

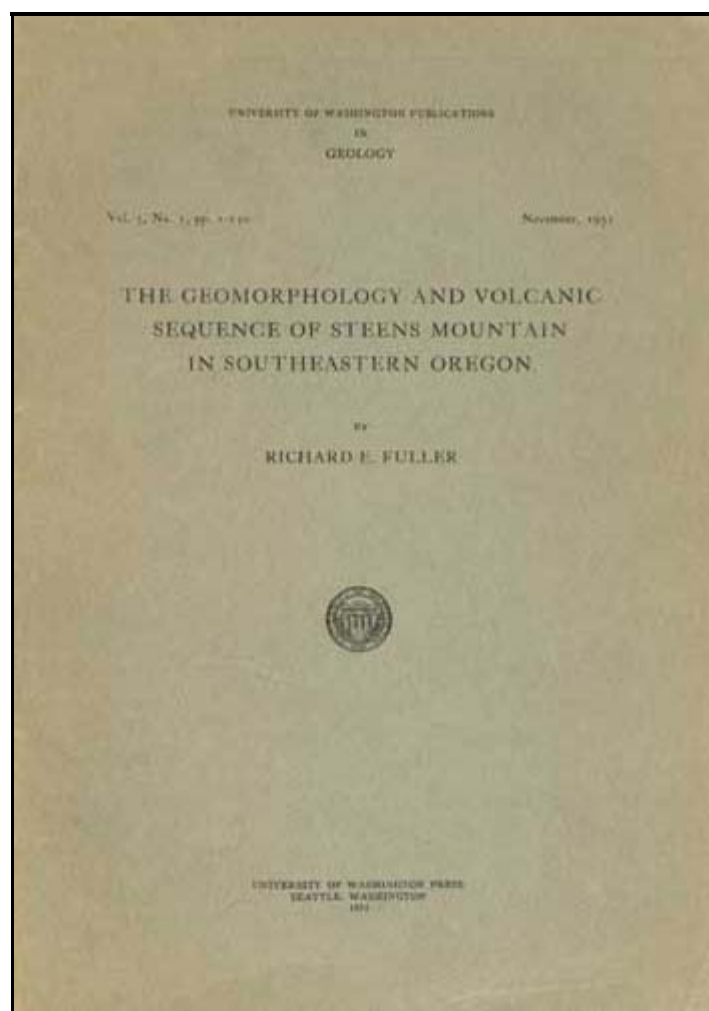


University of Washington Publications in Geology

The Geomorphology and Volcanic Sequence of Steens
Mountain in Southeastern Oregon

THE GEOMORPHOLOGY AND VOLCANIC SEQUENCE OF STEENS MOUNTAIN IN SOUTHEASTERN OREGON

By
Richard E. Fuller



UNIVERSITY OF WASHINGTON PUBLICATIONS IN GEOLOGY

This bulletin is modified from "The Petrology and Structural Relationship of the Steens

Mountain Volcanic Series of Southeastern Oregon," a thesis submitted at the University of Washington in 1930 in partial fulfillment of the requirements for the degree of doctor of philosophy

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INTRODUCTION

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THE GEOMORPHOLOGY AND VOLCANIC SEQUENCE OF STEENS MOUNTAIN IN SOUTHEASTERN OREGON

By RICHARD E. FULLER

LOCATION

Lying in the arid sage-clad region of southern Oregon, Steens Mountain forms by far the largest topographic feature in the northwestern part of the Great Basin (fig. 1). The major central mass of the mountain consists of a great fault block, which rises gently from the west with an even slope about 25 miles in length. The block, which is but slightly dissected by erosion, is truncated on the east by a scarp, which drops abruptly to Alvord Desert, 5,500 feet below. This scarp has been rendered extremely precipitous by valley glaciation. The summit, with an elevation of approximately 10,000 feet, lies in the south central portion of Harney County, a little less than 50 miles north of the Nevada line at a point approximately midway between the California and the Idaho boundaries (fig. 2).

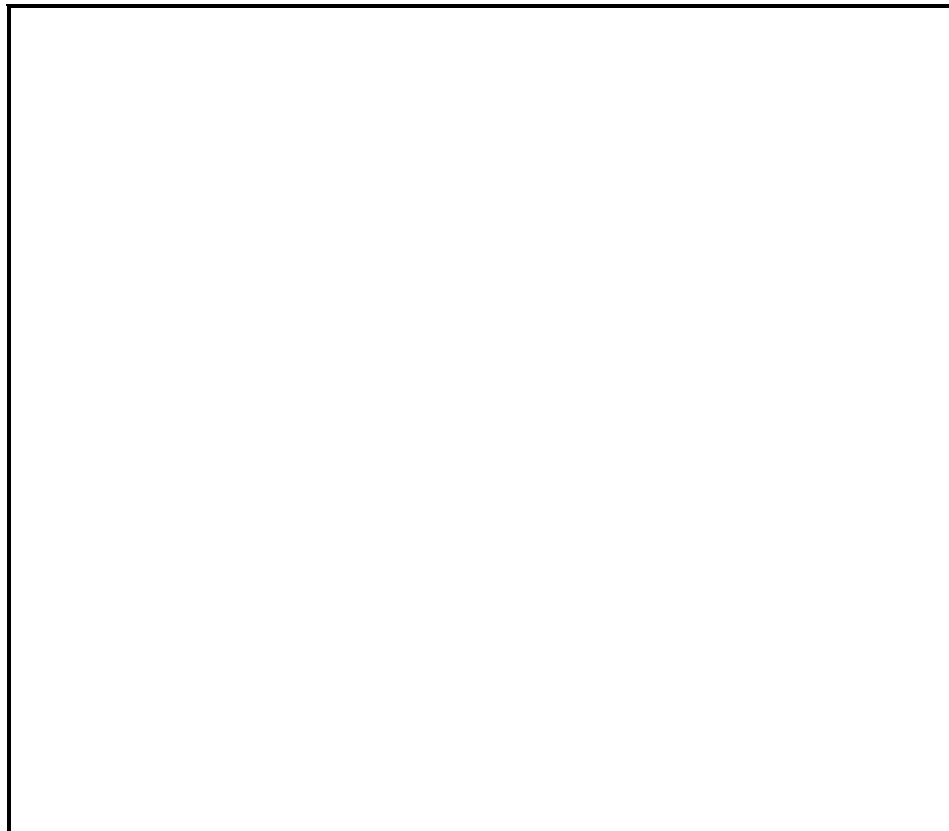




Fig. 1. The area shown in the sketch map in fig. 2 is here superimposed on a section of the "Physiographic Diagram of the United States" by A. K. Lobeck, Chicago, 1921. The scale is approximately 100 miles to an inch. ([click on image for an enlargement in a new window](#))

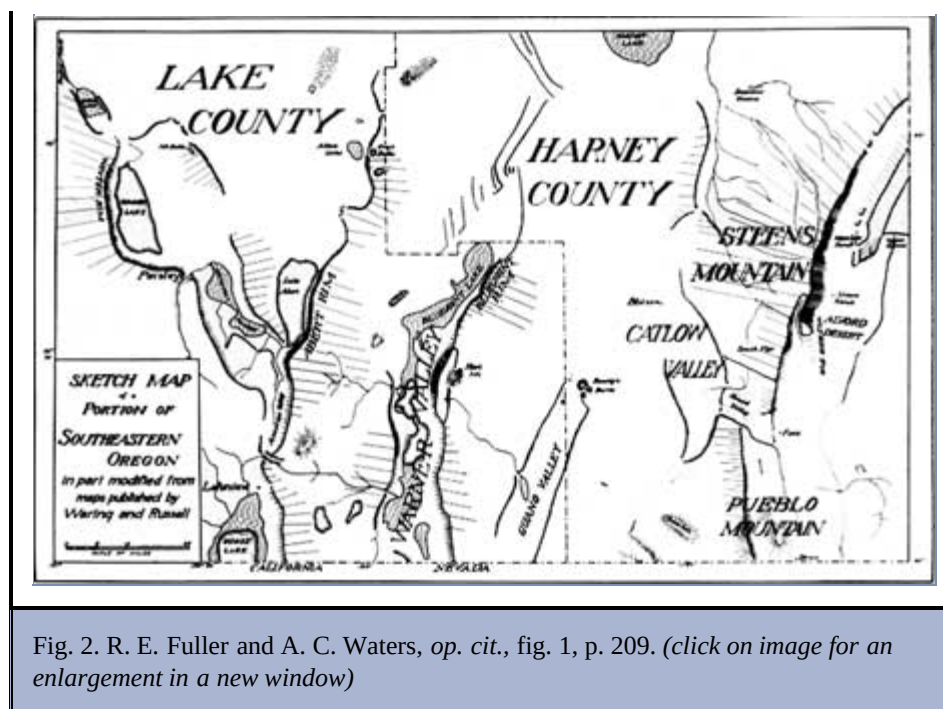


Fig. 2. R. E. Fuller and A. C. Waters, *op. cit.*, fig. 1, p. 209. (click on image for an enlargement in a new window)

NAME

In early reports the mountain is referred to as Stein Mountain, which according to hearsay in the region is attributed to the German word meaning "stone," in reference to the magnificent exposures of rock on the eastern scarp. Subsequently the word was corrupted to "Steins." For at least the last 20 years, however, popular usage of the present generation has firmly established the derived appellation "Steens Mountain."

FIELD WORK

The writer's field work in the region has been distributed over seven summers varying in duration from two to nine weeks in length. The first two years were devoted to reconnaissance and to the study of the basalt of the region in comparison to the Columbia River lavas. This investigation necessitated the examination and sampling of the basalt exposed on the major fault scarps.

Subsequently the origin of the structure formed a temporary objective. This culminated in 1929 in a joint publication with Aaron C. Waters on the "Nature and Origin of the Horst and Graben Structure of Southern Oregon."¹ In addition to a description of the structural features, this paper included brief comments on the volcanic sequence of the region.

¹Richard E. Fuller and Aaron C. Waters, "The Nature and Origin of the Horst and Graben Structure of Southern Oregon," *Jour. Geol.*, vol. XXXVII, p. 204-239, 1929.

CULTURE

Steens Mountain and the adjacent district is very sparsely populated, owing to the fact that its principal industry is sheep raising. In the summer the herds find good pasturage on the higher

mountains, while in the winter they forage on the scanty vegetation of the lower deserts, which are but seldom mantled with snow. This industry is largely in the hands of Spanish Basques. The region also contains several cattle ranches with hay land irrigated by the larger streams. The towns named on many of the maps commonly consist of a single store, which contains the post office. In addition, there are numerous deserted homesteads, which as a rule were established about 25 years ago.

