east face, appears in the distance in that view. Between are hills and table-lands less readily characterized and in some sense intermediate in structure.

The principal divisions of the range, named in order from north to south, are the Tatow Plateau, Antelope Mountain, Howell Peak, and Notch Peak.

The plateau character of the Tatow upland is most marked at the south, where a broad tabular surface is determined by a resistant limestone. The surface has an average slope eastward of about 6° but undulates gently and is also modified by a few faults of moderate throw. Above the plateau project a few knobs, remnants of a higher bed of limestone, and below it are carved steep-walled canyons that drain eastward. Northward the upland loses height gradually and its structure changes, becoming less simple. Toward its north end it is separated by a wide hollow into two ridges, of which the western is the narrower and steeper. The western ridge is composed of sandstone including the lowest local member of the Cambrian system, and the eastern is capped by Cambrian limestones, the stratigraphic position of which is several thousand feet higher. The formations have been brought to nearly the same level by a system of faults with downthrow toward the east. Some of the faults strike with the meridian, and others strike more nearly northwest. There is also a northward descent of the strata, partly through dips and partly through faulting, so that the formation which constitutes Tatow Knob (see pl. 33, *A*) at an altitude of 8,400 feet occurs also at 6,000 feet 5 miles farther north and in the northern part of the east ridge has reached a level more than 1,000 feet below the surface.

The structure of the north end of the House Range resembles that of the south end of the Fish Springs Range in that the dislocations have lifted the western blocks in relation to the eastern, but the resemblance goes no farther. The faults of the Fish Springs Range are associated with westward dips, those of the Tatow Plateau with eastward dips. The internal faults of the Fish Springs Range are harmonious with the great marginal fault, along which the range was lifted; those of the Tatow Plateau are not of the type that might create the westward-facing escarpment. The minor blocks along the Tatow escarpment, instead of being dropped below their neighbors in the range, like the blocks of the Wasatch frontal spurs, stand higher than their neighbors in the range. If the western escarpment of the House Range is a fault scarp—and there is independent evidence that it has that character—then the minor blocks along the face of the Tatow Plateau are not products of the diastrophism that created the range but are of independent origin. Presumably they belong to an earlier diastrophism.

The Sand Pass Ridge is in some sense a connecting link between the Fish Springs and House Ranges but is more closely related to the House Range. For the greater part of its length it parallels the west face of Tatow Ridge at a distance of a mile, but the interval is bridged by rocky spurs. There is no pronounced general dip in the rocks of the ridge, and most of the dips observed in it are gentle. It is divided by numerous minor faults. So far as noted the throw of the east-west faults is toward the north and that of the north-south faults to the east. In the principal spur that joins it to Tatow Ridge north-south faults of noteworthy displacement occur, and all these throw toward the east. They constitute a step-fault system by which the Sand Pass Ridge block has been lifted high above the Tatow Ridge block. Because of northward dip in the Tatow it is probable that the dislocation is greater at the north than at the south. Its amount was not measured but is probably not less than 5,000 feet and may be as great as 7,000 feet.

As shown by the map (pl. 31), the valley along the eastern base of the ridge is drained mainly northward and southward, but a middle part drains westward, its outlet dividing the ridge by a canyon. A line of drainage that heads in the western face of Tatow Ridge crosses without deflection the hollow eroded in weak rocks and continues its course across a ridge of stronger rock.

GENERAL FEATURES

For the profit and pleasure of a visit to the region of the Klamath Lakes, in Oregon, I am indebted primarily to Prof. D. W. Johnson and Mr. John P. Buwalda. Professor Johnson, while passing through the region by automobile and railway trains, noted that the basin of Upper Klamath Lake is probably a graben, that the fault scarps bounding the basin on the east are peculiarly fine illustrations of their type, and that one of them affords a remarkable exhibition of slickensides. These observations he communicated to me, and they excited an interest which led me to plan a visit. The visit was made in September, 1916, and its fruitfulness was greatly promoted by the cooperation of Mr. Buwalda, who was my companion. The observations here recorded were a joint work, and as many of the inferences here presented were developed by discussion in the field they also are a joint product. But as some of the inferences were afterthoughts, and as the afterthoughts and the writing have been mine, I can not avoid responsibility for such errors as may have been entertained.

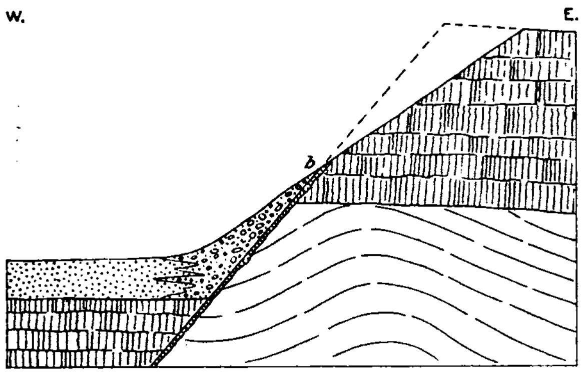


FIGURE 48.—Diagrammatic profile and section across the Plum Ridge fault scarp, Klamath County, Oreg. The broken line indicates the portion of the uplifted block which has fallen away since the beginning of the dislocation and has furnished the material of the talus

Upper Klamath Lake (pl. 34) is a sprawling body of water with an extreme length, north and south, of 25 miles. It is bordered by marshes almost as extensive as the lake itself, and the marshes are bordered by plains of gentle slope. These flat elements of the landscape are in strong contrast with the mountains and the hills that adjoin them on the west and east. On the west the Cascade Mountains present a bold and rather lofty front, and on the east are three cliffs, less lofty but bolder, which overlap in such way that each for a distance walls in the tract of plain and lake. The northernmost cliff, which may be called the Fort Klamath escarpment, has a general course that trends a little west of north and is 16 miles long. From Klamath Indian Agency to Fort Klamath its general height is 400 to 600 feet, and this height continues for 4 miles farther. Then it rises in a short distance to a height twice as great and holds this till its identity is lost on the southward slope from the rim of Crater Lake. The north end of the Modoc escarpment stands 5 miles east of the disappearing south end of the Fort Klamath escarpment. Its course is southward for 12 miles to Modoc Point and then south-southeastward for 18 miles to a sudden ending in the plain traversed by Lost River. Its general height is 600 to 1,200 feet. The Plum Ridge escarpment is parallel to the southern division of the Modoc escarpment and stands 2 miles farther west. It is 8 miles long, and its general height is 1,000 feet. It is on this escarpment that the slickensided surfaces are displayed.

PLUM RIDGE AND VICINITY

At its north end the base of the Plum Ridge scarp approaches Upper Klamath Lake, from which it is separated only by a narrow alluvial apron. A carriage road formerly traversed this apron, but a railway has recently displaced it, and now the carriage road is accommodated on the steep scarp by means of a sidehill cut. The fresh excavations for railway and roadway have revealed a fault plane—the plane of the fault which created the scarp. The general profile and section of the scarp are shown in Figure 48. Its slope is 34° except at the very base, where it passes into that of the apron. The fault plane meets this slope as drawn, its inclination being about 49°. To be specific, measurements at four points gave 47°, 48°, 50°, and 52°. Above the meeting of the fault plane and the external profile the visible material of the slope is rock in place, veneered in part by sliding talus; below the meeting only talus is seen. The line of meeting, traced along the face of the scarp, is relatively high at the south, although nearer the base of the scarp than the crest, and descends northward. It finally reaches the apron and then passes below the level of the lake. In its descent it crosses the two lines of excavation, first that for the carriage road and then that for the railway, and it is at these crossings that slickensides are seen.

The exposure of polished surface at the carriage road is 110 feet long and has a maximum height of 43 feet. Upward and on the north the surface terminates because the rock bearing it has been removed by erosion; downward and toward the south it passes behind talus. As shown in Plate 33, *B*, *C*, it has been utilized for billboards. The scratches upon it show a slight variation in direction, and some of them intersect at small angles, but collectively they indicate that the relative motion of the rock masses had no horizontal component within the fault plane. The "plane" is not a plane in the mathematical sense but, like other fault planes, is a warped surface. The more pronounced curvature here is that shown by contours, and the contours swing, within the field of this exposure, through an arc of about 10°.

The exposures near the railway track (pl. 35) occur in several patches, distributed through a space of several hundred feet, and they are similar to the one just described. The striae are vertical, and the flexures of the fault surface are of the nature of a broad fluting parallel to the striation. Readings of N. 58° W. and N. 22° W. indicate a local swing of the fault strike through an arc of 36°. The broader curves of the fault plane are in accord with the local curvature of the contours of the fault scarp, and when this fact is considered in connection with the way in which the fault line is traced on the face of the scarp it is easy to understand that deviations of the fault plane from flatness find topographic expression in variations of the trend of the scarp.

The material that bears the polish and striae is a soft fault rock, a powdery breccia of the local country rock, which is mainly basalt. It is so feebly coherent that a block of it falls apart in the hand, and the slickensides will probably be effaced by the weather in a few decades. Its observed thickness is only a few inches. In a number of places it is divided by oblique polished surfaces, which incline more steeply than the fault plane. The lines in which these oblique surfaces meet the fault plane, though irregular, are approximately horizontal.

The dominant material in the composition of Plum Ridge is basalt, which occurs in beds. So far as known basalt is everywhere the capping rock. Some intercalated sandstone was seen; and a railway ballast quarry at the base of the ridge, close to the north end, exposes tuffs and sands that have a complex structure. At a point 2 or 3 miles farther south the face of the scarp shows a small body of highly inclined clastic beds. Still farther south and at midheight on the face of the scarp there is an exposure of highly inclined beds which have an arrangement that suggests the quaquaversal dip of a cinder cone.

