Fuller bequest file

Memorial to Richard Eugene Fuller
1897–1976

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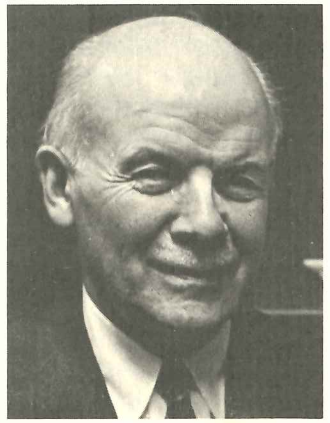

Richard Eugene Fuller was born in New York City June 1, 1897, the son of Dr. Eugene Fuller, for many years distinguished physician and Professor of Urology at the Postgraduate School of Bellevue Hospital, New York, and Margaret MacTavish Fuller. Mrs. Fuller, a native of New York, traveled widely in this country and Canada. In 1880 she made a trip with her father around the world in ninety days. She became fascinated with the Far East and developed an engrossing interest in Asian art objects.

Richard, the youngest of four children, graduated in 1915 from Hill School, Pottstown, Pennsylvania, then broke a long-time Fuller "Harvard tradition" by entering Sheffield Scientific School of Yale University, class of 1918, as a chemistry major. World War I intervened, and he left Yale in 1917 to serve as an ambulance driver in France with the American Field Service Committee. (His sister, Eugenia, was serving with the American Red Cross in Paris.) Richard returned to New York in 1918 and enlisted in the U.S. Coast Artillery Corps. He was commissioned a second lieutenant and sent back to France to attend the Artillery School at Angers. He served subsequently with Battery B, 42nd Coast Artillery and was mustered out at the end of the war.

Richard and Eugenia returned to New York from France early in 1919. The oldest Fuller son, Duncan, had completed his surgical internship; so Dr. and Mrs. Fuller and the three children soon left New York for the Orient, planning a year's stay. For some years Mrs. Fuller had been seriously collecting snuff bottles and other small Chinese antiques as a hobby, and her enthusiasm was picked up by her children during an enforced stay in Nikko, Japan, when Richard was stricken with acute appendicitis. The close family relationship of the Fullers was again demonstrated. Dr. Duncan Fuller, the brother, performed his first private surgery; he was assisted by the senior Dr. Fuller. Convalescence from an acute appendix operation in 1919 was slow. Duncan began a collection of netsukes, the small Japanese toggles, a collection eventually named in his memory when it was given to the Seattle Art Museum. Richard read widely while convalescing, and his interest was captured by jade. The enforced stay in Nikko led to his beginning the famous Jade Collection, now greatly augmented on permanent exhibition in the Seattle Art Museum.

The family returned to New York in 1920, and Richard re-entered Yale, receiving his bachelor of philosophy, honoris causa, in the spring of 1921. The family then moved to Victoria, B.C., whereupon Richard began what proved to be a short career in banking (1921–1922) in Eugene, Oregon. Illness forced his withdrawal. When he recuperated, the family toured South America and Western Europe, broadening its interest in art, particularly in pre-Columbian fabrics and ceramics. Returning west in 1923, the family settled in Seattle. Richard began the study of geology at the University of

Washington. His interest in minerals and rocks brought him under the influence of Professor George Edward Goodspeed. Fuller's background in chemistry, physics, and mathematics at Yale enabled him to complete a second bachelor's degree in record time, a bachelor of science in geology at the University of Washington in 1924. He immediately began his field work for graduate study and by December, 1925, was awarded his M.S. degree.

Fuller contributed early not only to the science of geology, but also to the production of geologists. Aaron C. Waters became his field assistant during the summer of 1925, beginning an association that influenced Waters's entire career. Fuller did his M.S. thesis research in the nearby Snoqualmie Pass area in the Cascades and clearly established that the Snoqualmie batholith broke through its roof and poured out as volcanics. Waters and others (U.S.G.S. Prof. Paper No. 444) and subsequent investigators have found the phenomenon to be typical of the Miocene-Pliocene intrusives along the Cascade Chain.