ACCESSIBILITY

A network of roads and the presence of playas enables one to motor to within a few miles of almost any locality. Some of the main roads have been improved. Many of them, however, consist merely of trails worn through the sage brush. Locally occasional cloud-bursts render them very rough. Owing to the trend of the faults, the chief difficulty in traveling lies in going east and west.

To the north, a branch line of the Union Pacific ends at Burns, about 20 miles north of Harney Lake. To the southwest, Lakeview, situated at the northern end of Goose Lake, is the terminus of another branch line. The third outlet of the region is Winnemucca, which lies about 120 miles below the Nevada border on the nearest railroad line to the south. These three towns are all prosperous centers of one to two thousand inhabitants. They are all on well constructed highways.

GENERAL GEOLOGY AND SCOPE OF INVESTIGATION

In southern Oregon, east of the Cascade Range, a varied series of late Tertiary lavas is cut by the northern continuation of the Basin Range faults. The differential movement of the fault blocks has resulted in the formation of seven major depressions which are commonly bounded by precipitous fault scarps varying in height from a few hundred to several thousand feet. These seven depressions, which trend roughly north-south, are in order from west to east: the Klamath graben (containing Klamath Lake), the Summer Lake-Chewaucan Marsh-Goose Lake depression, Warner Valley, Guano Valley, Catlow Valley, Alvord Desert, and McDermitt Valley.

These depressions are all relatively flat-floored owing to the accumulation of sediments in the vast system of lakes which they once formed. The many partially eroded beach terraces on the scarps throughout the region testify to a previous depth of water of about 300 feet above the lake deposits, which in themselves are probably many hundred feet in depth. The surface of the bolson deposit, varying but slightly in the different basins, is over 4,000 feet in elevation.

Since the melting of the Pleistocene glaciers on some of the higher mountains, the lakes have diminished until now their former presence is indicated chiefly by playa flats, which usually have only slight marginal vegetation. In recent years most of the perennial streams in the region have been utilized for irrigation. Denied this replenishment, the few surviving lakes are rapidly being reduced to playas that are flooded only by occasional rains.

The depressions, or grabens, are bounded longitudinally by the steep scarps of the gently tilted fault blocks that border them. Many of these blocks are defined by faults on both sides, and, in consequence, give rise to true horst and graben structure rather than the tilted fault block mountains, which are characteristic of much of the Great Basin. As a rule, the blocks dip away from the major fault.

Only the two highest scarps in the region have been appreciably modified by stream erosion. These two localities are the high eastern face of Steens Mountain and the western side of Hart Mountain, which forms the eastern wall of Warner Valley. Owing to their elevation and the consequent greater rainfall these mountains have many small active streams. The principal erosion, however, probably was confined to the Pleistocene when the climate is thought to have been more humid. To this same period, there is also attributed the marked valley glaciation of the higher portion of Steens Mountain. Fortunately these two localities form the centers of the principal volcanic activity of the region, for the magnificent exposures in the numerous valleys that cut the scarps furnish ideal opportunities for arriving at an interpretation of many of their volcanic phenomena. The higher members of the series, however, have survived erosion only on the lower scarps, which lack the stratigraphic complexity of these two localities. As a consequence their complete interpretation involves merely the study of sections at a few carefully chosen localities.

Although this report is confined principally to the Steens Mountain series, it includes evidence on the stratigraphic relations of these volcanic rocks to those exposed in the adjacent region. Since some of the abundant petrogenetic problems demand additional study, they have been omitted. The investigation practically ceases at the margin of the desert country which may be roughly outlined by continuing to the southwest the line formed by the western wall of the Summer Lake-Chewaucan Marsh depression until it reaches the western scarp of Warner Valley. West of this line, the exposures are less satisfactory, owing to the rapid increase in vegetation as the Cascade Mountains are approached.

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PREVIOUS LITERATURE

GENERAL RECONNAISSANCE WORK

The earliest report on the geology of the region is by James Blake.¹ In the early seventies he examined Pueblo Mountain, which lies directly to the south of Steens and is, in part, defined on both sides by continuations of the same faults. Here are exposed both the southern continuation of the Steens Mountain volcanic series and the underlying crystalline rocks on which it rests. Blake gave a brief description of both the metamorphic and the volcanic rocks and suggested that the latter might form the sequence for a large part of southern Oregon, perhaps even extending northward beyond the Columbia River.

¹James Blake, "On the Pueblo Range of Mountains," *Calif. Acad. Sci. Proc.*, vol. V, pp. 210-214, 1873.

In 1881 and 1882, I. C. Russell made a general survey of the geology of the northern end of the Great Basin. His subsequent report² contained a remarkably good reconnaissance map showing the major faults. He considered the structure to be due to normal faulting. About twenty years later he made a superficial examination³ of Steens Mountain. He noted the basal tuffs, but considered the lavas to consist entirely of basalt.

²I. C. Russell, "A Geological Reconnaissance in Southern Oregon," *U.S. Geol. Survey, Ann. Rept.* 4, pp. 431-464, 1884.

³I. C. Russell, "Preliminary Report on the Artesian Basins in Southwestern Idaho and Southeastern Oregon," *U.S. Geol. Survey, Water-Supply Paper* 78, pp. 16-23, 1903; "Notes on the Geology of Southwestern Idaho and Southeastern Oregon," *U.S. Geol. Survey Bull.* 217, pp. 33-34, 64-69, 1903.

In 1903, a week's study of the southern part of Steens Mountain enabled W. M. Davis to make some general observations⁴ on the structure and physiography of the mountain. In this report he suggested that the southern and middle parts of Steens Mountain are defined by faults on the western side as well as on the east, and therefore, that that portion of the mountain is a true horst. Time did not permit Davis to visit the western scarp, but observations by the writer have subsequently confirmed his impression.

⁴W. M. Davis, "The Mountain Ranges of the Great Basin," *Bull. Mus. Comp. Zool.* (Harvard University), vol. XLII, pp. 164-172, 1903-1905; reprinted in *Geographical Essays*.

About five years later, Gerald A. Waring spent two years in preparing a very able reconnaissance report and map on the geology and water resources of most of the volcanic region of southern central Oregon. This was published in two papers.⁵ Waring did not attempt to do detailed work on the stratigraphic succession, but merely subdivided the lavas into the Earlier Effusives and the Main Lava Flows. R. J. Russell has since called attention to the fact that the acidic lava forming one of the "Earlier Effusives is apparently a later intrusive."⁶

⁵Gerald A. Waring, "Geology and Water Resources of a Portion of South Central Oregon." *U.S. Geol. Survey, Water-Supply Paper* 220, 1908; "Geology and Water Resources of the Harney Basin Region, Oregon," *U.S. Geol. Survey, Water-Supply Paper* 231, 1909.

⁶R. J. Russell, "Basin Range Structure and Stratigraphy of the Warner Range, Northeastern California," *Univ. Calif. Publ., Bull. Dept. Geol. Sci.*, vol. XVII, p. 427, 1928.

LOCAL STRATIGRAPHY IN ADJACENT REGIONS

In 1910, Merriam published an article on the "Tertiary Mammal Beds at Virgin Valley and Thousand Creek in Northwestern Nevada."⁷ Owing to their proximity to the southern extension of the Steens Mountain volcanic series exposed on Pueblo Mountain, both the age and the relationship of these beds are of considerable importance.

⁷J. C. Merriam, "Tertiary Mammal Beds at Virgin Valley and Thousand Creek in Northwestern Nevada," *Univ. Calif. Publ., Bull. Dept. Geol. Sci.*, vol. VI, pp. 21-53, 199-304, 1910-1911.

South of Pueblo Mountain, and immediately west of the tilted spur formed by the southern extension of the volcanic series as it plunges southward, lies the Thousand Creek Basin. This basin, which is but superficially eroded, contains stratified tuffs of unknown thickness. These deposits directly overlie the Pueblo Mountain series which the writer correlates with the upper flows exposed on Steens Mountain. From their vertebrate fauna, these beds were considered by Merriam to be of Lower Pliocene age, but subsequent studies by Dr. Chester Stock⁸ indicate them to be "definitely Pliocene and fairly late in that period." These light colored tuffs are locally capped by a thin flow known as the Railroad Ridge Basalt. This lava was thought to have originally filled a river bed.

⁸Personal communication.

Immediately adjacent to the back of the Pueblo Mountain block no satisfactory exposures are apparent. Merriam observed that the sediments as they near Pueblo Mountain develop a slight dip to the southwest,⁹ but, although the contact was not exposed, he considered the tuffs to bear a strongly non-conformable relationship¹⁰ to the underlying lavas. This interpretation would place the period of faulting and its accompanying deformation relatively early in the Pliocene. This age would be contradictory to the prevailing evidence found elsewhere in the northern portion of the Great Basin, for Louderback's work¹¹ clearly indicated a late Pliocene or a post-Pliocene time for the beginning of faulting. Viewed at a distance from the south,

the tuffs appear to the writer to curve upwards to the east, conformably overlying the flows. These indications, however, are based only on indefinite criteria dependent upon the physiographic expression, soil color and vegetation.

⁹*Op. cit.*, p. 45.

¹⁰*Op. cit.*, p. 29.

¹¹George D. Louderback, "Period of Scarp Production in the Great Basin," *Univ. Calif. Publ., Bull. Dept. Geol. Sci.*, vol. XV, no. 1, pp. 1-44, 1924.

The Thousand Creek Basin is bounded on the south by a steep fault scarp exposing a thickness of rhyolite of at least 400 feet. To the south a series of tuffaceous sediments about 1,500 feet in thickness lies on the irregular surface of this acidic lava, which is referred to as the Canyon Rhyolite. These sediments are overlain by a thin cap of basalt called the Mesa Basalt in reference to its physiographic form. This basalt was thought by Merriam possibly to correlate with the similar Railroad Ridge Basalt in the down-faulted basin to the north. Immediately beneath the Mesa Basalt the exposures are either very steep or covered with talus and unsuitable for the collecting of fossils.

The fauna of the lower beds was considered by Merriam to belong to the Upper Miocene, while the upper part was considered possibly to correlate with the very similar beds in the Thousand Creek region. Subsequent work by Stock,¹² however, indicates the beds in Virgin Valley to be of Middle Miocene age and, therefore, unrelated to those exposed in the basin immediately to the north. Traced northward the great volcanic series of Pueblo Mountain, which is but 10 miles away, also overlies sediments of supposed Middle Miocene age. To prevent the Virgin Valley Beds from being flooded with these relatively fluid northern lavas it is necessary to postulate a barrier, which may have been formed by the great mass of Canyon Rhyolite.