The throw of the fault can not be stated, but a rough estimate is possible. The quantity of material eroded from the raised block is definitely represented in section (fig. 48) by the triangle between the existing profile of the block and its restored profile. Much of that material was separated in blocks and is lodged as talus directly beneath its source; some of it doubtless traveled farther and has joined the fine sediments of the valley. So the section of talus may be somewhat less but is not greater than the section of removed material. The slope assumed by the talus is nowhere steeper than that of the rock face above but is in some places a little less steep. On the other hand, it can not be assumed that the visible slope of the talus is continued without modification below the level of the valley deposits (as it would be if the talus had been completed before deposition in the valley began), for the growth of those deposits has probably been contemporaneous with the progress of the faulting and the growth of the talus. The combination of these considerations yields the compromise conclusion that the total height of the talus is about the same as the vertical distance from the outcrop of the fault plane to the top of the cliff, or that the last-mentioned distance is about half the vertical throw. As computed on this basis, the throw of the fault is nearly 2,000 feet at the north end of the ridge and diminishes rapidly southward. At 2 miles from the end it is about 1,200 feet. The inferred position of the top of the downthrown block is shown in Figure 49.

The northern part of the face, about 3 miles in linear extent, was seen at short range and examined critically. A remarkable feature is its uniformity of slope. The uniformity from top to bottom is illustrated by the profiles in Plate 35, *B*. The uniformity from point to point is illustrated by the fact that measurements at five different places show a range of only 3°—from 33° to 36°. As the creation of the slope has been mainly a work of degradation, and as the angle of slope is approximately the angle of rest for angular waste, it is not difficult to infer the processes involved. Disintegration of the basalt, which is the dominant resistant rock, has occurred chiefly through cracking into blocks and chips, and transportation has occurred chiefly through the direct

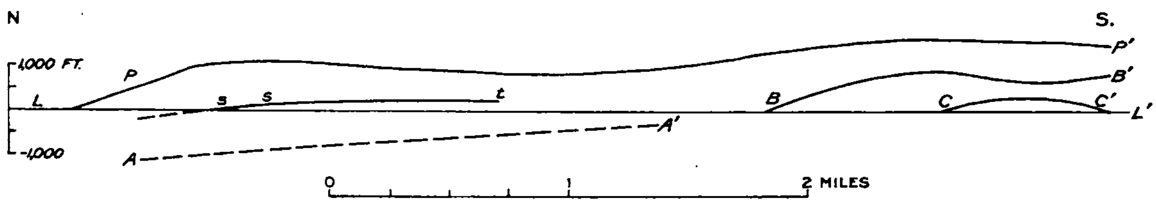


FIGURE 49.—Longitudinal profile of northern part of Plum Ridge, Klamath County, Oreg., with profiles of lower hills adjoining on the west. LL', level of lake surface. PP', Profile of Plum Ridge; AA', inferred profile of downthrown block adjoining Plum Ridge block; BB', profile of hill adjoining Plum Ridge, crest line of lower fault block, possibly continuous with AA'; CC', profile of hill adjoining BB'; *s*, *s*, localities of exposed slickensides; *sst*, trace of fault plane on Plum Ridge scarp

action of gravity. As fragments have been broken away, because the rock was strained by rapid changes of surface temperature or by frost, they have rolled down the slope to form talus below. This action may have promptly followed each movement on the fault plane, or it may have lagged behind the development of the scarp, but in any event it found its limit when the angle of rest was reached. Thereafter the degradation of the face must depend on the slower processes of chemical disintegration and aqueous transportation; and the face is still too young to show evidence of sculpture by these processes. In the course of time, if movement is not renewed on the fault plane the scarp will come to be diversified by ravines and spurs, and the details of its slopes will come to express inequalities in the resistances offered by the underlying rocks. As compared with many high fault scarps of the Great Basin this one is youthful.

The absence of dissecting ravines indicates, in the first place, that the escarpment is not crossed by drainage from the upper surface of the ridge. If the prefaulting drainage ran westward it was turned back by eastward tilting at the time of the uplift. We did not visit the top of the ridge, and no direct evidence was obtained as to direction of slope, but beds of basalt exposed in the north face were seen to dip eastward.

The absence of ravines indicates further that there is little tendency toward the concentration of drainage, and I infer from that fact that water descending the slope has little power to erode, for it is through the deepening of a slightly favored channel that it is able to divert to itself additional drainage. This line of thought leads again to the idea that transportation of waste by the direct action of gravity is still dominant on the face and transportation by water is still subordinate. Triangular facets, which depend on segregation of drainage, belong to a later stage of topographic development.

No evidence was found of recent movement on the fault plane. If such a movement had occurred, and if the entire body of talus had moved down with the descending block, there would have been created at the rock base (*b*, fig. 48) a little cliff having the steepness of the fault plane. If such a cliff existed it would mark the rock base by a conspicuous line across the face of the escarpment; but the position of the rock base is not thus marked. If less than the whole body of talus moved downward an earth scarp would be created at some lower level, and it could be preserved only by traversing a slope gentler than that of the talus. The alluvial slope below this talus was scrutinized in search of such an occurrence, but none was discovered.

The ridge ends at the north in a face which is approximately plane, although not so even as the western face. Its contours make a right angle with those on the west. Its slope is about 20°, and it is not dissected. It is obscurely terraced, and the terracing is apparently connected with outcrops of eastward-dipping beds of basalt. Suggestions as to the origin of the face are (1) that it belongs to the prefaulting topography, in which case it is a product of postlava erosion, (2) that its inclination was given by tilting during the epoch of faulting, (3) that it is a fault scarp. Evidence as to the first suggestion is purely negative. The little that I saw of the prefaulting topography and the greater amount which is suggested by the mapped contours of a neighboring upland do not indicate the probable existence of an eroded valley or canyon of which this sloping face might be the wall. The second suggestion appears to be negatived by the fact that ledges of basalt cross the face. Examination of the ledges was too cursory to warrant a definite statement about them, but the impression was obtained that they conform in structure with those exposed in neighboring parts of the western face. The third suggestion is countenanced by the fact that many features in the immediate neighborhood are due to faulting and is thought to be the most probable. If the face is in fact a fault scarp then the horizontal displacement involved in the faulting was about three times as great as the vertical, and its extent exceeded half a mile. If the downthrown block lies as far below the lake surface as that on the west side of the ridge the horizontal displacement was about 1 mile.

The central and southern parts of Plum Ridge are flanked on the west by a lower ridge, which is less regular in form. The bases of the two ridges join, or perhaps the relation might better be expressed by saying that a narrow sag, or high valley, separates their crests. The indication of the contours on the map that this valley is everywhere walled on the east by the Plum Ridge scarp was borne out by such distant views as we obtained. The slopes of the lower ridge are in general less steep than those of the higher, its smoother curves gave less information as to its structure, and as it was seen only from the road along its western base, there would be small advantage in describing such features as attracted attention. It was thought to contain a number of minor fault blocks, and two of these are indicated in profile 5 of Figure 50.

Plum Ridge is about 1 mile wide at the base. A valley 1 mile wide separates it from the Modoc escarpment. For about half its length this valley has a flat alluvial bottom, but in its north end stand two small ridges, and its southern part is occupied by a multitude of small ridges and hills. The ridges at the north are designated in Figure 50 by the letters *a* and *b*.

Ridge *a* lies parallel to its larger neighbors and is perhaps a mile in length. From a middle width of one-third mile and a height of about 200 feet it tapers and slopes toward each end. On the east its middle part is joined to the lower slope of the Modoc escarpment. It is a monocline, with gentle eastward dip and a relatively steep face toward the west. The north end of ridge *b*, which lies between ridge *a* and Plum Ridge, is also monoclinal, and the relations of the three parallel ridges, all controlled by bedded basalt dipping east and all presenting scarps to the west, are strongly indicative of faulted structure. The relations are shown in profiles 1 and 2 of Figure 50. The north end of ridge *a* appears at the right in Plate 36, *C*.

Ridge *b* is 2 miles long. Near its north end it is joined to Plum Ridge at the base and farther south it becomes a shoulder of that ridge. In its middle course it is relatively low, but toward the south it rises again. Its northern part, as already mentioned, shows a dip to the east, but farther south there appears to be no dip in the transverse direction, although there may be a longitudinal inclination toward the north. On the assumption that these attitudes of its basalt beds have resulted from deformation, the ridge comprises not less than two minor fault blocks. In Figure 50 profiles 1 and 2 show features of the northern part, and profiles 3 and 4 of the southern part. These four profiles are separated by subequal intervals of about half a mile. The interval between profiles 4 and 5 is three times as great, and profile 5 shows new features. Plum Ridge is here higher and narrower and bears on its flank a ridge, *c*, which is independent of ridge *b*. The structure of ridge *c* was not seen, and its description is based largely on the contours shown on the map. It appears first at the base of Plum Ridge and rises southward along the flank of that ridge, and its crest becomes at last the main crest of Plum Ridge and stands next to the main fault scarp. So the body of Plum Ridge probably contains more than one faulted block.

South of the middle of Plum Ridge the entire interval between Plum Ridge and the Modoc escarpment is occupied by small ridges. They are forested, and I saw them only from the road which winds and climbs among them. So far as observed, their prevailing trend is parallel to that of the greater features, they are of moderate length, and they resemble in general arrangement the sliced country or rift belt of the San Andreas fault in California. At one place they inclose a drainless hollow a third of a mile long that has a flat alluvial floor. Their material appears to be basalt, but their structure was not made out. A continuation of the same group south of the end of Plum Ridge contains hills of sandstone on which no basalt was seen.