Goodspeed, Fuller's supervisor, urged him to continue graduate work, suggesting the Columbia Plateau basalts as a suitable topic for his Ph.D. His sister, Eugenia, was very supportive, and her encouragement enabled Dick to balance the disparate pulls of family duty, the art world, and geology, a problem he faced the rest of his life. The family always came first; geology sometimes nudged out art for second place, but only momentarily. So he began his field work in the Columbia Plateau of Washington in 1926, with Aaron Waters again as his field assistant, gathering material for three papers that appeared in 1927–1928. His was a creditable explanation of the origin of the Asotin craters in Washington, and he brought to the attention of American petrographers and petrologists the many occurrences of palagonitic alteration of basaltic glass in the Columbia Plateau. Fuller (with M. A. Peacock) set up standards still useful in distinguishing cloropaeite, sideromelane, and palagonite, three mineraloids characteristic of Cenozoic basaltic fields of the world.

Fuller soon realized that the Columbia Plateau basalt problem was too big for a Ph.D. dissertation and concentrated his study on the Steens Mountain area in southeastern Oregon. His initial purpose was to compare the thick volcanic sequence in southern Oregon with that composing the Columbia Plateau of Washington. The origin of the structure of Steens and the associated mountains temporarily diverted him, but he completed the field study with the devoted assistance, at various times, of Aaron C. Waters, Charles W. Flagler, Howard A. Coombs, and Keith Whiting, all of whom went on to notable careers in the profession. His Ph.D. degree was awarded in 1930, and in 1931 an expanded version of the dissertation was published, complete with twenty-nine chemical analyses of the diverse assemblage of rhyolite, andesite, basalt, and latite that forms Steens Mountains, together with their calculated norms. Fuller found that the basalts are chemically conventional, but that their colors and textures are unique. Perfectly fresh basalt in Steens is a far lighter shade of gray than one would expect. Most of the flows, in spite of thinness, consist of relatively coarse holocrystalline feldspar and olivine, with open cavities existing between the crystalline constituents. Fuller proposed the name "diktytaxitic" for the texture (Greek, *diktuon,* net, + *taxis,* arrangement) and it has become a standard glossary term. The publication was superbly illustrated by aerial, as well as conventional photographs and remains a valuable contribution to Oregon geology.

Fuller was a very busy man during his Ph.D. interval. He was elected vice-president of the Art Institute of Seattle in 1929 and president in 1930. The Fuller collection of jade had been growing steadily for more than ten years. The Art Institute was losing its quarters in a private house. Many decisions were necessary, requiring much of the president's time. That same year his father died, leaving a considerable estate acquired over the years from successful investments. Full responsibility as head of the Fuller family devolved on Richard, and he was temporarily lost to the field of geology he loved.

Once the estate was settled, the Fuller family offered to the Seattle Art Institute on December 31, 1931, the sum of $250,000 for the purchase and construction of a museum to be located in city-owned Volunteer Park. The building was completed in 1933 and given to the city to maintain while the Seattle Art Museum, the successor to the Art Institute, assumed the cultural operation. Fuller served as president and director, without pay, for the next forty years, bringing the Seattle Art Museum to rank among the best in North America.

Fuller made a valiant effort to continue geological research. He gave numerous papers at section and national meetings in the 1931–1941 interval, nine of which he found time to complete for publication. Most were concerned with the Columbia Plateau basalts. His major contributions in this period dealt generally with basaltic glass and its alteration products, and particularly with the structures and products resulting from aqueous chilling of basaltic lava.

The University of Washington appointed Fuller assistant professor in 1930, associate professor in 1933, and research professor in 1940. He served the University part-time without pay for thirty-two years. It was my good fortune to share his office from 1936 to 1942, to use his library and bound journals, and to benefit from his friendship and counsel. He taught my structural geology class at least one quarter when I was away on active duty during World War II. During 1942–1943 he also served as Major, U.S. Army Specialist Corps for Procurement, in Seattle.

The birth of a basaltic volcano in a Mexican cornfield in February, 1943, brought Fuller back into active geological participation. United States scientists from several governmental agencies and universities wanted very much to participate in the study of the eruption and its effects on the various fields of science before the record was lost. The State Department was insistent that care be taken not to tread on delicate Mexican sensibilities. A coordinator with scientific standing, tact, and managerial ability was found in Fuller who, as President of the Volcanological Section, American Geophysical Union, became Chairman of the U.S. Committee for the Study of the Paricutin Volcano in 1944. He served with great effectiveness for six years of the committee's existence. His interest in the volcano and the region was to continue for the rest of his life. Fuller met a young topographer working at Paricutin on one of his earliest visits and subsequently converted him to geology as a career, as he had done many others. By extended correspondence and conversations over the years, Kenneth Segerstrom kept Fuller informed on the posteruption history of the volcano and the region. As late as 1976, Fuller was contributing to the support of an extraordinary amateur Mexican volcanologist who has kept daily records of the Paricutin area from the time of premonitory earthquakes to the present day, and who recently has fallen upon hard times.