¹²Personal communication.

Recently, Richard J. Russell published an excellent report¹³ on the geology of the Warner Range of California, which forms the western scarp of the southern continuation of the Warner Valley lying about 70 miles west of the southern spur of Pueblo Mountain. Russell was primarily interested in the structure and physiography of the region, but for the purpose of mapping, he divided the volcanic series into stratigraphic units. Although most of this series is probably of a relatively local distribution, a broader correlation was suggested for two of the upper members.

¹³Richard J. Russell, "Basin Range Structure and Stratigraphy of the Warner Range, Northeastern California," *Univ. Calif. Publ., Bull. Dept. Geol. Sci.*, vol. XVII, no. 11, pp. 387-496, 1928.

Near the top of the volcanic series in the Warner Range, basaltic flows form a sheet 30 to 600 feet in thickness. This lava, which Russell named the Warner Basalt, was indicated by its stratigraphic relationship to be Lower Pliocene. Russell considered that this basaltic series thickened to the north to form the great exposures in the northern part of Warner Valley and at Abert Rim. He also correlated it not only with the Mesa Basalt and the Railroad Ridge Basalt, but considers "that it is very likely that this same sheet is, at least, in part, his

(Merriam's) Pueblo Mountain series.¹⁴

¹⁴*Op. cit.*, pp. 416-417.

In northeastern California, a variable thickness of rhyolitic lava caps the Warner Basalt and forms the uppermost member in the local stratigraphic sequence. In a similar manner the extrusion of the acidic lava in this broad volcanic field was thought by Russell to have been confined chiefly to a prolonged rhyolitic period subsequent to the basalt.¹⁵ In order that the sequence in Virgin Valley and Thousand Creek basin might coincide with the type locality he considered that Merriam failed to appreciate the full significance of faulting and, in consequence, misinterpreted the geologic history. Although his evidence is not very coherent, Russell apparently considered that the great exposures of rhyolite adjacent to Virgin Valley and Thousand Creek are due to post-Mesa Basalt extrusion, followed by the down faulting of these capping volcanics.

¹⁵R. J. Russell, *op. cit.*, pp. 427-429.

The present writer, however, is in full accord with Merriam in considering the Canyon Rhyolite to be below the sediments. The actual contact was locally excavated by the writer, and fragments of the glassy rhyolite were found to be included in the stratified tuffs. In addition, the acidic flow capping the Pueblo Mountain series is definitely older than the Thousand Creek Beds. The basaltic series which it caps has no apparent analogy to either the Mesa or the Railroad Ridge Basalt.

Although the base of the Canyon Rhyolite is not exposed, it shows a thickness of at least 300 feet within a horizontal distance of a few hundred yards from the flat persistent cap of Mesa Basalt. If the rhyolite was subsequent to the Mesa Basalt, a considerable thickness must have extended over this level cap. It seems impossible to the writer to have erosion completely strip this resistant acidic lava and still leave the undissected surface that characterizes the thin basaltic cap. Russell, however, gives evidence of local acidic volcanic activity subsequent to the Mesa Basalt. Scattered pebbles of obsidian resting on the surface of this lava offer additional testimony. These may have been deposited in tuffs, which have since been eroded.

Russell's correlation of the Warner Basalt with the Steens Mountain series will be considered in later pages.

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ORIGIN OF THE STRUCTURE

In 1927, after a brief reconnaissance, W. D. Smith published a paper¹⁶ on the stratigraphy and structure of Steens and Pueblo Mountains, chiefly for the purpose of advancing a compressional interpretation of the origin of the former. Smith points out that a similar theory¹⁷ had been previously propounded to explain the structure of apparently analogous features in central Africa.

¹⁶Warren D. Smith, "Contribution to the Geology of Southeastern Oregon," (Steens and Pueblo Mountains). *Jour. Geol.*, vol. XXXV, pp. 421-441, 1927.

¹⁷E. J. Wayland, "Some Account of the Geology of the Lake Albert Rift Valley," *Geog. Jour.*, vol. LVIII, p. 353, 1921.

This hypothesis demands that the tilted fault blocks in the region owe their elevation to steep reverse faults either with or without horizontal movement. This displacement was thought to be due to shearing at approximately 45° to the direction of compression. A graben such as that forming Alvord Desert was considered to be due to mutually opposing thrust faults raising their blocks above an intervening flat floor which was thought to represent the undeformed prefaulting surface.

Without considering the many inaccuracies on which this theory is based, the writer will review briefly, or quote, the eight main arguments advanced by Fuller and Waters¹⁸ to indicate the lack of compressional faulting in the regional structure. A definite establishment of this basic principle is essential for the correct interpretation of many features in the volcanic history of the region, as well as in its physiographic expression.

¹⁸*Op. cit.*, pp. 223-238.

NORMAL FAULTING

No thrust fault has been discovered in southern Oregon, although a number of normal fault planes are well exposed. On Steens Mountain most of these are in zones near the scarp and roughly parallel to it. They result locally in the development of step faults. The step fault blocks cannot be confused with landslides, for they lack the characteristic reverse rotation, and where the faults are exposed the planes show no tendency to flatten even when they can be traced downwards for a thousand feet. Although definite fault surfaces are locally well exposed, the step faulting in this region usually is apparent only from physiographic evidence. Locally the thin blocks may be traced along the scarps for a mile or more. Several miles west of the main fault zone on Steens Mountain there are also some minor normal

faults which dip into the scarp.

GENETIC IMPORTANCE OF STEP FAULTS

"The writers are of the opinion that the numerous step faults defining narrow step blocks which extend for a considerable distance along the fault scarps of southern Oregon are a direct proof of normal faulting and are inexplicable by the compressional hypothesis. Some advocates of the compressional hypothesis have explained these features as superficial phenomena consequent on the overhang produced by the emergence of a thrust along a valley side. A diagrammatic representation of this idea given by E. J. Wayland in his account of the Albertine Rift¹⁹ is reproduced by Smith²⁰ in his paper on Steens Mountain, and has even been reproduced and the explanation quoted with approval in a standard textbook of structural geology.²¹ Therefore, it may be worth while to digress for a moment in order to point out some very obvious fallacies which it contains. The diagram in question is reproduced as fig. 3. In the sketch of the scarp due to thrusting, the overhanging portion of the emerged block is assumed to have fallen as two narrow step blocks so that a result is achieved very similar to the escarpment produced by normal faulting. These step blocks are, then, according to Wayland's hypothesis, nothing more than landslides. No explanation is offered as to the failure of these blocks to show the characteristic reverse rotation²² of ordinary landslides. Wayland states that movement on a thrust of this type could only be initiated by 'enormous pressure' and that 'tremendous reliefs' are necessitated in satisfaction of this pressure.²³ A natural consequence of this pressure would be the extreme shearing, crushing, and granulation of the rocks adjacent to the thrust surface. When this crushed mass emerged overhanging the valley, one would expect it to give way and fall in an indiscriminate jumble of debris. No large blocks arranged in an orderly step-like fashion such as Wayland has drawn would be expected, and their occurrence could only be regarded as fortuitous. That blocks of this type could extend unbroken for long distances along the face of the escarpment is inconceivable.

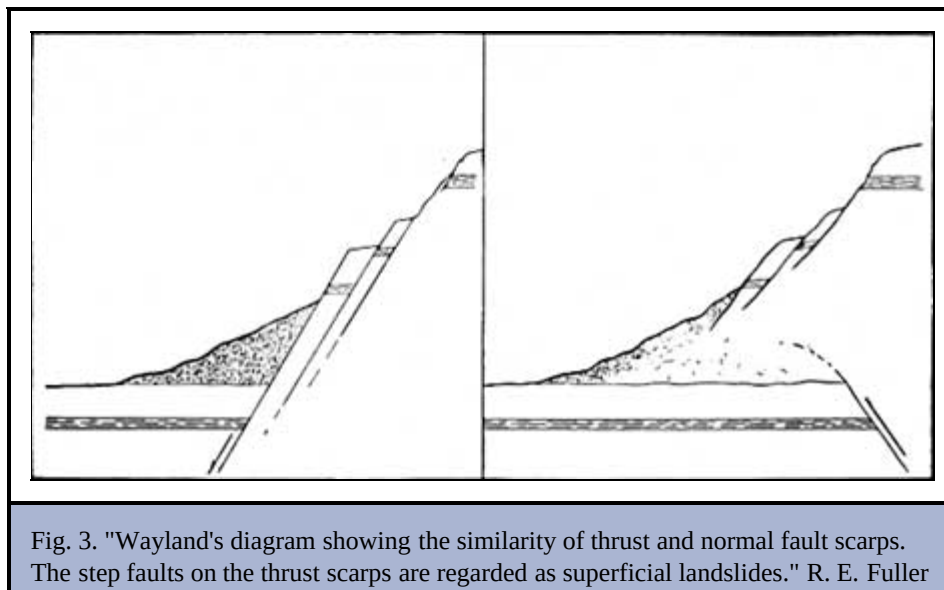
¹⁹*Op. cit.*, p. 353.

²⁰*Op. cit.*, p. 434, fig. 8.

²¹Bailey Willis, "Geologic Structures," p. 81, fig. 57.

²²I. C. Russell, "Geology of the Cascade Mountains in Northern Washington," *U.S. Geol. Survey, Ann. Rept.* 20, pt. II, p. 194, 1900. "Topographic Features Due to Landslides," *Pop. Sci. Monthly*, vol. LIII, pp. 480-490, 1898. Bailey Willis, *op. cit.*, p. 44. C. K. Leith, "Structural Geology," pp. 202-204, New York, 1923.

²³*Op. cit.*, p. 357.



and A. C. Waters, *op. cit.*, fig. 13, p. 226.

"It is characteristic, however, that the narrow blocks bounded by step faults commonly extend for distances of a mile or occasionally several miles without marked disruption.²⁴ Obviously the faults which bound them extend down parallel, or approximately parallel, to the main fault along which the maximum displacement of the range occurred and are not surficial features that stop at the valley floor.