In general, Plum Ridge and the associated hills owe their forms chiefly to faulting. The terrane, which has been dislocated, had a complicated structure that recorded an earlier geologic history. A late event of that history was the spreading of basalt in broad sheets. Earlier events were the formation and the deformation of clastic sedimentary beds and the eruption of tuff and volcanic sand. As the basalt beds near by everywhere overlie the other members it is possible that the prefaulting surface was a lava plane, but such a condition is not proved by the data gathered.

There are two major faults (the Plum Ridge and Modoc), and these are parallel, as well as similar in magnitude and in direction of throw. They are marked in the topography by similar bold, sharply cut scarps and are associated with the most striking features of the relief. Minor faults are numerous. The terrane is broken into many blocks, and these have many attitudes. In general the longer axes of the blocks are parallel or subparallel to the major faults, which strike N. 25° W. The ordinary ratio of longer axis to shorter is a small number. It is

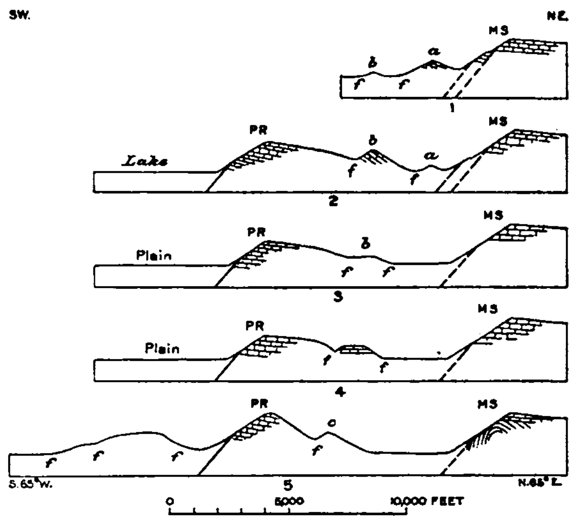


FIGURE 50.—Cross profiles of northern part of Plum Ridge and of associated ridges and valleys, Klamath County, Oreg. PR, Plum Ridge, MS, Modoc scarp; *f, f, f*, approximate positions of faults; *a, b, c*, smaller ridges

probably true that many more blocks incline eastward than westward, but the evidence on this point is obscure.

Many of the ridges and hills are softened in outline. No minor scarps were seen which preserve the sharp definition of the major scarps. This difference suggested the possibility that much of the minor faulting had preceded the faulting which produced the major scarps; and that view was for a time entertained. The explanation, however, was unsatisfactory. Because any deformation of large pattern develops local stresses which produce deformation of smaller pattern (for example, crumpling inside a large fold and breccia along a fault plane), it seems easier to explain minor faulting as ancillary to major faulting than as independent and antecedent. I sought, therefore, a different explanation of the comparative indefiniteness of the topographic expression of minor faults and have the following to propose. The prefaulting surface was weathered, and its rocks were seamed and disjointed. When faulting began, the resulting scarps were not sharply cut, because the incoherent rocks yielded to transporting agencies. With the continuance of faulting, unweathered rocks became exposed in the scarps, and their resistance tended toward the preservation of steep slopes. Thus the greater dislocations acquired a strong expression, whereas the smaller did not.

The incoherence of the crushed rock bearing the slickensides is a noteworthy feature, although its interpretation is not clear to me. The localities at which it was observed are on the face of the uplifted block and about 1,200 feet below its top. The places were therefore 1,200 feet below the surface when the faulting began. The creation of a fissure occupied by crushed rock was the creation of a conduit for the circulation of underground water, and some of the conditions essential to cementation were evidently present. The fact that no cementation took place shows that an essential condition was absent but does not specify the absent condition.

MODOC ESCARPMENT

As already mentioned, the strike of the Modoc escarpment changes abruptly at Modoc Point. In the space of a mile it swings through an arc of about 40°. The southeastern division starts from Modoc Point with a course which, except for minor undulations, is due southeast. After curving slowly southward for about 5 miles, it acquires a general direction S. 27° E., which it holds for 13 miles. In its curved course it borders Upper Klamath Lake, then for 2 miles it borders a tract of marsh land, and beyond that it borders the trough which separates it from Plum Ridge.

Through the entire distance it has the bold habit of the Plum Ridge scarp, and its average height is somewhat greater. Such excavations as have been made for railway and roadway have not revealed the plane of a determining fault, but the existence of such a fault is shown by independent evidence.

While Professor Johnson's train stood at the village of Algoma in 1915 he wrote in his notebook:

> From the northern end of Plum Hills one looks northward against the finest scarp of an undissected fault block I have ever seen. Scarcely a particle of dissection; smooth, steep scarp with even-topped crest, apparently all lava. Wonderfully good overlapping block or fault splinter (south of Modoc Point).[1]

The "fault splinter," which his phrase aptly characterizes, is shown in Plate 36, *B*, and its cross profile and section in Figure 51. It is a narrow block from the original terrane, separated from the hanging wall and footwall by subdivisions of the fault fracture and lodged on the face of the footwall. It has been rotated in such a way that its top slants southward. Its cap rock retains an eastward dip, which gives the terrace a backward slope, so that the terrace constitutes an inclined gutter and intercepts storm waters that flow down the scarp. A similar slab, smaller and less tilted, buttresses the scarp opposite ridge *a*, and its profile appears in the upper diagrams of Figure 50.

Such splinters, which are known only as details of fault scarps, are related genetically to the intermediate blocks of a step-fault system and also to the "horses" of fissure veins. The only topographic features with which they are likely to be confused are landslides, and there are in fact instances in which the discrimination has been found difficult.[2] In this locality, however, there is little room for question. If the detached mass in Figure 51 had broken loose and slid down after the formation of the escarpment its lower part would protrude, instead of conforming, as it does, to the normal grade of the escarpment.

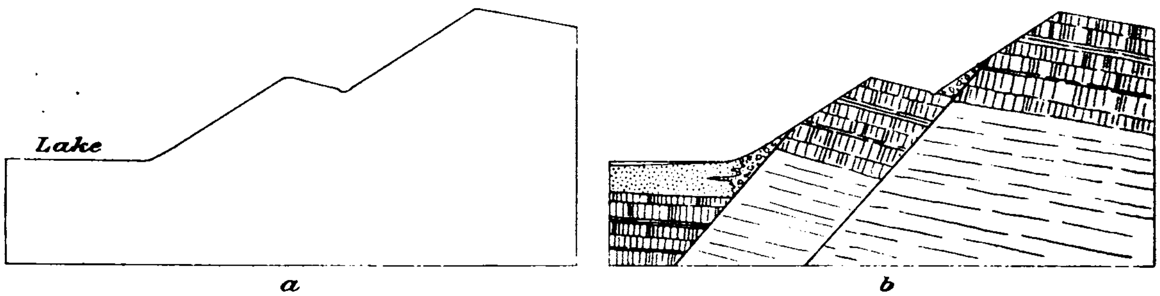
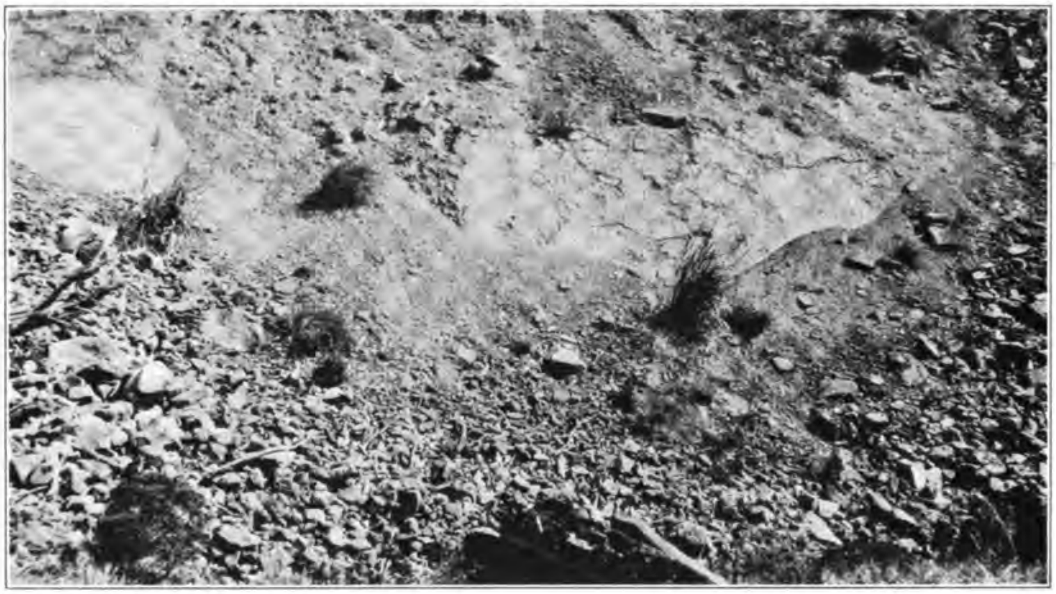


FIGURE 51.—Fault splinter on Modoc scarp, near Naylox, Oreg. *a*, Cross profile; *b*, hypothetic section

The escarpment bears also a number of thinner dislocated slabs, which I think must likewise be classed as fault splinters, although their characters are less demonstrative. They occur in the space between the two well-marked splinters, and their arrangement is shown in Plate 36, *B* and *C*. Their upper edges have arrested slide rock from above, and as the coarser talus material, where free from soil and vegetation, has a dark color, the positions of the edges are marked in the views by contact lines between dark patches above and paler patches below. The marking is approximate only, because in some places the vegetation that borders the coarse talus is also dark, but it serves to bring out the fact that there is a general alinement of the upper edges, their positions being progressively higher from left to right. The first and second dia-

[1] Communicated in letter.