Fuller's final geological publication came in 1950, but he never lost interest in the science or in the department in which he continued to served as research professor until 1962. He kept up his fellowship in the Geological Society of America and the American Association for the Advancement of Science. He was also a member of Phi Beta Kappa and Sigma Xi. His interest in geology was encouraged by his wife, Elizabeth Morrison Emory, to whom he was married in 1951. She was a delightful hostess, and her annual dinner for the geology department was a highlight for many years. The period from 1951 to the time of her death in 1975 was, without doubt, the happiest of Dick Fuller's long and eventful life, which quietly came to an end in Seattle on December 10, 1976. He is survived by his sister, Eugenia, Mrs. John C. Atwood, Jr., of Philadelphia.

Fuller was a quiet, modest, cultured benefactor who influenced many lives. A recognized scientist, art scholar, and administrator, he also enjoyed and supported symphony and opera in Seattle. He played an enormous and varied role in the community. The many honors that came to him for these endeavors are recorded, in detail, in the public print. His nature, however, was such that he would not have liked them repeated here. Among his honors were Honorary LL.D. degrees by Washington State (College) University in 1944 and Seattle University in 1969. He was designated Alumnus Summa Laude Dignatus by the University of Washington in 1961. His financial contribution to geology will long continue at his alma mater through his generous gifts to the department and through his endowment of the Howard A. Coombs Geology Scholarship in honor of a longtime chairman of the department, one of his early field assistants, of whom he was very proud.

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THE GEOMORPHOLOGY AND VOLCANIC SEQUENCE OF STEENS MOUNTAIN IN SOUTHEASTERN OREGON

BY

RICHARD E. FULLER

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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THE GEOMORPHOLOGY AND VOLCANIC SEQUENCE OF STEENS MOUNTAIN IN SOUTHEASTERN OREGON

INTRODUCTION

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).

NAME

In the 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.