²⁴F. Dixey, "The Nyasaland Section of the Great Rift Valley," *Geog. Jour.*, vol. LXVIII, pp. 120, 124-125, 1926. J. W. Gregory, "The African Rift Valleys," *ibid.*, vol. LVI, p. 23, 1920. Douglas W. Johnson, "Block Mountains in New Mexico," *Jour. Geol.*, vol. XXXI, pp. 136-137, 1903. Waldemar Lindgren, "The Tertiary Gravels of the Sierra Nevada," *U.S. Geol. Survey, Prof. Paper* 73, p. 42, 1911. G. D. Louderback, "The Basin Range Structure of the Humboldt Region," *Geol. Soc. America Bull.*, vol. XV, pp. 324, 334, 341-342, 1904. "Morphologic Features of the Basin Range Displacements in the Great Basin," *Univ. Calif. Publ., Bull. Dept. Geol. Sci.*, vol. XVI, no. 1, pp. 1-31, 1926. John Parkinson, "The Great African Troughs in the Neighborhood of the Soda Lakes," *Geog. Jour.*, vol. XLIV, pp. 33-49, 1914. John A. Reid, "The Geomorphogeny of the Sierra Nevada Northeast of Lake Tahoe," *Univ. Calif. Publ., Bull. Dept. Geol. Sci.*, vol. VI, pp. 115, 117, 135-136, 1911. H. L. Sikes, "The Structure of the Eastern Flank of the Rift Valley near Nairobi," *Geog. Jour.*, vol. LXVIII, pp. 386, 389-390, 401, 1926.

"However, let us grant for the moment that step faults might be formed as assumed by Wayland, and inquire into the possibility that the lower blocks would still preserve their step-like relationship to those higher upon the escarpment. The diagerammatic sections in fig. 4 convey the writers' impressions of the necessary result. Upon a relatively small emergence of the thrust block, the first step (1) would form, further thrusting would overturn this block, and its lower part would be overridden by the advancing mass. The second step block (2), therefore, would not have a step-like relationship to the first, and this train of events would be continued as long as thrusting took place. The only way in which the relationship pictured by Wayland could occur would be to have the block thrust up unbroken to a position actually overhanging the valley (fig. 5), then to have step block (2) form, and this later split asunder and the outermost part dropped to form step block (1). The difficulties that such a hypothesis must encounter to explain a number of parallel step blocks extending unbroken for a considerable distance along a high fault scarp are too obvious to merit discussion.

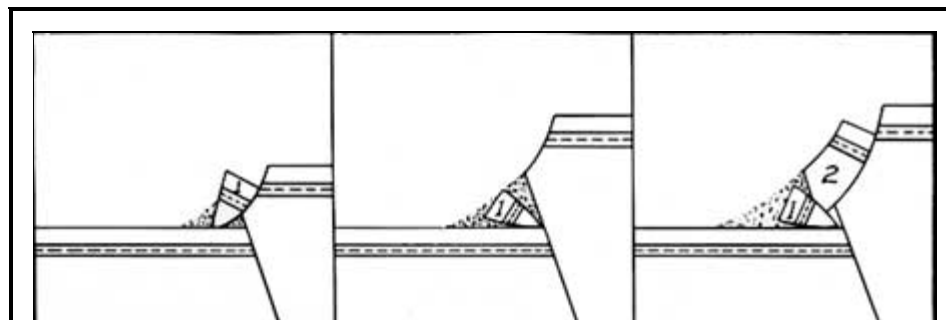


Fig. 4. "Supposed stages in the evolution of a thrust fault scarp, provided step blocks actually do form. On slight emergence the tip of the thrust block would slip off, forming step block 1. Further movement would overturn and override this block. If a second step block 2 is formed it will no longer have a steplike relationship to the first block." Compare fig. 5. R. E. Fuller and A. C. Waters, *op. cit.*, fig. 14, p. 227.

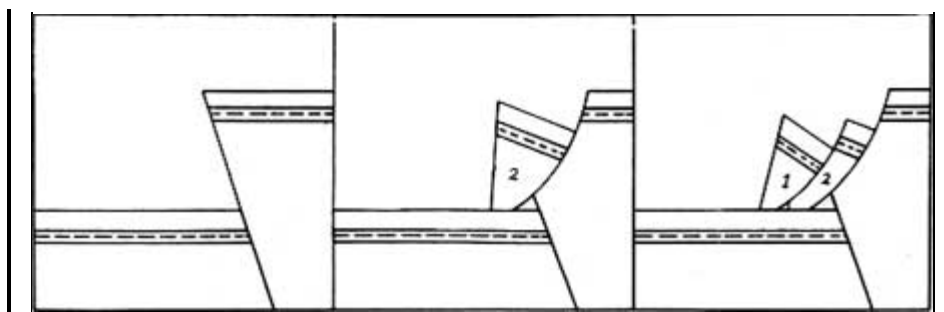


Fig. 5. "Stages in the evolution of a thrust fault scarp according to Wayland's diagram (fig. 4). The entire block must first be shoved up to a position overhanging the valley, then step block 2 must slide down and later break and the outer portion of it slip down to form step block 1. Such a mechanism appears to be very improbable." Compare with fig. 4. (Talus omitted from diagram.) R. E. Fuller and A. C. Waters, *op. cit.*, fig. 15, p. 228.

"A necessary corollary to Wayland's method for the formation of step faults is that these faults are confined entirely to the main rift scarp and are not found on the back of the rift blocks or on the floor of the valley below. This is entirely out of accord with the evidence from southern Oregon, where subsidiary faults parallel to the main fault escarpment can be found, not only on the back of the blocks, but also on the floors of the grabens."

"The general conclusion is reached, therefore, that the narrow well-defined step blocks of considerable longitudinal extent, which are a common feature of normal fault scarps, are not to be confused with the irregular landslides and heterogeneous masses of debris that accumulate at the base of the scarps produced by steeply dipping thrusts."

VOLCANIC VENTS ASSOCIATED WITH THE SCARPS

"The prevalence of volcanic vents along the graben escarpments of southern Oregon . . . with a predominant orientation parallel to a potential fault which later cut them, suggests that they occupied a line of tensional weakness even before the actual faulting had begun. Compression would close the fault fractures tightly and make them very unfavorable *loci* for vulcanism. In fact, some authors have stated as a general principle the theorem that magmas characteristically shun the thrust planes and tend to work inward toward the central portion of the deformed belt.²⁵ Where magmas have been intruded into areas undergoing severe compression they usually form concordant bodies parallel to the schistosity or bedding, and not the roughly discordant types that are characteristic of volcanic feeders. Although some authors have considered the presence of volcanic vents to favor the compressional hypothesis, the occurrence of these features along definite thrust planes has been very rarely recorded. Their common association with normal faults, however, is now well established, and numerous examples are forthcoming from widely separated parts of the world.²⁶ If we grant that the so-called "normal faults" are really thrusts we are at a loss to explain their common association with volcanic feeders, since in ordinary thrusts these are usually absent. On the other hand, if the normal faults are tensional this association is entirely logical."

²⁵Rollin T. Chamberlin and T. A. Link, "The Theory of Laterally Spreading Batholiths," *Jour. Geol.*, vol. XXXV, p. 347, 1927.

²⁶A. R. Andrew and T. E. G. Bailey, "The Geology of Nyasaland *Quar. Jour. Geol. Soc.*, vol. LXVI, p. 235, 1910. G. L. Collie, "Plateau of British East Africa," *Geol. Soc. America Bull.*, vol. XXIII, p. 313, 1912. J. W. Gregory, "The African Rift Valleys," pp. 16, 20, 23, 28, 29, 33, 36. D. W. Johnson, "Block Faulting in the Klamath Lakes Region," *Jour. Geol.*, vol. XXVI, p. 229, 1918. G. D. Louderback, *op. cit.*, p. 312. G. R. Mansfield, *U.S. Geol. Survey, Prof. Paper* 153, pp. 128, 135, 379, 390. John Parkinson, *op. cit.*, p. 36. H. L. Sikes, *op. cit.*, p. 388. E. O. Theile, "Further Notes on the Physiography of Portuguese East Africa, between the Zambezi River and the Sabi River," *Geog. Jour.*, vol. XLVI, p. 279, 1915.

CIRCULAR FAULT BASIN

"If roughly elliptical to circular depressions, exemplified by Summer Lake, Silver Lake, and the Upper Alvord playa are due to compressional faulting, then the forces must have acted centripetally like the closing of a camera shutter. Seemingly a dome would have been the more logical structure under these conditions. It is particularly difficult to understand how, in the case of the Upper Alvord playa, the deformation could have been restricted to a very small central area only about three miles in diameter, and yet was sufficiently severe to result in the walls of this tiny basin being thrust up as much as 1000 feet above the playa surface. The actual mechanism of the formation of features of this type is somewhat obscure, but regional tension allowing the release necessary for movement of such small units appears to be absolutely essential."

ABSENCE OF FOLDING AND OTHER COMPRESSIONAL EFFECTS

The rocks associated with steeply dipping thrust faults are practically always greatly buckled and folded, yet the blocks formed by the volcanic series in southern Oregon are astonishingly simple in structure. The most severe deformation should be found on the overthrust block adjacent to the thrust plane, yet the hundreds of thin sections from the lava samples collected on the face of the scarps show no evidence of granulation or crushing. Even vertical open bands of lithophysae in a rhyolite vent on the Steens escarpment have retained their most delicate structure intact, and the bedding of the highly incompetent waterlaid tuffs at the base of the mountain is still undisturbed (fig. 27).

EVEN DISTRIBUTION OF THE DEFORMATION

"Certain more general features of the southern Oregon fault-block country have no obvious explanation if we assume that these structures are due to compression. From west to east across the faulted portion of the state is a distance of more than 200 miles, and we have no indication that the fault structure ceases short of the areas that Mansfield has mapped in southeastern Idaho—a total distance of over 500 miles. In southern Oregon there are seven well defined north-south fault depressions of about equal magnitude. It would require a rather unusual distribution of stress, if we assume compression, in order to produce such uniform structures as these. Compressional stress generally tends to localize the failure in narrow zones, but in this district the failure is practically uniform over the entire area."

EFFECTS OF COMPRESSIONAL DEFORMATION IN THE COLUMBIA RIVER PLATEAU

"Comparison with adjoining districts shows that there is no reason why the basalts of southern Oregon should not fold if subjected to compression. To the north the compression of the Columbia River basalt appears invariably to have resulted in folds²⁷ rather than faults. . . . These anticlines are a very different kind of structural feature from that commonly observed in southern Oregon. Rising as long narrow ridges of from 1000 to 3000 feet in height and from two to twelve miles in width, they are striking contrast to the anticlines of southern Oregon (if we assume that the grabens represent the sunken keystones of anticlinal arches). These anticlines would be from 25 to 50 miles in width and would probably average around 4000 feet in height."