[2] For a discussion of certain criteria see Lawson, A. C., in California Univ. Dept. Geology Bull., vol. 4, pp. 331-343, 1906.



A. VIEW NORMAL TO THE STRIKE OF THE FAULT

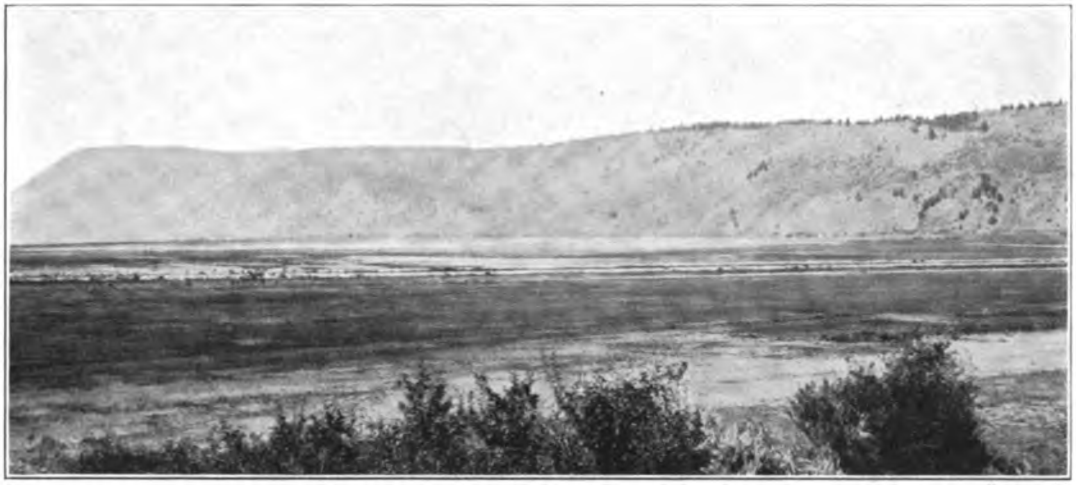
B. OBLIQUE VIEW FROM THE SAME POINT

The smoothed footwall, which dips about 50° W., is here vertically fluted. The nearest exposure and the one next beyond are on opposite sides of a groove (of the fluting) from which the overlying talus has not been fully cleared

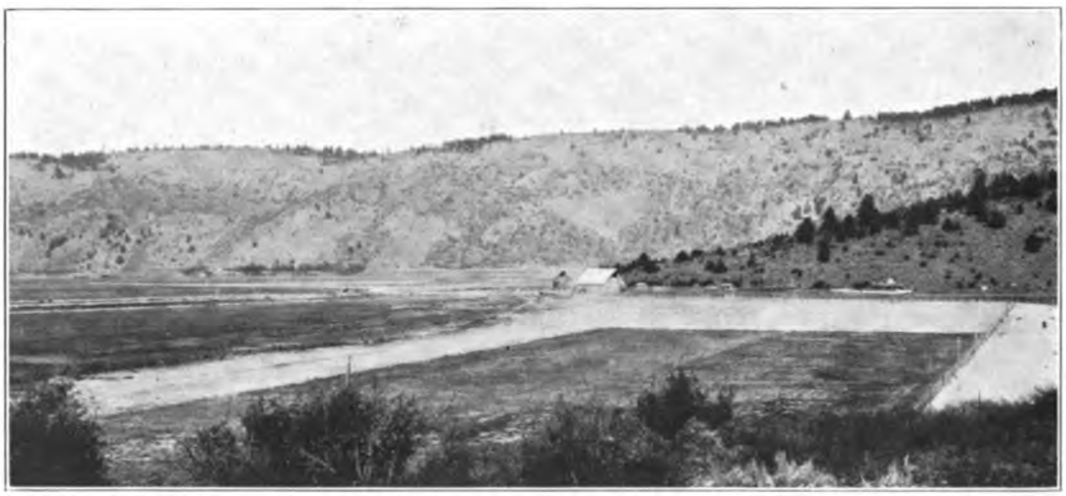
SLICKENSIDED FACES ON FOOTWALL OF PLUM RIDGE FAULT, 1 MILE SOUTH OF ALGOMA, OREG.

The locality is at the base of the ridge, which here trends S. 25° E. The exposures of the planed surface have been made by excavations along a railway. Photographs by John P. Buwalda

A



B



C

THE MODOC FAULT SCARP, NEAR ALGOMA, OREG.

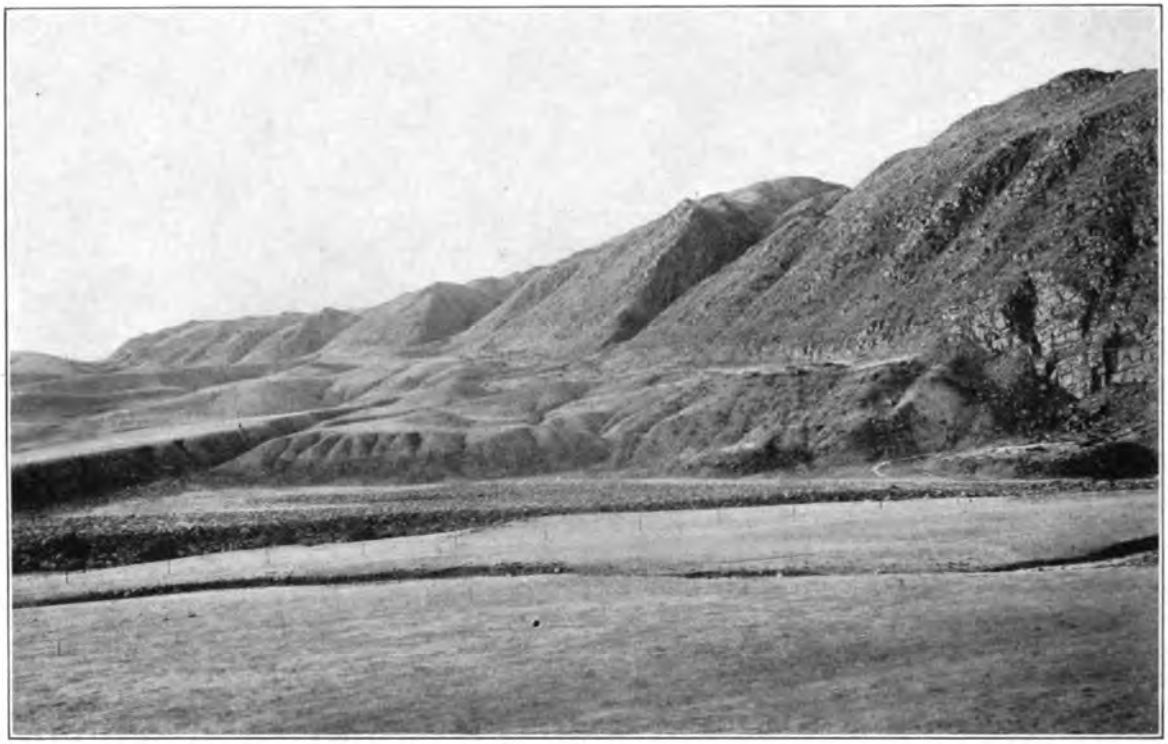
The views overlap and were taken from the same point, a school yard in the village of Algoma. The scarp here faces west-southwest, overlooking Upper Klamath Lake and the bordering marshes. In *A* at the right is Modoc Point, a salient angle of the scarp, which there assumes a more northerly course. Two notches in the sky line of the scarp mark structural valleys truncated by the fault. In *B* at the left of the center is shown a large inclined fault splinter, the north end near the top of the scarp and the south end near the base. From the center of the view to the right edge are thinner fault splinters, with less definite boundaries. In *C* the train of thinner splinters continues. At the right is the north end of a short ridge, the tilted fault block marked *a* in Figure 50

A. LENTICULAR BUTTRESS ON MODOC FAULT SCARP, A LITTLE SOUTH OF MODOC POINT

B. HILLS SOUTH OF LAKE, FROM THE EAST

The forms of the hills are ascribed to block faulting. In the distance are volcanic mountains of the Cascade system

TOPOGRAPHIC DETAILS NEAR UPPER KLAMATH LAKE, OREG.



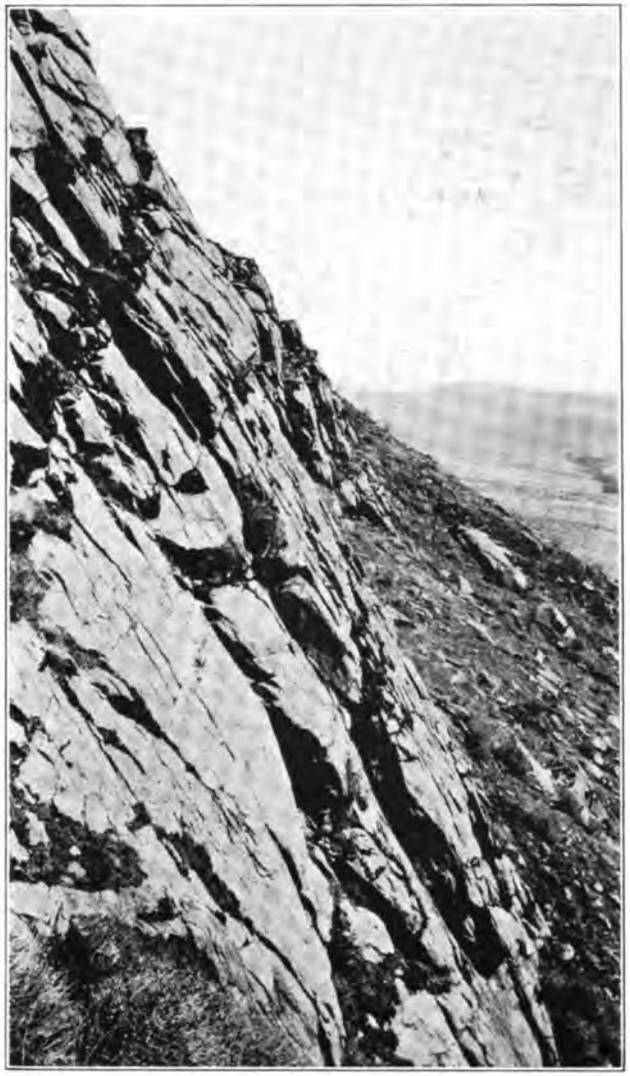
A

B

FAULT SCARP AT MOUTH OF LOWER CANYON OF KERN RIVER, CALIF.