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

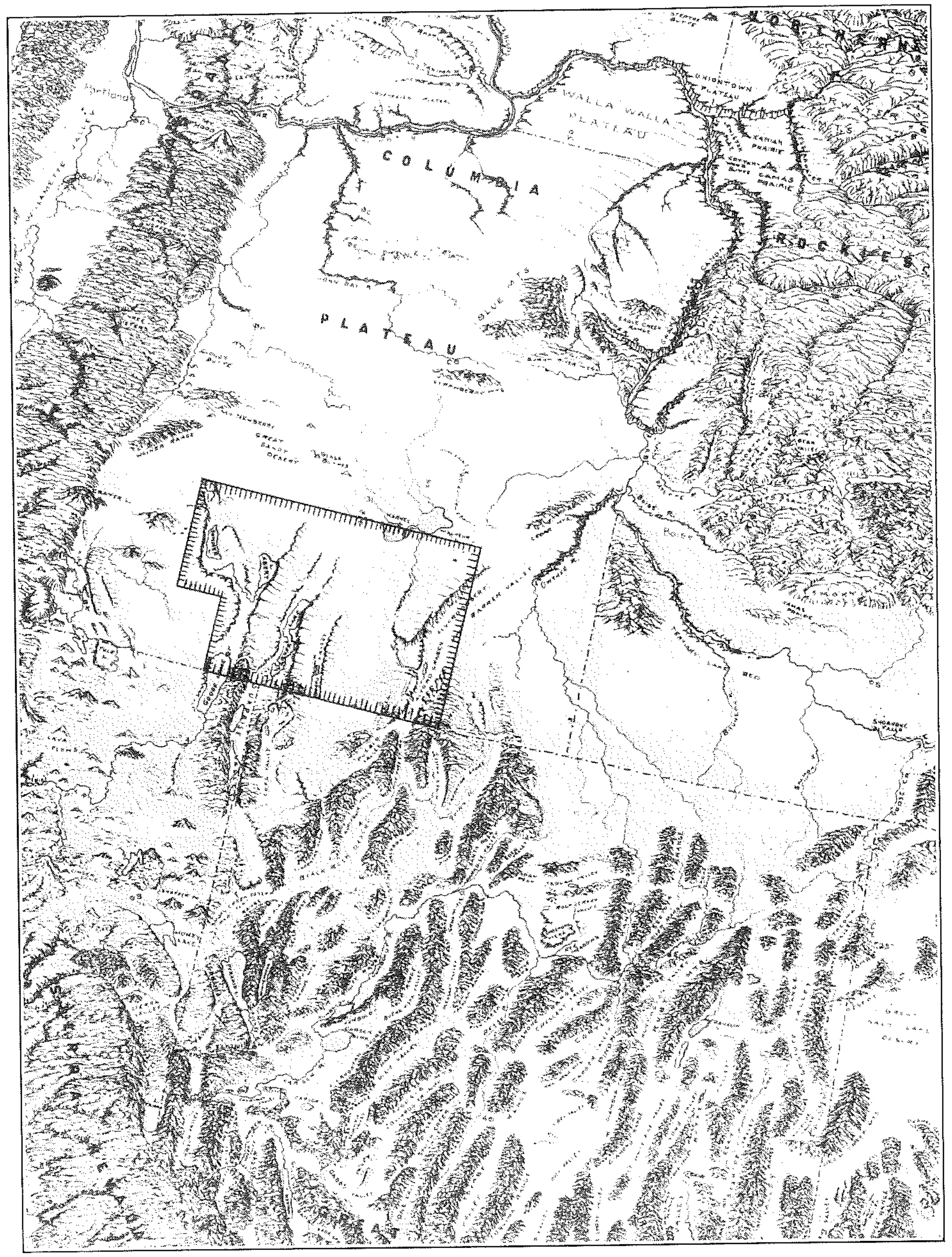

Fig. 1. The area shown in the sketch map in fig. 2 is here superimposed on a section of the "Physiographic Diagram of the United States" by A. K. Lobeck, Chicago, 1921. The scale is approximately 100 miles to an inch.

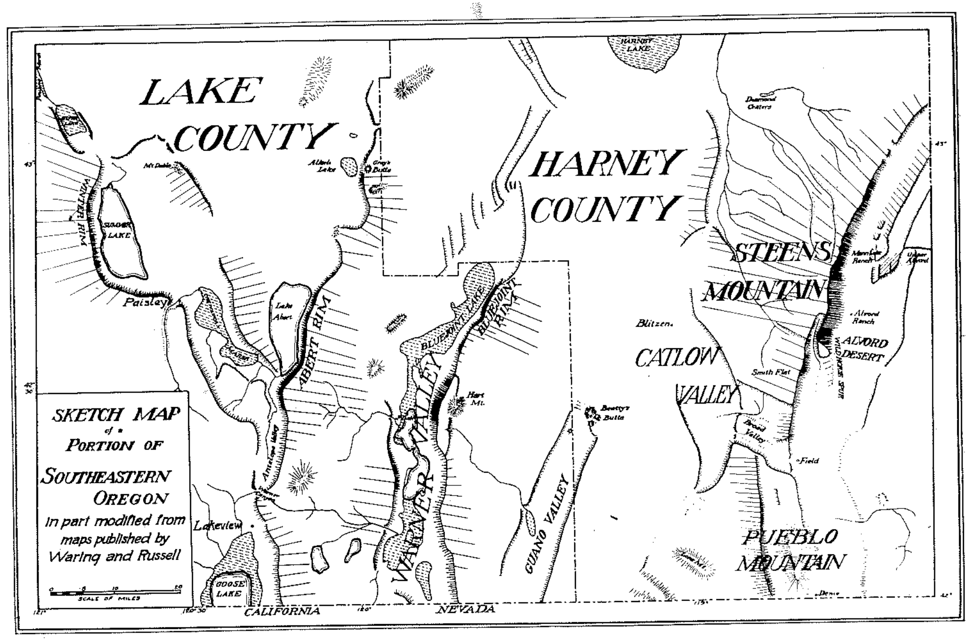

Fig. 2. R. E. Fuller and A. C. Waters, *op. cit.*, fig. 1, p. 209.

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 travelling 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 deposits, 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 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.

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.

In 1881 and 1882, I. C. Russell made a general survey of the geology of the northern end of the Great Basin. His subsequent report[2] 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 examination[3] of Steens Mountain. He noted the basal tuffs, but considered the lavas to consist entirely of basalt.

In 1903, a week's study of the southern part of Steens Mountain enabled W. M. Davis to make some general observations[4] 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.

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]

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

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

[3] I. 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.

[4] W. 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.*

[5] Gerald 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.

[6] R. 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.

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 Stock[8] 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.

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 relationship[10] 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 work[11] 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 on the physiographic expression, soil color, and vegetation.

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.

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[7] J. 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.

[8] Personal communication.

[9] *Op. cit.*, p. 45.

[10] *Op. cit.*, p. 29.

[11] George 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 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.