²⁷George Otis Smith, "Anticlinal Ridges in Central Washington," *Jour. Geol.*, vol. XI, pp. 167-177, 1903. "Geology and Physiography of Central Washington," *U.S. Geol. Survey, Prof. Paper* 19, pp. 1-40, 1903. Bailey Willis, "Physiography and Deformation of the Wenatchee-Chelan District, Cascade Range," *ibid.*, pp. 41-102. Gerald A. Waring, "Geology and Water Resources in South-Central Washington," *U.S. Geol. Survey, Water-Supply Paper* 316, pp. 22-25, 1913. Frank C. Calkins, "Geology and Water Resources of a Portion of East Central Washington," *U.S. Geol. Survey, Water-Supply Paper* 118, pp. 40-41, 1905. J. Harlan Bretz, "The Spokane Flood beyond the Channeled Scablands," *Jour. Geol.*, vol. XXXIII, pp. 236, 242, 249, 1925. J. P. Buwalda, by verbal communication testifies to the folding of the basalt in the John Day region of North Central Oregon (see also *Geol. Soc. America Bull.*, vol. XXXIX, p. 270, 1928).

ABSENCE OF MARKED LATERAL MOVEMENT

In later pages an additional argument of importance was advanced in consideration of Smith's suggestion that the northeasterly trend of the northern part of Steens Mountain and of the eastern scarp of Warner Valley is due to shearing in both the horizontal and the vertical section at 5° to the direction of compression.

". . . . If these mountains are considered to have risen on shears oriented 45° to the direction of pressure in both sections, there must have been considerable horizontal displacement along the fault planes. According to this interpretation, Steens Mountain moved northward in relation to the Alvord graben while the Bluejoint Rim moved southward relative to the adjacent Warner graben."

"This horizontal movement entails numerous difficulties. A long fault splinter, such as the Wildhorse Spur, which marks the position where one fault dies out and another continues the escarpment, somewhat offset from the first, would be sheared off by this horizontal movement; yet such features are common in southern Oregon. Horizontal movement of the Bluejoint Rim scarp appears to be impossible, for the scarp shows a pronounced series of zigzags and other irregularities which would lock the fault plane against lateral movement. Another obvious difficulty is found in explaining the horizontal movement for those faults which have uniform arc-like curves such as Winter Rim and the eastern scarp of Catlow Valley. If the strike of the plane of failure is normal to the direction of thrust, there would be no lateral movement. If, however, the strike were inclined, horizontal movement would occur which would necessitate subsidiary compressional effects in a salient of the thrust block and tensional effects in a re-entrant. No indication of these effects was observed in the blocks bounded by curving and zigzag faults."

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The Geomorphology and Volcanic Sequence of Steens
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GEOMORPHOLOGY OF STEENS MOUNTAIN

Although the absence of the upper members of the local stratigraphic sequence suggests that Steens Mountain has undergone considerable erosion, the topography is still almost a direct expression of the structure. In general, it consists of a great structural mass dipping gently westward from a high eastern fault scarp, which is continuous for over 50 miles. The Southern and central portion of this scarp lies approximately on a north-south line, but to the north it swings eastward about 30°. The mountain can be divided roughly into three parts, of which the most striking feature is an extremely simple high central block. On both the north and south, this is bounded by lower more complex units which will be referred to as Northern and Southern Steens.

NORTHERN STEENS

Northern Steens is bounded on the east by a continuous scarp over 25 miles in length with a predominant trend N. 30° E. (fig. 16). At its southern end it rises to a height of nearly 3,000 feet, but to the north it decreases to less than 1,000 feet. This decrease in elevation is accomplished largely by transverse faults trending roughly east-west. At its northern end the scarp is truncated by an east-west fault depression.

The southern half of Northern Steens is a relatively homogeneous tilted block dipping gently away from the eastern scarp for a distance of about 15 miles. The northern half, however, is far more complex. This region was well described by I. C. Russell¹ in his reconnaissance of 1882 in the following passage:

"A narrow belt of country to the eastward of the northern part of Stein Mountains is extremely rugged and difficult to traverse, owing to the abruptness of the upturned edges of the long, narrow blocks into which it has broken. The fault lines that have determined this topography are branches of the great fault along the eastern base of the main range, and trend approximately north and south."

¹I. C. Russell, "A Geological Reconnaissance in Southern Oregon," *U.S. Geol. Survey, Ann. Rept.* 4, p. 439, 1882-1883.

This tilted fault block structure has, as usual, been accompanied by the sedimentation of the depressed areas. Farther to the west this part of the mountain merges into a region of irregularly tilted small fault blocks.

HIGH STEENS

The central portion, known as High Steens, is structurally the simplest of the three units, although, due to erosion, its topography is locally more complex. For approximately 15 miles

its eastern scarp towers about 5,500 feet above the desert (fig. 6), and reaches an elevation of at least 2,000 feet greater than that of Northern or Southern Steens.



Fig. 6. Aeroplane view of High Steens from the northeast. Mann Lake Ranch lies in the foreground. The scarp of Southern Steens and part of Pueblo Mountains may be seen on the extreme left.

The crest is formed by the eastern margin of a homoclinal block (fig. 7), which dips westward at about 3° for a distance of over 20 miles, until it reaches the richly alluviated lower valley of the Donner und Blitzen River. Although the block is truncated on the north by several definite fault scarps, this transition to Northern Steens is accompanied by a slight northerly dip. The scarp bounding High Steens (fig. 8) on the southern side is far more pronounced, although it gradually decreases in throw towards the west as the elevation of the northern block diminishes.

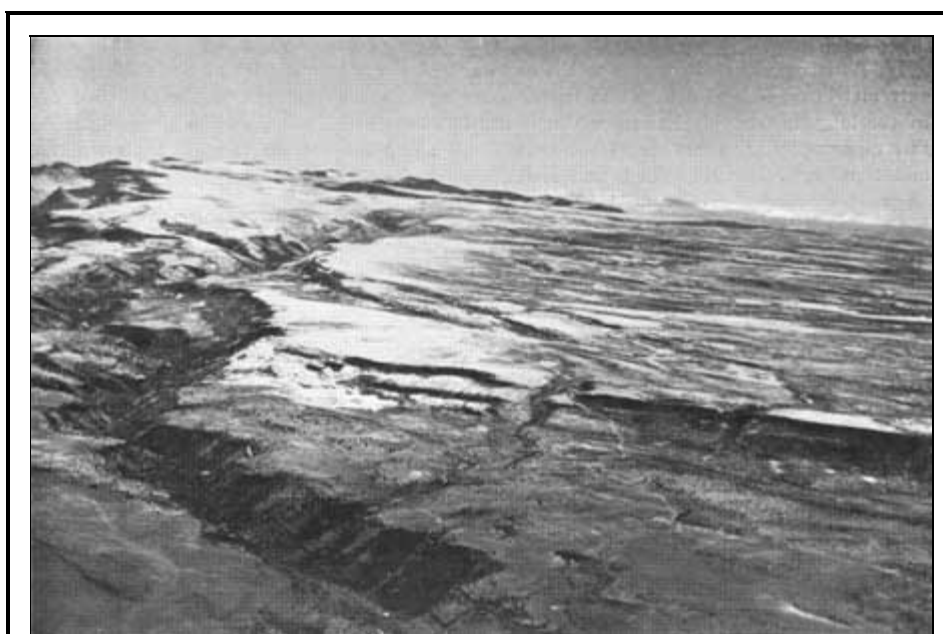


Fig. 7. Aeroplane view of High Steens from the northwest showing the gently tilted

surface of the block. The scarp in the middle foreground is formed by one of the east-west faults that bounds the lower block of Northern Steens. Kieger Canyon is visible on the left.



Fig. 8. Aeroplane view of the scarp bounding the High Steens block on the south taken at a distance of several miles west of the summit. The more level block in the foreground is that portion of Southern Steens known as Smith Flat.

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GEOMORPHOLOGY OF STEENS MOUNTAIN

(continued)

SOUTHERN STEENS AND ITS RELATION TO PUEBLO MOUNTAIN

Southern Steens is a true horst, bounded on the western side by another well defined fault (fig. 9) which continues southward to the northern end of Pueblo Mountain (fig. 10). At the northern end, this scarp has an orientation about N. 30° W., but traced southward, it swings toward the west in a fairly even curve, which increases more sharply near the southern extremity until it reaches approximately N. 70° E. Where the scarp first appears above the alluvium north of Catlow Valley it is very low, but as its even arc to the south cuts higher on the gently tilted fault block it increases in magnitude to well over 1,000 feet.



Fig. 9. Aeroplane view showing the curving western scarp of Steens rising over 1000 feet above Catlow Valley. The scarp on the right divides Southern Steens. The higher block is Smith Flat.



Fig. 10. Aeroplane view from the north of the curving western scarp at the northern end of the Pueblo Mountain block. This scarp is the southern continuation of the one defining Southern Steens. Lone Mountain is visible in the middle distance. R. E. Fuller and A. C. Waters, *op. cit.*, fig. 6, p. 218.

Southern Steens is divided by a fault trending roughly N. 60° W. into a northern and southern part. The northern division, which is about 10 miles across, is a very level and homogeneous block known as Smith Flat. At its eastern scarp this block dips westward at 2° or 3° but within a few miles to the west, the slope gradually decreases. Towards the western fault there is a reverse dip of about 1°, forming a very shallow, poorly defined sag on the north-south axis. On the north, Smith Flat is bounded by the southern scarp of High Steens. Owing to the slightly greater dip of the latter, the fault gradually increases in throw as it is traced eastward (fig. 8).

The downthrow of the fault dividing Southern Steens is to the south. Several miles south of this scarp the southern division is cut by many subsidiary faults, which are accompanied by the tilting of the small blocks, raising their summits considerably higher than the even slope of Smith's Flat. These blocks progressively decrease in elevation to the west. At the main eastern scarp a rugged crest is formed by a trachyte flow which dips S. 60° W. at about 12°. This inclination closely corresponds to that of the lavas forming the Pueblo Mountain series, which gradually increase in dip to approximately 20° as they continue southward.

Viewed from the north, the stratigraphic sequence and structure of the two mountains appear continuous (fig. 11). Between the southern portion of Steens and the northern continuation of Pueblo Mountain there is, however, a down faulted area known as Broad Valley, forming the only break in the Pueblo-Steens Range, which is nearly 100 miles in length. This depression is due to the presence of a number of minor tilted blocks which lie at low elevation and have a predominant strike of approximately N. 65° W., and a dip to the southwest of about 10° to 15°.