From photographs by W. C. Mendenhall. The scarp trends northwest. The two views were taken from the same point, *A* toward the north and *B* toward the northeast. The lifted block is granite (granodiorite), a batholith of the Sierra Nevada. Against this rest Miocene beds, which constitute the hills of the lowland. The facets of the scarp have a slope of 40°. The footwall of the fault, exposed at several points, dips 55°-60°

A. FOOTWALL OF FAULT ABOUT 1,000 FEET NORTH OF THE RIVER, LOOKING SOUTHEAST



B. VIEW SOUTHEASTWARD ACROSS THE MOUTH OF THE CANYON

The profile of the granite body at the left (lifted block) shows two slopes. Where protected by talus and other material its slope is the dip of the fault plane. Above the talus it has been graded to a slope little steeper than that of the talus

DETAILS OF FAULT SCARP AT MOUTH OF CANYON OF KERN RIVER, CALIF.

A. SLUMP TERRACE UNDER SCARP

B. UNSLUMPED SCARP

DETAILS OF FAULT SCARP AT MOUTH OF CANYON OF KERN RIVER, CALIF.

grams of Figure 52 show two types of cross profile, with associated surface material, displayed by the slabs, and the third gives a hypothetic section. The upper parts of all these slabs resemble the higher part of the escarpment and appear to consist of bedded lavas. In most places their lower slopes are of talus, but in one place outcrops of bedrock occur close to the lower edge.

The hypothetic section assumes that these slabs are fault splinters, or parts of a single splinter, and that the dip of the fault is about the same as the measured dip of the Plum Ridge fault. As to the second assumption there may be much question. The surface features would be substantially the same whatever the dip, unless it were at a lower angle than the angle of rest. The assumption under which the sides of the splinter are drawn as parallel is likewise gratuitous. It is also improbable, for the fact that several splinters have been inclined by rotation suggests that they do not extend indefinitely downward but wedge out.

Close to Modoc Point is a rounded buttress of uncertain origin. Its contours as well as its profile are convex, and its visible part may be described as lenticular. No evidence was obtained as to its internal structure. As we drove past it I classed it with the thin splinters, but later study of its photograph (see pl. 37, *A*) inclines me to the view that it is a landslide. If it is a splinter its type is distinct from that of its neighbors.

The dominant material of the escarpment is basalt, and this is disposed in beds which in the scarp section appear horizontal. They may be assumed to incline northeastward, parallel to the slope of the upland, and to their inclination may be ascribed the backward slope of the fault-splinter terrace shown in Figure 51. Different rocks and a different structure were seen only at a point east of the middle of Plum Ridge, where high on the scarp lie rocks distinguished from the basalt by color and weathering and showing high dips in two or more directions. This portion of the Modoc scarp is not creased by streams from the upland above it. The contours on the map indicate that the slope of the upland is eastward from the very crest. The notch seen in the crest line near Modoc Point (pl. 36, *A*) does not mark a valley of erosion antecedent to the Modoc fault but a diastrophic valley, presumably contemporaneous in origin. The trend of the valley is a little east of north, as indicated by the map, and its main drainage is northward. The divide is close to the Modoc scarp. Its sides, so far as visible from Plum Ridge, are of unequal slope, the eastern having the habit of a fault scarp and the western rising more gradually. According to the contours on the map neither side is of simple form, but the slope of each is interrupted by a trench parallel to the main valley and draining northward. One of these trenches, running south to the Modoc scarp, makes a small notch in the scarp crest, a notch recorded by the camera in Plate 36, *A*.

It appears to me legitimate to interpret these features, which are known only through map contours and imperfect distant views, in terms of the physiographic types of the region to which they belong. If the region were one of Appalachian structure and Appalachian sculpture we should infer that these ridges and hollows mark severally the outcrops of resistant and yielding strata. If the general expression of the landscape had been given by glaciers we might surmise that the ridges are morainic. And so, because all the great features, as well as many minor features, of the environment have their origin in dislocation, I am confident that dislocation is responsible for these also—that the fault block of which the Modoc scarp is the southwestern is here locally sliced by a group of north-south faults with downthrow to the west and that the intervening blocks are tilted to the east.

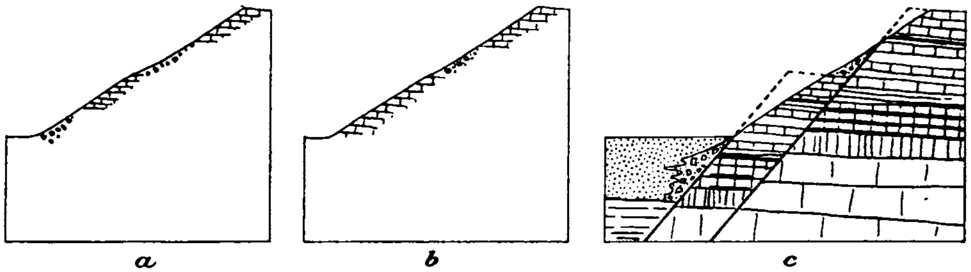


FIGURE 52.—Thinner fault splinters of Modoc scarp, near Naylox, Oreg. *a* and *b*, Cross profiles, with observed elements of structure; *c*, ideal section

I note in passing that the lenticular buttress above described lies immediately below the smaller notch in the crest of the Modoc scarp.

For 7 miles north of Modoc Point the escarpment faces an open plain, and in following the road across the plain we had an unobstructed view of it, although mostly at a distance. Farther north the country is timbered, and our route through the timber afforded only here and there glimpses of the escarpment. In the portion best seen the face resembles that of Plum Ridge. There are no fault splinters. The slope is approximately at the angle of rest. Outcrops of rock appear to be of bedded lava, and these are visible from the crest downward. On the average their lower limit is at midheight, but at one place they leave only the lower fifth of the profile to talus. The profile of the detritus does not clearly distinguish a talus portion from a flatter basal apron but shows a continuous curve from the top of the talus to the alluvial plain. There is no furrowing of the face by erosion, but it is divided by four sharply cut canyons.

The upland slopes backward from the crest of the scarp, and the back slope meets within a few miles the fore slope of another less regular ridge, thus defining an upland valley. The canyons carry the drainage from this valley. At the mouth of each canyon lies an alluvial fan, whose slope is adjusted to the slope of the canyon bed. Two of the fans are small and steep, and the ravines above them look youthful. The other fans are broad and flat, and the associated canyons are shown by the map to drain larger areas.

The valley with four outlets is the structural valley that forms the notch in the sky line near Modoc Point (p. 81 and pl. 36, *A*). The fact that its drainage escapes at four points instead of one indicates that before the uplift and eastward tilting the tract was divided by eastward-trending ridges, and its drainage ran either eastward or westward. It is therefore probable that the present lines of westward drainage are antecedent to the uplift. A few miles farther north Sprague River crosses the upland in a youthful canyon that is clearly antecedent. The fact that the river was not diverted to an easier route around the north end of the uplift and the further fact that the small streams retained their courses give assurance that the rising of the fault block was gradual.

At the mouth of its canyon Sprague River is bordered by volcanic agglomerate, and the same material occurs in a hill that stands west of the main fault scarp. At several points west of the scarp sedimentary strata, chiefly sandstone, are exposed, and at one point these are overlain by agglomerate. In a railway cut north of Chiloquin station the sedimentary beds show folds that have steep dips.

Most of the general statements concerning the Plum Ridge scarp apply also to the Modoc. The terrane dislocated in the creation of the Modoc scarp included sedimentary beds, clastic volcanic rocks, and bedded lavas, of which the lavas are the latest wherever sequence was noted. The prefaulting topography was of moderate relief. Faulting was accompanied by tilting. The blocks east of the fault were tilted eastward.

Except at the extreme north the dominant rock in the scarp face is basalt, and the associated scarp profile approximates the slope of angular talus. At the extreme north other rocks are exposed, and the scarp is less regular and less youthful in appearance. Through a middle tract the fracture was compound and the scarp face shows many slablike splinters. South of Modoc Point the drainage of the uplifted block is consequent, and the higher edge of the block parts the waters. North of Modoc Point the principal drainage is antecedent, five streams having persisted and cut trenches through the ridge.

The sharpness of these trenches and the fact that the scarp face is in general unfurrowed testify to the youth of the scarp. The persistence of antecedent streams speaks of gradual growth, but no evidence was found that growth has continued to the present time.

FORT KLAMATH ESCARPMENT

The scarp running north from Klamath Agency was seen only from carriage roads. Our route lay parallel to the bluff as far as Fort Klamath and then turned westward. The scarp seemed in general less bold than its companions, except at one place, and there it presents a basaltic cliff so steep that only a few trees find foothold. Near Klamath Agency copious springs rise at its base.