Recently, Richard J. Russell published an excellent report[13] 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.

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]

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.

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

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[12] Personal communication.

[13] Richard 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.

[14] *Op. cit.*, pp. 416-417.

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

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.

ORIGIN OF THE STRUCTURE

In 1927, after a brief reconnaissance, W. D. Smith published a paper[16] 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 theory[17] had been previously propounded to explain the structure of apparently analogous features in central Africa.

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 Waters[18] 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.

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

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

[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 Rift[19] is reproduced by Smith[20] 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

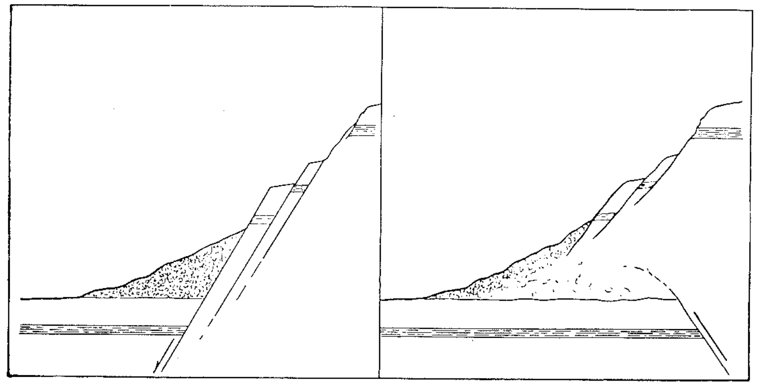

Fig. 3. "Wayland's diagram showing the similarity of thrust and normal fault scarps. The step faults on the thrust scarps are regarded as superficial landslides." R. E. Fuller and A. C. Waters, *op. cit.*, fig. 13, p. 226.

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[19] *Op. cit.*, p. 353.

[20] *Op. cit.*, p. 434, fig. 8.

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

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 rotation[22] 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.

"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.

"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 diagrammatic 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

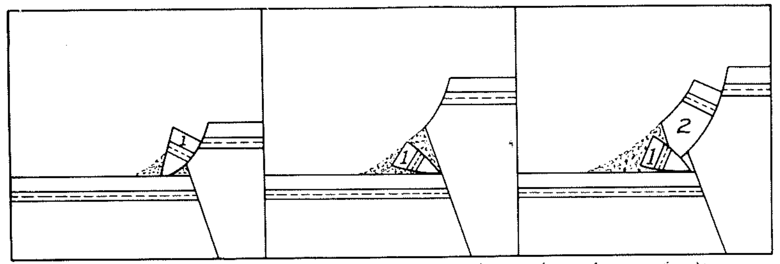

Fig. 4. "Supposed stages in the evolution of a thrust fault scarp, provided step blocks actually do form. On slight emergence the tip of the thrust block would slip off, forming step block 1. Further movement would overturn and override this block. If a second step block 2 is formed it will no longer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

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[22] I. 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.

[24] F. 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.

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.

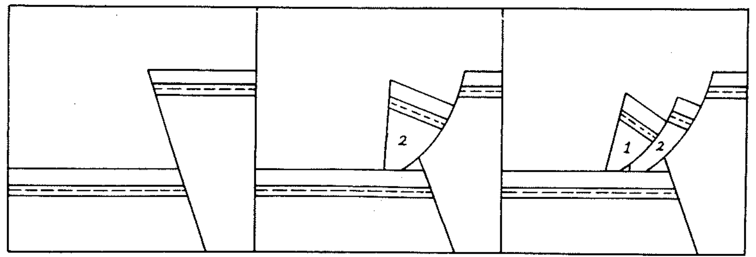

Fig. 5. "Stages in the evolution of a thrust fault scarp according to Wayland's diagram (fig. 4). The entire block must first be shoved up to a position overhanging the valley, then step block 2 must slide down and later break and the outer portion of it slip down to form step block 1. Such a mechanism 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

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

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."

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."

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[26] A. 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.

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 folds[27] 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."

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 45° 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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[27] George 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 Harlen Bretz, "The Spokane Flood beyond the Channeled Scablands," *Jour. Geol.*, vol. XXXIII, pp. 236, 242, 243, 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.

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. Russell[1] 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."

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.