Fig. 11. Aeroplane view from the north of the tilted blocks forming the southernmost limit of Southern Steens. Broad Valley lies in the middle distance to the north of the extensive re-entrant. Still farther south on the extreme left the older metamorphics form the dome-like eastern crest of Pueblo Mountain, while the southern continuation of the great volcanic series is exposed on the right. R. E. Fuller and A. C. Waters, *op. cit.*, fig. 7, p. 219.

To the south of Southern Steens at the eastern end of Broad Valley, an extensive re-entrant in the main scarp is bounded on the west by a high escarpment which exposes the previously mentioned tilted series of lavas. Continuing southward with a gradual increase in elevation, this tilted block forms the western ridge of Pueblo Mountain. The northern part of this ridge is undoubtedly defined on the east by a fault, but the throw must decrease with the elevation of the eastern ridge. To the west the dip of these tilted lavas decreases rapidly until the block is approximately flat adjacent to the western scarp.

The re-entrant which this ridge bounds is filled at least at its northern end with soft sediments whose conglomeratic facies contain the predominant types of lava characteristic of Steens and Pueblo Mountains. With north-south faulting or a continuation of it, the block on which these sediments rest has been tilted to the west at an angle of about 5° raising the eastern end 400 feet or more. These soft, easily eroded deposits still retain a distinct scarp which connects the main eastern fault of Steens with that bounding the metamorphics forming the eastern ridge of Pueblo Mountain. This evidence of recent faulting supports the conclusions which W. M. Davis attained from studies farther to the north.² Similar testimony is also clearly defined at several other localities in this region (fig. 12).

²W. M. Davis, "Mountain Ranges of the Great Basin," *Mus. Comp. Zool. Bull.* (Harvard University), vol. XLII, p. 1, 1903-1905.



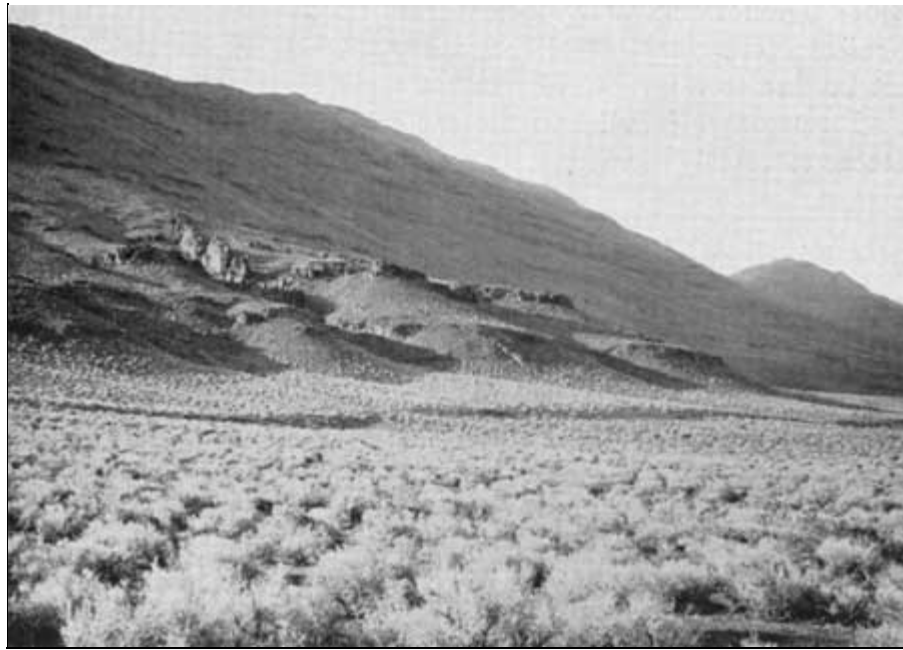


Fig. 12. View of the scarp southwest of Upper Alvord Basin showing in the foreground the displacement caused by a recent fault. The partially dissected miniature scarp, which is about six feet in height, can be traced for at least a mile.

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GEOMORPHOLOGY OF STEENS MOUNTAIN

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THE EASTERN SCARP OF STEENS MOUNTAIN

STRUCTURE

At the eastern scarp of Southern Steens the displacement has occurred in two main faults that converge towards the north. The southern continuation of the eastern one, which trends roughly north-south, defines Pueblo Mountain on the east. The resulting scarp varies greatly in height, depending largely on the differential resistance of the rocks exposed. The western fault trending in general N. 20° E. forms a more persistent topographic feature exposing a relatively uniform series of flows. Below this scarp an irregular broad shoulder, which has been extensively faulted, shows minor exposures of various volcanic rocks complicated locally by vent characteristics. No conclusive evidence was obtained on the stratigraphic relation of these lavas to the main series. It is possible that they represent a graben filling which was extruded during an early stage of the faulting.

The major faults defining this shoulder converge to form a single steep scarp which continues approximately due northward and merges into the western wall of Wildhorse Canyon. Here just as it reaches High Steens the southern fault dies. Northward, its place is taken by another scarp offset about four miles to the east (fig. 13). This northern scarp rises from the playa as a thin tilted block, known as Wildhorse Spur. These two scarps were probably once joined by one that survives on the south side of an isolated plateau north of the spur. This plateau forms a slightly depressed erosion remnant of Smith Flat.





Fig. 13. Aeroplane view of the summit of High Steens from the south. On the left the scarp of Southern Steens continues up Wildhorse Canyon, while the main northern scarp is offset about four miles to the east. The isolated plateau in the foreground is a remnant of the northeastern corner of Smith Flat, which has been slightly depressed by the Wildhorse Canyon fault.

West of it, Wildhorse Canyon continues northward for a total distance of about 10 miles. The position of the valley directly in line with the southern scarp must be due to a structural weakness caused by a minor continuation of the fault. Its presence parallel to the eastern scarp renders the southern crest of High Steens extremely serrate.

Owing to erosion and to minor deformation the eastern scarp of the spur is not very well defined, but it trends approximately N. 20° W. The northern continuation of this fault bounds the southern extremity of the High Steens block for about a mile, after which a slight re-entrant marks a change in the predominant direction of the scarp to approximately north-south. Between Pike Creek and Toughey Creek, which lie directly to the south of this point, there are a number of well-defined step faults (fig. 14) showing slickensided surfaces. These individually show a maximum displacement of several hundred feet. Only the most westerly one of these faults can be traced northward, owing to the above mentioned re-entrant. Bearing approximately the same orientation as the eastern margin of the spur, this fault cuts higher on the scarp to the north of Pike Creek. Its throw, however, gradually decreases and it disappears within about half a mile.





Fig. 14. In Toughey Creek a view of the main scarp shows one of the numerous step faults, which occur in this locality.

Similar step faults are relatively common throughout the region. The blocks liberated by this faulting as a rule vary in width from a few feet to several hundred yards. The displacement observed in the individual faults usually has been only a few hundred feet. In the lower scarps, where erosion has been less severe, these subsidiary faults form marked physiographic breaks, which in some instances may be traced for several miles (fig. 16). In the fault zone exposed near the southern end of High Steens however, the actual step fault blocks are either so narrow or so eroded that they have no obvious effect on the topography. These step faults cannot be confused with landslides, for the blocks lack the characteristic reverse rotation. The fault planes, where exposed, show no tendency to flatten. One in fact retains a uniform inclination for a vertical distance of almost 1,000 feet.

This locality was the only one where the actual surface of the faults forming the scarps was observed.³ These fault planes dip eastward at an inclination varying from about 50° to 65°. They appear to average about 60°. In a few instances inclined slickensided grooves indicate a slight lateral movement. In adjacent planes, however, the direction of the strike slip showed no regularity. Most of the polished surfaces testify to its absence.

³R. E. Fuller and A. C. Waters, *op. cit.*, fig. 11, p. 223.

To the north of this point for over 10 miles, the scarp continues approximately on a north-south line. North of Alvord Creek, however, there are a number of low salients in the interfluvial areas. These form irregular benches at about 1,000 feet above the desert (fig. 6). Usually the exposures are not sufficient to permit the interpretation of their relationship to the main scarp. In the valley of Cottonwood Creek, however, a vertical fault, exposed at the western margin of the bench, indicates that the eastern side has been elevated. The extent of displacement was not determined but it must be several hundred feet. In Willow Creek, the next valley to the north, a similar fault shows a minor displacement. These faults are roughly parallel to the main scarp.

In proof of the tensional origin of the structure a few minor faults, exposed at about two miles west of the scarp, are of considerable importance. Although these are approximately parallel to the major fault, some of them dip westward. In the valley of Alvord Creek, the

displacement of a dike proves the western block to be downthrown about 200 feet.⁴ To the north, in the valley of Mosquito Creek, two of the smaller faults converge downward, permitting the depression of a wedge-shaped block. The presence of interbedded grey tuffs near the base of the series renders this deformation apparent. This same bed of tuft adjacent to a basaltic vent on the northern margin of the lower cirque shows miniature normal faults dipping westward (fig. 15). The intersection of vertical faults with these normal ones has, in this instance, also permitted the depression of minute wedge-shaped blocks. The displacement is only a matter of inches, but it furnishes additional testimony of tensional forces.

⁴R. E. Fuller and A. C. Waters, *op. cit.*, fig. 12, p. 224.

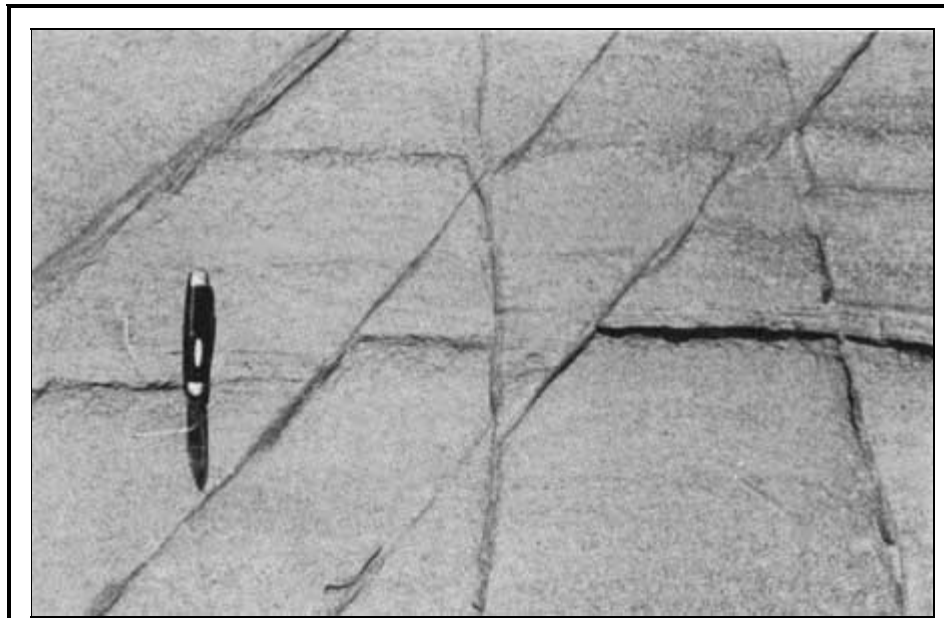


Fig. 15. View of the miniature faults exposed in the bedded tuffaceous sediments on the northern side of the lower cirque in Mosquito Creek. The inclined normal faults dip westward towards the main mass of the mountain. Some of the vertical fractures show a slight displacement, which permits the depression of miniature wedges.