Midway between Fort Klamath and the Indian Agency the level sky line of the scarp is interrupted by a notch in the form of a broad U, whose width across the top is about four times its depth. The bluff is here perhaps 300 feet high, and the sill of the notch is halfway up. This hanging valley was noted by Professor Johnson, and his interpretation that it is the valley of an eastward-flowing stream, which was beheaded by the uplift, seems to me well grounded. The remnant of the drainage line which is tributary to Williamson River is shown on the map. Where it crosses the scarp the valley is a sharply delimited groove, but it has developed somewhat beyond the ravine phase. It records rejuvenation, and the stimulation of the stream's local activity may plausibly be ascribed to the uplift that created the scarp. The edge of the uplifting block may be pictured as an obstruction to the stream, through which it erodes a ravine, and the stream has time to begin the broadening of its narrow way before the continuance of dislocation opens another outlet for its water.

About a mile north of the hanging valley a fault splinter was noted.

I did not visit the region immediately south of the Klamath Agency, but certain details of the map indicate that the scarp, instead of ending at the agency, continues southward with lessened height for about 7 miles. There is a suggestive contour: the east shore of the north arm of the lake is nearly straight and is not bordered by marsh, and a road deviates to follow the lake shore instead of taking a more direct course. If the scarp has the extent thus indicated its entire length is 23 miles. It is possible that the fault continues still farther and curves eastward, to join the Modoc fault of Modoc Point, its topographic expression being concealed by the valley deposits.

THE FACE OF THE CASCADE RANGE

The Fort Klamath scarp springs abruptly from a plain of peculiar evenness, which in that part is 6 to 8 miles wide, and west of the plain rise mountains of the Cascade system. (See map, pl. 34.) Farther south the plain is wider and is in part flooded by the waters of Upper Klamath Lake. Beyond the end of the Fort Klamath scarp it is walled on the east by the Modoc scarp. South of the latitude of Modoc Point it is divided by a chain of hills.

The mountains that stand next to the plain on the west side have the appearance of volcanoes long extinct and, for the most part, maturely dissected. Their principal peaks, from 2 to 3 miles back from the edge of the plain, rise from 2,000 to 4,000 feet above it. From the north end of the plain to Pelican Bay, a distance of 20 miles, the mountain mass is continuous, and a broad but isolated mountain stands south of Pelican Bay.

The mountains are forested to their base, but the plain is open. Our observations included distant views from the plain and such inspection of the base as could be made by following a carriage road through the forest. As inferred from the distant views, and especially from the contours on the map, the character of the topography changes at this line of front. Parallel ridges and linear escarpments, which are characteristic features on the east side, occur on the west only as spurs between gorges of erosion and as the walls of canyons. The mountain front is rather bold and exhibits a notable amount of alinement, features which in their combination are strongly suggestive of a line of dislocation. The examination of the mountain base failed to discover evidence of faulting coordinate with that of the scarps east of the plain. The rock base is definitely marked, and its outline is simple except where it is crossed by large streams, but the slope does not approach the talus angle. The rock base is fringed by an apron of alluvium, and large low-grade fans have been spread by the larger of the creeks that issue from the range. Opposite Pelican Bay, where the chain of volcanoes is interrupted by a transverse valley, both apron and fan are submerged beneath lake waters and marshes.

From these data I infer, as probable, that the eastern face of the Cascade Mountains was here determined by a fault with throw to the east; that the dislocation occurred after the principal eruptions by which the range was built but before the excavation of the great canyon valleys by which the mountains have been dissected; and that the valley which is occupied in part by Upper Klamath Lake was created afterward by the uplift of tracts along its eastern and southern margins. The scarps described on earlier pages pertain to the later epoch of dislocation.

RIDGES WEST OF UPPER KLAMATH LAKE

Mention has been made (p. 79) of a group of small ridges about the south end of Plum Ridge. This group may be thought of as the eastern end of a barrier which runs west-southwest to Klamath River and separates the basins of Upper Klamath and Lower Klamath Lakes. The outlet of the upper lake crosses the barrier at Klamath Falls. The barrier is irregular in form and is composed of many hills or small ridges which individually trend parallel to Plum Ridge, or at right angles to the general line of the barrier. North of the barrier are scattered small ridges with the same general trend, and a chain of somewhat larger ridges runs northward for 15 miles, separating Long Lake Valley from Wocus Marsh and Aspen Lake from Upper Klamath Lake.

I had a near view of ridges about Long Lake Valley and distant views of many others, so that I was able to extend an observation made by Professor Johnson that the fault-block system west of Plum Ridge is antithetic or complementary to the Plum Ridge-Modoc system in that the prevailing throw of the faults is on the east side and the prevailing tilt of the blocks is to the west.

The number of distinguishable ridges is large, and the number of component fault blocks is larger. From data in my notes and photographs I could enumerate about 15 blocks, and the actual number must be several times as great. It is a region of minute slicing of the preexistent terrane.

Plate 37, *B*, shows a group of westward-dipping ridges, as seen from the southeast.

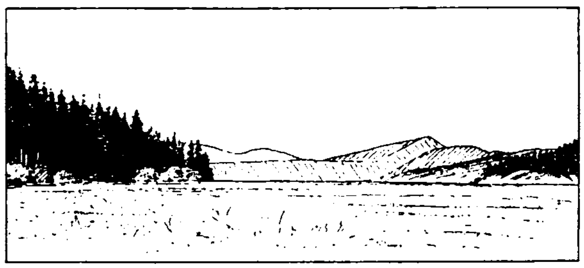


FIGURE 53.—North end of Long Lake Valley, Klamath County, Oreg.

A few scarps have such height and length that they may be distinguished as major, although they are not comparable with the major scarps of the eastern system. Perhaps the most prominent of these is the scarp that borders Wocus Marsh, but this I know chiefly from the map. Another borders Upper Klamath Lake from Squaw Point to Porcupine Point and is strongly expressed by the contours. The bedding of the associated ridge, as seen from the east, appears to lie nearly level.

A third major scarp walls Long Lake Valley on the west and l as the sharp definition of the Modoc scarp. It is about 8 miles long and 300 to 400 feet high. At the north end of the valley it is intersected by a southward-facing scarp, and the topography suggests that two faults here cross. Figure 53, although based on a photograph, is in part sketched, for the distant hills, of which the camera recorded only the sky line, have been interpreted by the aid of a notebook diagram. At the right are shown profiles of the east wall of the valley, a dip slope. At the left is shown a salient of the west-side scarp, here less steep than elsewhere. Beyond the salient the scarp reappears in the distance with its normal facies and then abruptly ascends, as if climbing over the intersecting scarp and ridge.

If the tentative interpretation of these features is correct, and one fault is here crossed by another, the occurrence is exceptional rather than typical. Ordinarily in this region the meeting of two faults is by the ending of one against the plane of the other.

THE VALLEYS

The only valleys of the district which can be ascribed to erosion are narrow and youthful, the canyons of the uplands. Although the surface rocks are chiefly volcanic, none of the lake basins of the district have originated through the obstruction of drainage by lava flows. All the lowland valleys and most of the upland valleys, except in the Cascade Mountains, are tectonic.

The valley of Upper Klamath Lake, which was created by uplift on the east and south, has received large deposits and is conspicuously flat—so far as its bed is visible. Its flatness is evidently due to deposition. The largest of its plains, built by outwash from the slopes of the Crater Lake mass, is composed of pumice, and that material is presumably the chief factor in the filling of the valley. From the edge of this plain to the main body of the lake the valley for 10 miles is occupied by marsh, and there are many other marshy tracts about the shore. The presence of these marshes suggests that the gentle slopes of the visible parts of the valley floor are continued beneath the water.

As already mentioned, the fault-block hills which diversify a part of the valley all lie south of Modoc Point. If such hills were formed in the northern tract they have been buried by the flood of pumice.

Southwest of Pelican Bay a carriage road follows for some distance a beach ridge which is adjusted in height to the present level of the lake but is no longer washed by the lake waves. Between the beach and the open water lie 2 miles of marsh, and the age of the beach is measured by the time necessary for the development of the marsh. The fact that the local lake level has not changed in that time indicates stability not only of this part of the coast but of the sill at Klamath Falls and accords with the physiographic evidence that the fault scarps have not grown in very recent time. Of the same tenor is the statement, by a resident for 30 years, that no earthquakes have visited the region.

Long Lake Valley, the valley east of Plum Ridge, and, in less degree, the valley of Aspen Lake are notable for the flatness of their floors, and the same remark applies to the broader valleys of Upper and Lower Klamath Lakes. The sharp change in slope at the base of a scarp is commonly due in large part to the burial of its base by the flat-topped valley deposit. Hills that rise from the floors of the larger basins have inconspicuous alluvial aprons and appear as islands in a sea of alluvium. It has occurred to me that the association of mature gradation of valley floors with the youthful topography of fault scarps may be connected with an abundance of volcanic ash. Pumiceous sand such as was seen near Fort Klamath is so little heavier than water that it can be redistributed by streams with great rapidity. Its available quantity,