Although individual exposures on High Steens are very precipitous, the scarp as a whole shows a slope close to 20°. On the other hand, the basaltic series at Bluejoint Rim, in the northern portion of Warner Valley, has preserved locally a slope of almost 70°, if one disregards the insignificant accumulation of talus at the base. There is no proof, however, that this surface represents the uneroded foot-wall of the fault. The extreme inclination probably is due in part, both to the vertical jointing of the rock, and to the erosion caused by the former presence of Bluejoint Lake. Possibly the sapping may have been increased by the presence of underlying tuffaceous beds now unexposed.

Elsewhere in the Great Basin the scarps show a relatively uniform slope, usually of about 30°, although the actual faults, as on Steens Mountain, have averaged close to 60°.⁵ In southeastern Oregon, however, the slope of the scarps varies greatly. This is probably due in part to the intensity of subsequent erosion at different elevations, but chiefly to the differential resistance of the various volcanic rocks, which are exposed.

⁵W. M. Davis, "The Basin Range Problem," *Nat. Acad. Sci. Proc.*, p. 389, 1925.

J. Gilluly, "Basin Range Faulting along the Oquirrh Range, Utah," *Geol. Soc. America Bull.*, vol. XXXIX, p. 1113, 1928. A. C. Lawson, "Recent Fault Scarps at Genoa, Nevada," *Seismological Soc. America Bull.*, vol. II, pp. 193-200, 1912. I. J. Pack, "New Discoveries relating to the Wasatch Fault," *American Jour. Sci.*, vol. XI, pp. 398-410, 1929.

Although the scarps in the northern part of the Great Basin have a predominant north-south trend, many of them show marked local irregularities. Some show broad curves, which even define circular fault basins (fig. 16), while others show sharp changes that produce a marked zigzag course. These changes in direction generally are accompanied by subsidiary faults. In spite of these minor faults, the scarps as a rule are continuous. A good example of this type may be observed at the northern end of High Steens (fig. 17), where the scarp curves sharply eastward to about N. 30° E. This curve is attained by the formation of branching faults. The main fault may be observed to continue northward with diminishing displacement, while the eastern branch develops the main scarp, until another branch trending slightly farther to the east takes its place. These faults also permit the downthrow of the northern block. The major displacement, however, appears to have taken place in a fault that branches to the west from the main scarp at the southern end of the curve. This normal fault with a displacement of many hundred feet lies about N. 25° W.



Fig. 16. Aeroplane view from the south of the circular fault basin known as Upper Alvord. The playa is about two miles in diameter. In the distance, to the left of the center, the scarp of Northern Steens shows the offset with the formation of the step fault (fig. 20). To the east, the minor blocks parallel to the main fault are clearly defined.





Fig. 17. Aeroplane view of the northern end of High Steens from the east. The curvature in the scarp, attained by the branching faults, occurs at the junction with the lower block known as Northern Steens.

To the north of this curve, the eastern scarp of Northern Steens continues for nearly 30 miles, gradually diminishing in elevation from approximately 3,000 feet to a few hundred. The most marked irregularity occurs about 15 miles to the north of High Steens at Stone House Creek. Here the scarp is offset over a quarter of a mile to the east. The eastern scarp emerges from the valley alluvium as a tilted block plunging southward at about 7° (fig. 18). Traced northward it flattens within the distance of a mile to form a well-defined step fault block (fig. 16) several hundred yards in width, with a surface about 300 feet below the local crest of the mountain. Gradually increasing in elevation, this thin subsidiary block continues for several miles until truncated by a transverse scarp. Northward the surface of this step fault block widens from less than a quarter of a mile to probably close to a mile, due to the fact that the orientation of the high scarp is approximately N. 20° E., while that of the eastern scarp is about N. 30° E.



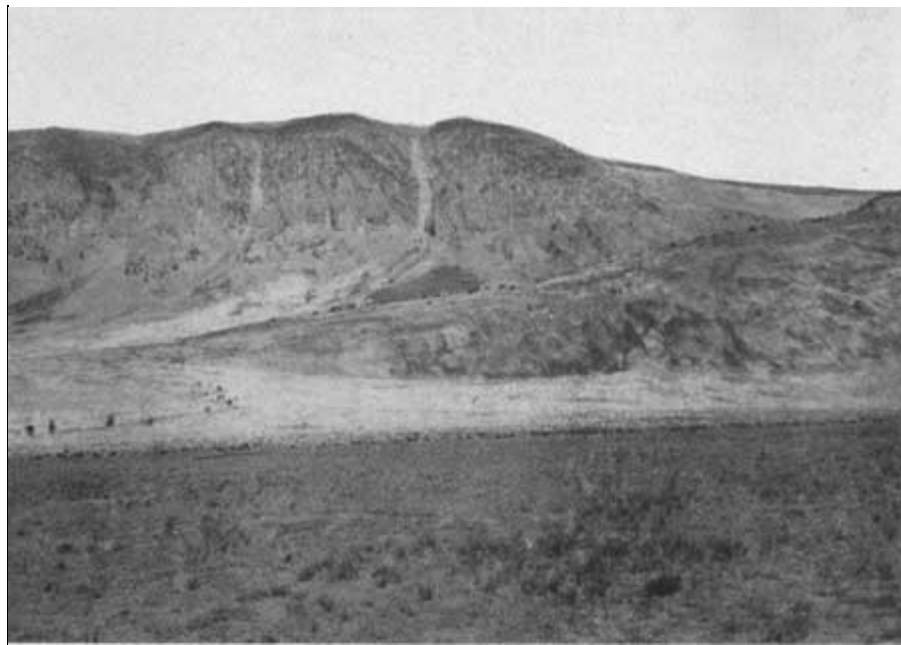


Fig. 18. View of the scarp of Northern Steens about ten miles north of the Mann Lake Ranch. The southern end of the inclined step fault block is clearly defined. This block becomes horizontal after attaining an elevation of about 1000 feet.

This step fault block dips westward at about 3° which corresponds to the inclination of the main mountain mass. At the southern end of this block, there is a longitudinal depression on its surface adjacent to the northern continuation of the main scarp. This depression is less than 100 feet in depth, and is bounded on the east by a sharp escarpment which slightly suggests another fault. It is more probable, however, that the basin is due to erosion originating in a manner similar to Wildhorse Canyon. The depression has been blocked to the south by a landslide so that it now forms a small lake basin filled with sediments (fig. 19).



Fig. 19. Looking southward on the top of the above mentioned step fault block. The formation of the playa lake is attributed to the damming of an erosional valley by a landslide.

To the north the eastern scarp of Northern Steens retains a remarkably straight orientation, at about N. 30° E., and an approximately even elevation of the crest. At intervals, however, it is cut by branching faults trending northward. The pronounced modification of Northern Steens by these faults has previously been mentioned.

On the scarp of Northern Steens, the effect of drag is still locally visible. This effect is apparent from the rapid change in the inclination of the beds on approaching the scarp. From a slight dip away from the fault plane they curve until almost parallel to the present slope. As a rule this indication of drag survives only on the lower scarps where erosion has been less severe. It is also clearly defined on the western margin of Southern Steens and east of Alvord Desert. At the base of the scarp of High Steens there are some isolated exposures showing highly inclined structure which is also attributed to drag.

Opposite to the southern end of Northern Steens a number of isolated fault blocks rise above the playa flats (fig. 20). The dip of these blocks is very varied. To the east of them, lies the circular fault basin referred to as Upper Alvord although actually its floor is slightly lower than the playa to the south. To the north, however, the structure is dominantly parallel to that of Northern Steens, and two blocks dipping to the northwest define elongate alluviated valleys (fig. 16). These blocks, which are also cut by transverse faults, lie in the center of a graben bounded on the east by a high scarp paralleling that of Northern Steens.



Fig. 20. Isolated fault blocks at the northern end of Alvord Desert viewed from the south. A small recent fault cuts their eastern scarp. Note the encroachment of vegetation at the margin of the playa.

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GEOMORPHOLOGY OF STEENS MOUNTAIN

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THE EASTERN SCARP OF STEENS MOUNTAIN

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EROSION

DRAINAGE

At the southern end of High Steens a rugged crest separates the previously mentioned Wildhorse Canyon from the headwaters of the streams of the eastern scarp. In a similar manner, towards the northern end of the mountain Kieger Canyon parallels the scarp for several miles until it gradually swings westward as a tributary to Donner und Blitzen River. The cirques at the head of these two valleys, which are on the same north-south line, lie within six miles of each other. This alignment probably has been caused by a minor structural displacement parallel to the scarp, although the actual fault plane was not observed by the writer.

Most of the creeks on the eastern scarp have been developed by consequent drainage. Structural control due to branching faults was observed only in the north fork of Mann Creek and in the adjoining valley to the north. The differential resistance of the rock has resulted merely in small irregularities. The minor forks of most of the streams are insequent, but the large forks of two valleys appear to have originated as independent consequent streams.

Erosional depressions near the base of the scarp suggest that both forks of the south fork of Alvord Creek originally flowed directly westward. The gathering ground is too small to attribute the re-adjustment to normal capture. They each were probably diverted to the deeper valley on the north by their own valley filling. There is similar evidence in the valley of Willow Creek. The south fork of the latter appears to have originally formed the headwaters of Little Willow Creek.

Many of the names (see sketch map, fig. 23) used for different creeks on the eastern scarp are well established by local usage, but, in some cases, the name is more indefinite and varies with different inhabitants. Most of the larger creeks have a smaller adjacent valley to which the diminutive is applied. Owing to the fact that two small parallel valleys between Dry Creek and Mann Creek are apparently unnamed, the author, following this precedent, has called them Little Dry and Little Mann. The valley designated as Toughy Creek is also locally known as Little Indian.