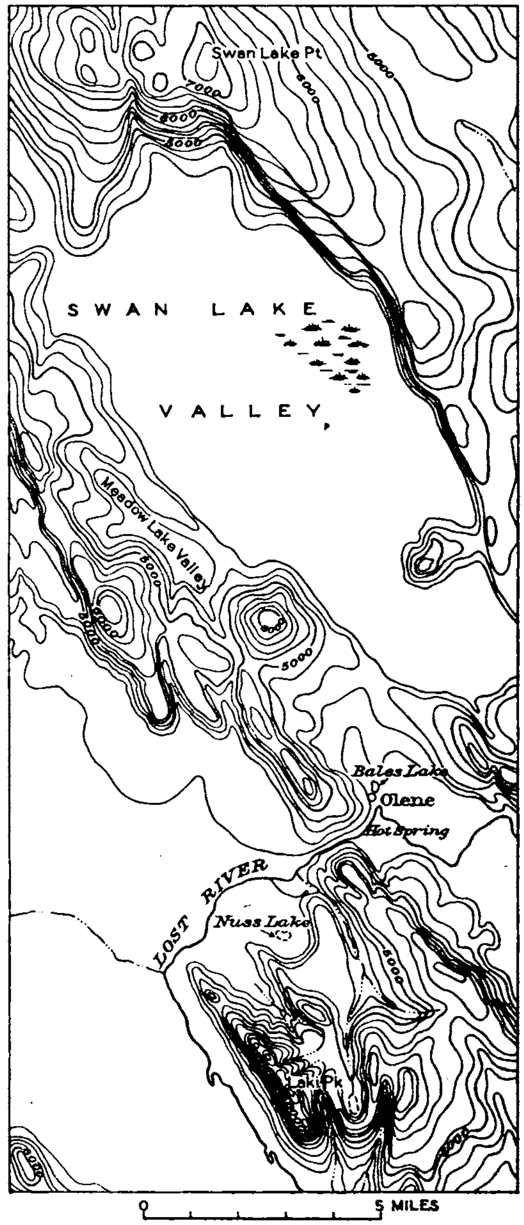


FIGURE 54.—Map of Swan Lake Valley and vicinity, Oregon. From the Klamath topographic map. Contour interval, 200 feet

unlike that of other easily moved débris, is independent of the slow processes of rock decay. The sheet spread over the land by an explosion may be quickly gathered in the hollows and graded to gentle slopes.

THE PREFAULTING TOPOGRAPHY

The occurrence of parallel beds of basalt in the upper parts of the principal scarp faces suggests the existence of a broad lava plain before the period of dislocation in which the scarps originated, but there is also evidence that the lava plain was neither omnipresent nor uniformly level.

Near the north end of the Modoc scarp lie tracts that are occupied by sedimentary rocks and agglomerates, the former older than the latter. Near the south end of Plum Ridge stand hills of sandstone without lava caps, and not far away there is an exposure of sandstone beneath a lava bed, It is not to be supposed that the sedimentary rocks were wholly covered by lavas at the time of the dislocations that produced the Modoc and Plum Ridge scarps, for a period of erosion sufficient for the removal of the lava caps would not have left the scarps unfurrowed. It is possible that the sedimentary rocks were not everywhere buried, and it is also possible that, after having been buried, they were locally denuded in consequence of uplifts which preceded the dislocations associated with the existing scarps. My data are too meager for the discussion of such suggestions.

Although the long scarps are in many respects remarkably uniform, their crest lines, or the upland strips immediately adjacent to them, are somewhat uneven. The forms of a few inequalities are such as to indicate origin by erosion, and the forms of a few others indicate dislocation, but there are yet others which are more plausibly explained as features of the prefaulting topography. They are smooth hills of moderate slope, except as affected by faulting, and may be the worn remnants of small volcanoes. They were not visited, and the suggestion as to their nature comes in part from their association with the widespread lava flows and in part from Russell's description of an unfaulted lava field in central Oregon.[3]

[3] Russell, I. C., U. S. Geol. Survey Bull. 252, 1905.

The hypothesis that before the period of dislocation the general features of the region were a lava plain and volcanic hills to mark points of eruption is in accord with the shapes of hills and small mountains a little farther south, as interpreted from distant views and from the windows of railway trains. The Laki Peak group, as seen from the northwest, has unmistakable block-fault characters; its southwest face, straight and cliff-like (see fig. 54), which springs abruptly from a plain that inclines toward it, is clearly a fault scarp, and a strong spur farther east is bounded on the southwest by a fault scarp; but the summit forms, except at the extreme west, are of a distinct type. A group of hills that trend southwestward and border Lower Klamath Lake on the northeast appear from the north to be bounded on both sides by fault scarps, and their tops include plain elements that have a gentle tilt toward the east, but above the plain elements are also rounded summits. A line of southeastward-trending hills, which is crossed by the railroad near Dorris, shows tabular summits with moderate inclination, as if faulted up from an even lava plain, but the forms of the group of larger hills south of Dorris, though equally characteristic of block faulting, suggest a less even antecedent surface.

These neighboring uplands, which offer for study distinct phases of fault-born relief, aroused longings for close acquaintance that could not be gratified. I commend them to students of mountain structure and add as a special attraction that close at hand is a fault splinter of magnificent proportions. One may read from Mr. Ricksecker's faithful contours in Figure 54 that the northeast wall of Swan Lake Valley is a fault scarp that is comparable with the Modoc, and that a splinter more than half a mile in width slopes southward along its face

Chapter V. FAULT SCARP NEAR BAKERSFIELD, CALIFORNIA

GENERAL FEATURES

The photographs reproduced in Plate 38 were made by my colleague Mr. W. C. Mendenhall and gave me my first intimation that the western base of the Sierra Nevada is in part defined by a fault. The fact was well known, however, to others and has been recorded in the literature of the range. Mention of faults in this particular locality is made by Anderson.[1] The scarp as pictured has a strong family resemblance to the western faces of the Wasatch and Logan Ranges and is a fine example of a youthful fault scarp in nearly homogeneous material. I availed myself of the first opportunity to visit the locality (in October, 1914) and was so fortunate as to have the companionship and guidance of Mr. C. L. Moody, of the University of California, who, as a student of the Miocene formations of the district, had acquired an intimate acquaintance with the local geography and geology.

At a point about 15 miles by road east of Bakersfield, Kern River leaves the great granite body of the Sierra and enters a district occupied by easily eroded rocks of Miocene age. It is possible that but for the work of the river the contact of the two formations would not have a strong topographic expression at this point, but the river, while carving only a narrow passage for itself through the granite, has developed a terraced valley just beyond. Through that development and through the activity of small tributary streams the face of the granite has been exposed.

My primary motive in visiting the locality was to learn whether the photograph's testimony to the existence of a fault is supported by other evidence. The picture shows a mountain block dissected by youthful canyons and bounded by a nearly straight face. The face is divided by the canyons into facets, which are triangular where narrowest and trapeziform where broader. The general slope of the face seems to be about as steep as that which has been acquired through gradation by scarps in the Klamath Lake region, but at the left of the river canyon the lower part of the face is steeper and smoother—just as the fault face on Plum Ridge, in the Klamath region, is steeper and smoother than the graded part of the scarp. So one of the questions to be answered by close inspection was whether the steeper wall bears the polish and striae of the footwall of a fault. Other questions pertained to the character and attitude of the Miocene beds at and near the contact. If the granitic batholith were younger than the strata (a relation for various reasons highly improbable) there might be metamorphism. If the granite face were a sea cliff created or steepened by the waves of the Miocene ocean, the waste from cliff erosion should appear in the adjacent sediments, whereas if the present relation were brought about by the upfaulting of the granite the sediments would not have characters indicative of the immediate presence of a granite cliff.

VERTICAL GROOVING AND JOINTS

Near-by inspection of the steeper face found no well-defined slickensides, which the surface of the granite is evidently too weather-worn to preserve, and no fault rock. There is, however, a vertical grooving, or coarse striation, which is best seen at a little distance, and there are many small patches of thin quartz vein which are vertically fluted in harmony with the grooving. These features tell of differential movement along the exposed plane—or rather planes, for the face is made up of several plane elements, which are parallel and separated by narrow terraces. A portion of the lowest plane element is pictured from a photograph in Plate 39, *A*, and the relation of the elements to the terraces is shown diagrammatically in Figure 55. The terraces are narrow, they are occupied by soil and other loose waste, they are parallel, and the lines they trace across the face are oblique, rising from left to right.

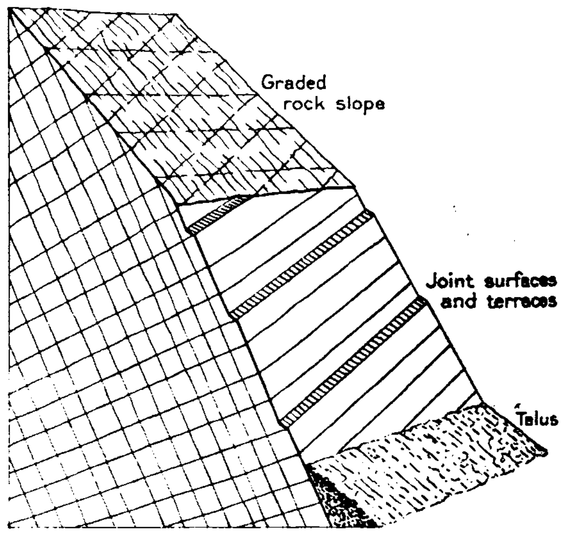


FIGURE 55.—Ideal segment of the granite body near mouth of Kern River Canyon, Calif., showing graded and ungraded portions of scarp and the relations of terraces to joint systems

Both the plane elements and the terraces are associated with joints. Among the many joints by which the granite is riven it is possible to distinguish three sets as relatively notable. One of these coincides

[1] Anderson, F. M., The Neocene deposits of Kern River, Calif., and the Temblor Basin: California Acad. Sci. Proc., 4th ser., vol. 3, p. 82, pl. 6, 1911.

in strike (southeast) and dip (59°) with the plane elements of the rock face. The joints of the second set dip obliquely into the mountain at about 25°, in such a way that the lines in which they meet the rock face are parallel to the terraces. Those of the third set dip 80° SE. and strike at right angles to the rock face. Only the first and second sets are indicated in Figure 55. The plane elements of the rock face are either joint surfaces of the first set or dislocated parts of a single joint surface. The terraces are in some way determined by joints of the second set. It appears to me most probable that the plane elements were once united as parts of a single joint surface and that after the differential movement which produced the vertical striation they were separated by small movements of the nature of step faulting, which took place on joints of the second set.