GLACIATION

I. C. Russell⁶ and Waring⁷ considered the broad U-shaped valley of Kieger Canyon (fig. 21)

to be due to stream action subsequently modified by glacial erosion. Smith⁸ later observed the well-marked evidence of glaciation in Wildhorse Canyon. In addition, however, the presence of broad shallow cirques *roches moutonnees*, glacial lakes and moraines on the top of the mountain indicate that it suffered considerable erosion from an extensive snow field, reaching five or six miles from the crest.

⁶I. C. Russell, "Hanging Valleys," *Geol. Soc. America Bull.*, vol. XVI, pp. 83-87, 1905.

⁷Gerald A. Waring, "Geology and Water Resources of the Harney Basin Region," *U.S. Geol. Survey, Water-Supply Paper* 231, p. 28, 1909.

⁸*Op. cit.*, p. 424.



Fig. 21. Looking northward down the U shaped glacial valley of Kieger Canyon from the top of its cirque directly west of the head of Mosquito Creek.

All the larger valleys on the eastern scarp of High Steens also show marked indications of glacial erosion in their upper parts. At about two miles from the foot of the scarp, they usually end in a broad cirque some 2,500 feet above the desert (fig. 24). Here two or three small tributaries as a rule descend precipitously from well-defined glacial valleys about 1,500 feet above. These shallower valleys extending locally almost a mile farther to the west, end in small higher cirques in which favorably situated snow banks usually survive the summer's heat.

It is probable that this glaciation was superimposed on a previously well developed drainage system. Russell⁹ commented on the absence of marked morainal material in Kieger Canyon. In like manner there is little suggestion of glacial debris in the valleys of the eastern scarp, but it is possible that it may have been removed by subsequent rigorous erosion. As they approach the scarp the valleys lose their glacial characteristics.

⁹I. C. Russell, "Hanging Valleys," *Geol. Soc. America Bull.*, vol. XVI, p. 84, 1903.

DIFFERENTIAL EROSION

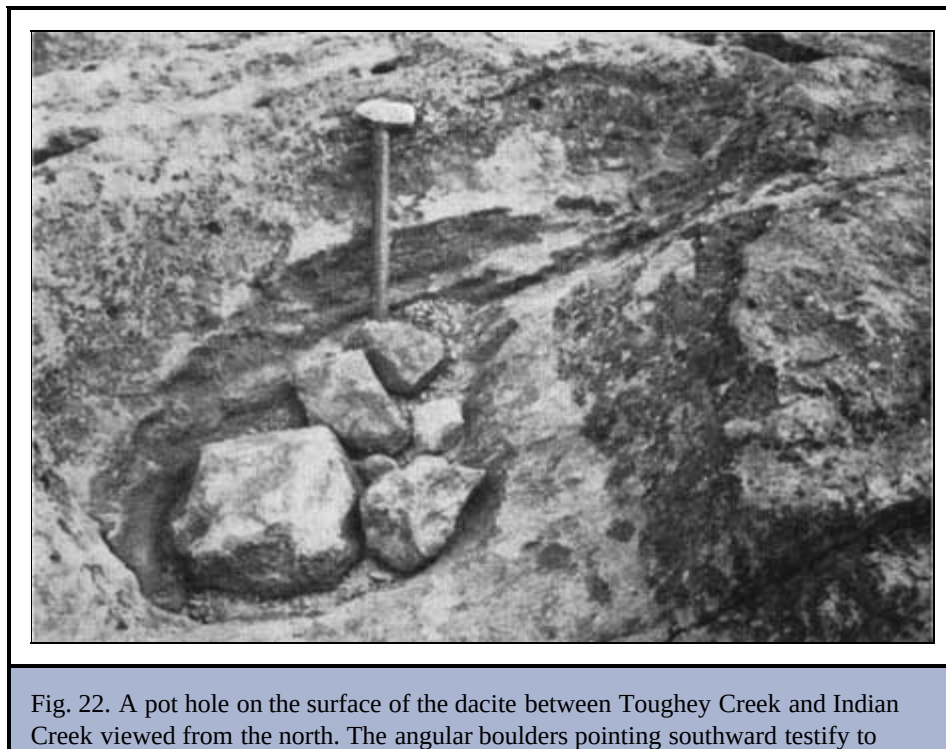
There are many irregularities in the erosion of the eastern scarp. Some of these are controlled by minor faults. A few of the features low on the scarp have been modified by landslides. The major factor, however, is the differential erosion of the various volcanic rocks. The distribution of these rocks, their many intrusive phases, and their variations both in jointing and in resistance to erosion are all factors which have contributed to the rugged topography of the eastern scarp.

The approximate concordance of elevation of some of the shoulders (fig. 6) on the scarp suggests a periodic uplift, permitting a great erosional break. Although they are locally bounded by faults, these shoulders all appear to be the direct physiographic expression of a change in rock type.

WIND EROSION

At the southern end of High Steens, the scarp presents a broad shoulder over a mile in width. Here, irregular prominences project abruptly from a gently rolling terrain. The surface rock is formed by a thick flow of dacite, which welled from a local vent. Steeply inclined flow structure and differential alteration account for the topographic irregularities. The predominant resistance of this lava explains the preservation of the relatively level surface, but not the extensive removal of the basaltic series, which is about 3,000 feet in thickness.

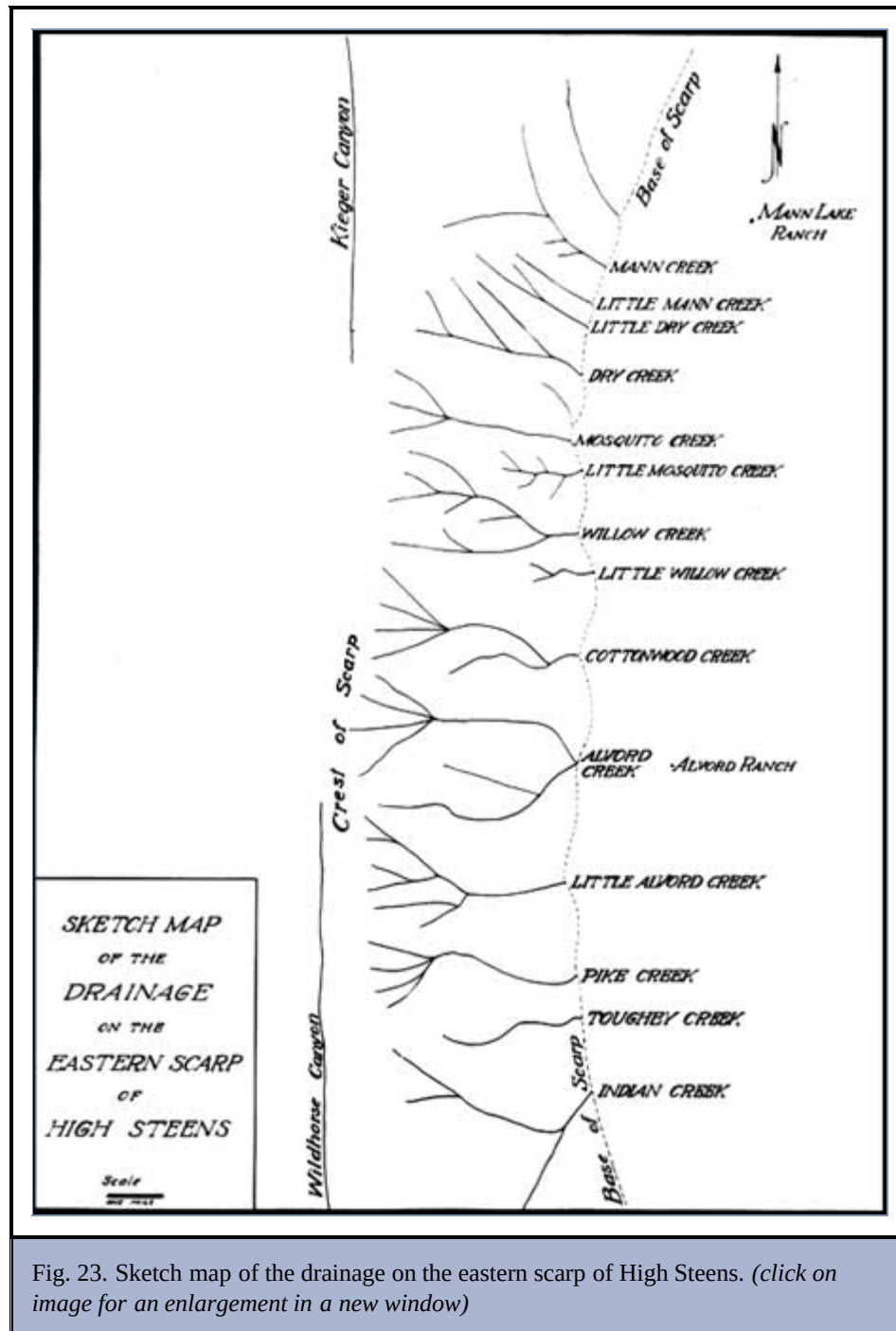
The surface of the dacite shows indications of extreme wind erosion. In the highest portion of the shoulder, the rock has been completely stripped of soil even in relatively level areas. The rock, thus exposed, shows marked abrasion. Locally it exhibits shallow pot holes containing angular blocks that have been faceted by the wind (fig. 22). The best defined angle is predominantly pointed slightly south of west. The abrasive agent would have been formed by the disintegration of the dacite, for a minutely hackly jointing causes the latter to break into a fine gravel.



wind erosion from that direction. The orientation of the boulder at the base of the hammer was disturbed.

The distortion of the juniper trees on this shoulder testifies to a high westerly wind, which results in the dust storms frequently encountered in the region. This particular locality is especially exposed for it is situated at the southern end of High Steens and only slightly to the north of a well-defined gap in the eastern wall of Wildhorse Canyon.

With these points in mind the writer attributes the formation of the shoulder to wind erosion. Unlike typical basalt, the series, which has been removed, is characterized by a peculiar porous texture which renders it extremely susceptible to mechanical disintegration. Its own coarse particles would have formed a fairly effective abrasive agent.



LANDSLIDES

Landslides have occurred at several localities on the lower part of the eastern scarp. They appear invariably to have been associated with incompetent tuffaceous beds. The characteristic reverse rotation causes the development of a humocky topography, which locally has permitted the formation of small ponds. The slides are best defined on the shoulder north of Alvord Creek, to the south in the broad valley formed by its southern fork, and on the northern side of the valleys of both Pike and Little Alvord Creeks.

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