The evidences of differential movement were seen only on rock surfaces belonging to the system of joints first mentioned. They were well observed only on the outer surfaces associated with the terraces, but patches of white ascribed to vein quartz were seen far up the slope on inner joint surfaces which have been exposed by erosion (that is, on the "graded rock slope" of fig. 55), and if such occurrences are similar to those on the outer surfaces it would appear that the differential movement was not restricted to a single plane but was more or less diffused through a zone.[3]

The steep face partly shown in Plate 39, *A*, and diagrammatically represented in Figure 55, is about 400 feet high. There is no suggestion as to the vertical extent of the rock surface to which it belongs, except that the visible part is a part only. Above the upper limit of the exposure the surface has been destroyed by erosion; below the lower limit it is covered by a mantle of talus. No other large exposure occurs, but a series of minor exposures (see pl. 40, *A*) show that the surface continues northeastward for at least 2 miles, and its presence southeast of the river is clearly indicated by Plate 39, *B*. In taking that photograph the camera was placed approximately in the plane of the steep rock surface, with the result that the lines of the view bring out the essential relations. The granite above the head of the talus has been graded to a slope little steeper than that given by the talus profile, and the slope of the granite where protected by talus and associated formations is about the same as that of the exposed wall north of the river. The body of protecting material is composed superficially of talus and near the river of coarse alluvium, but its principal constituent is doubtless a remnant of a Miocene formation, which occurs in neighboring hills at the same level.

The steep granite face revealed by the exposures and by the quasi section, which stands at an angle greater than the angle of rest, is a cliff and as such is a feature to be explained. Cliffs have many modes of origin, but the only ones that need be considered here are those by wave attack and by faulting. The association of the cliff with marine deposits may properly raise the question whether the waves of the Tertiary sea created it as a shore cliff by sapping at its base. If such were its origin the accordance of the cliff with a joint plane, or with a few joint planes, must be ascribed to coincidence; but the difficulty thus suggested is perhaps less serious than the difficulty of accounting for the burial of the cliff by marine sediments. In order that the sediments might be deposited after the creation of the cliff the land must have been submerged, and during the submergence the waves would attack the cliff at levels above its base and remodel it—unless, indeed, the submergence were catastrophic. It is evident that the hypothesis of origin by faulting does not encounter these difficulties.

CHARACTER AND RELATIONS OF THE MIOCENE BEDS

I turn now to the evidence which may be afforded by the character of the Miocene beds and by their relation to the granite. The beds are in general so soft and they weather so readily into a condition of incoherence that their sequence and structure are not apparent. Outcrops that show dips are rare and discontinuous, and there has been so much slumping of hillsides that many observable dips are of doubtful significance. Several miles north of the river the formation includes a thin limestone, and 1 or 2 miles south of the river it includes a conglomerate, but these exceptional strata are of slight extent, and their order of sequence has not been established by stratigraphic evidence.

At the river the granite upland stands 2,500 feet above the Tertiary lowland. Toward the northwest the upland loses in height and the Tertiary hills gain in height, until at a distance of 3 miles no noteworthy difference remains. The line of contact between the two formations, which for that distance is direct and distinct, then becomes sinuous and indefinite and swings toward the northeast. It ceases to be the boundary of a Tertiary formation resting against the granite face and becomes that of a Tertiary formation overlying the granite. In the region in which the Tertiary overlies the granite the limestone bed crops out on the side of Pyramid Hill, at an altitude of 2,000 feet above sea level. Where the Tertiary beds rest against the granite face 2 miles farther south there is an outcrop of the same bed at about 1,400 feet above sea level. The difference in height is not accounted for by such observations of dip as are available and may plausibly be ascribed to dislocation.

At the lower locality the outcrop is so close to the granite as to give significance to the testimony afforded by the limestone on conditions of deposition. The slope of the granite face is there about 40°, and a narrow

[3] Becker, G. F., Geology of the Comstock lode and the Washoe district; U. S Geol. Survey Mon. 3, ch. 4, 1882.

spurlike hill of the Tertiary formation rests against it, essentially in the manner represented by Figure 56, which is a diagrammatic sketch from memory. The limestone bed appears in the side of the hill, 40 feet from the granite, and dips away from the granite at 19°. The stratum consists largely of unbroken shells of *Pecten*, *Dosinia*, *Chione*, *Natica*, *Dentalium*, *Bullia*, and other forms and tells of deposition in quiet water. It is manifestly out of place in its present relation to a granite cliff if that cliff was carved out by the waves of the Tertiary sea, but its position and attitude are in accord with the hypothesis that the cliff was created by faulting.

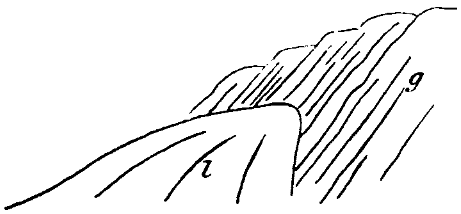


FIGURE 56.—Ideal sketch to show the relation of an observed outcrop of limestone (*l*) on a hill of Miocene beds to the granite face (*g*) against which the hill rests, Sierra Nevada, Calif.

The bed of conglomerate is not closely associated with the granite face. Its outcrop is 2,000 feet from the contact, and the plane of its dip is such that when projected upward from the outcrop it passes above the granite.

SUMMARY AND CONCLUSIONS

To recapitulate: The granite escarpment is nearly straight for about 5 miles, except that where it is graded by recent weathering it has the steepness of a cliff, and it is faceted. These features indicate that the mass has been truncated. The possibility of truncation by fluvial or glacial erosion need not be considered, because no companion wall faces the escarpment. The hypothesis of the formation of the cliff by wave action is discountenanced by the smoothness of those parts of the cliff which are well preserved, by the difficulty of explaining its preservation during burial by marine sediments, and by the fact that the character of the sediments does not indicate the near presence of a granite shore cliff. Truncation by faulting is indicated by the coincidence of smooth cliff faces with joint planes and by the evidence on those planes of differential movement but lacks the confirmation which would be afforded by the presence of fault rock.

The local exposure of 400 feet of the fault wall (see pl. 38) is a noteworthy feature. The locality is not far from a low terrace made by the river, but no evidence was found that the river in the swinging of its meanders actually washed the base of the cliff. The local details indicate rather that the approach of the river caused a landslide, and that the slid body of Miocene beds, after moving into the track of the river, was washed away, with the exception of a small remnant. Since that event the river has shifted to a new position and has sunk its channel to a lower level. The time that has elapsed since the occurrence of the landslide is the time during which the fault wall has been exposed to agencies of weathering.

The remnant of the slid mass, which may be seen in Plate 38 and which appears at *a* in Figure 57, is sheathed by large angular blocks of granite, quite distinct from the worn boulders of the river terrace. These blocks must have come from the upper slope of the granite, *b*, but could not make the journey under present conditions. It may be assumed that they once rested on a graded slope of Miocene beds, became more or less mingled with the material that composed those beds during the sliding, and have been concentrated on the present surface by the washing out of finer material. The talus at *c* has been built since the slide, and so has the sloping plain of alluvium between *c* and *a*.

A series of peculiar terraces associated with smaller exposures of the fault wall admit of a similar explanation. Their type is illustrated by Plate 40, *A*, where numerous angular blocks (at the left) are separated from the parent body of granite (at the right) by an alluvial plain of gentle slope which is the platform of a terrace. The outer face of the terrace is outside the field of view but may be seen in Plate 38. Here also the phenomena are ascribed to sliding. A large body of Miocene deposits has moved forward from the

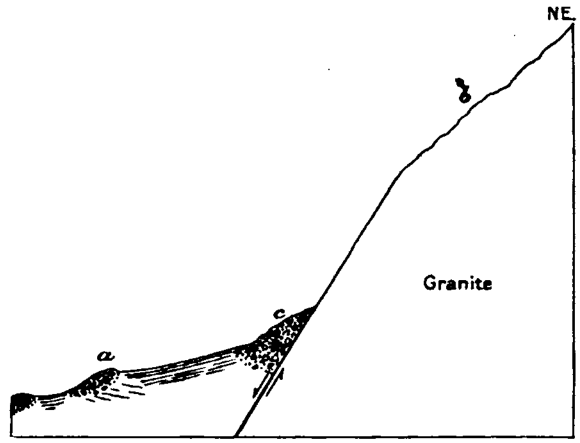


FIGURE 57.—Profile of fault scarp at principal exposure of footwall north of Kern River, Calif.

granite and has at the same time either rotated toward it or else slumped along its upper edge, with the result that its crest stands at some distance from the granite. The interspace has since been aggraded by waste, fine and coarse, from the upper slope of the granite, but degradation of the crest has been arrested by the coarse waste there lodged. The outer faces of such terraces bear many large angular blocks, and so do certain terraces and outlying hills at lower levels. It is evident that the history of sliding has not been simple, but it can not now be read in full because much of its record has been effaced by subsequent erosion.

I discovered no evidence of recent renewal of faulting. Because the jar of an earthquake is often the immediate cause of a landslide, such sliding as has here taken place would have been a natural accompaniment of renewed faulting, but if the baring of the fault wall were due to renewed faulting it would be more general in its distribution than is actually the case. South of the river the yielding formations in contact with the fault wall are undisturbed, and north of the river tracts without disturbance (see pl. 40, *B*) alternate with tracts affected by sliding. The sliding appears to have occurred only where the stability of the Temblor Hills was impaired by the sapping work of the river and its tributaries.

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