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

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

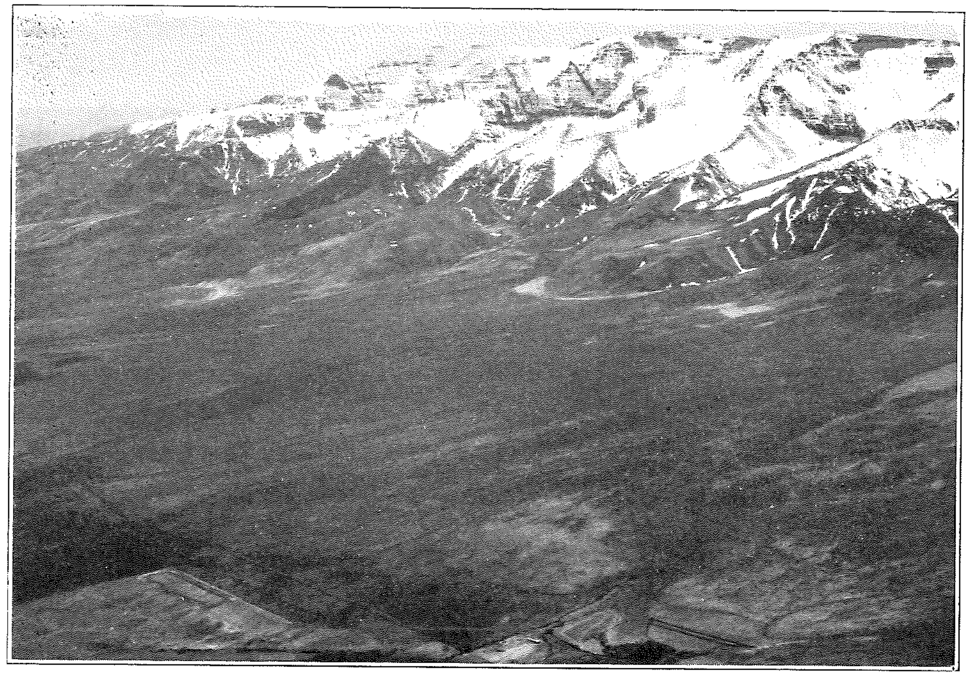

Fig. 6. Aeroplane view of High Steens from the northeast. Mann Lake Ranch lies in the foreground. The scarp of Southern Steens and part of Pueblo Mountain may be seen on the extreme left.

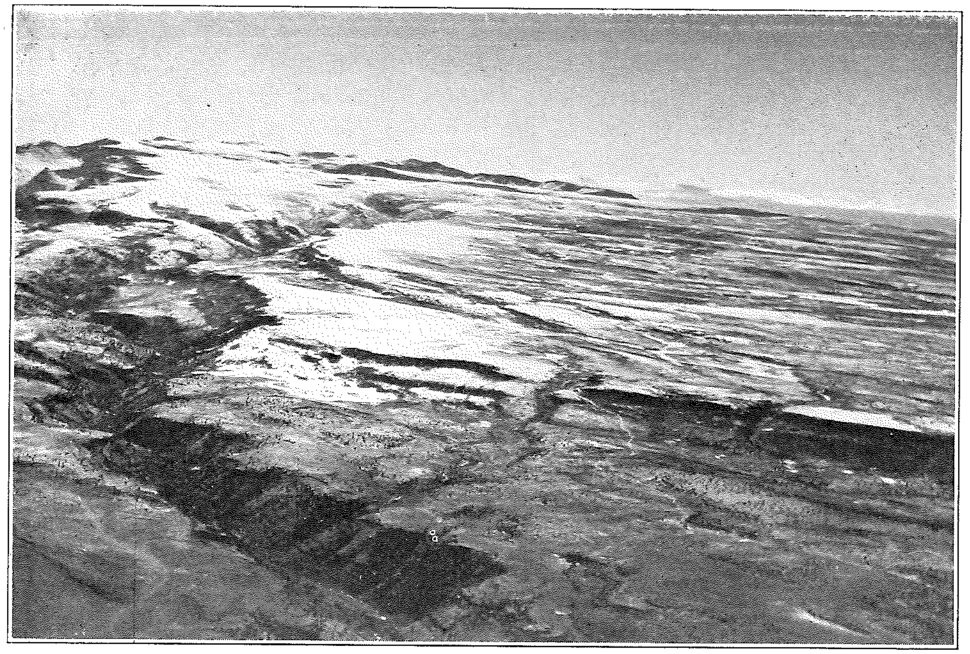

Fig. 7. Aeroplane view of High Steens from the northwest showing the gently tilted surface of the block. The scarp in the middle foreground is formed by one of the east-west faults that bounds the lower block of Northern Steens. Kieger Canyon is visible on the left.

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. 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.

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.

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

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.

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.

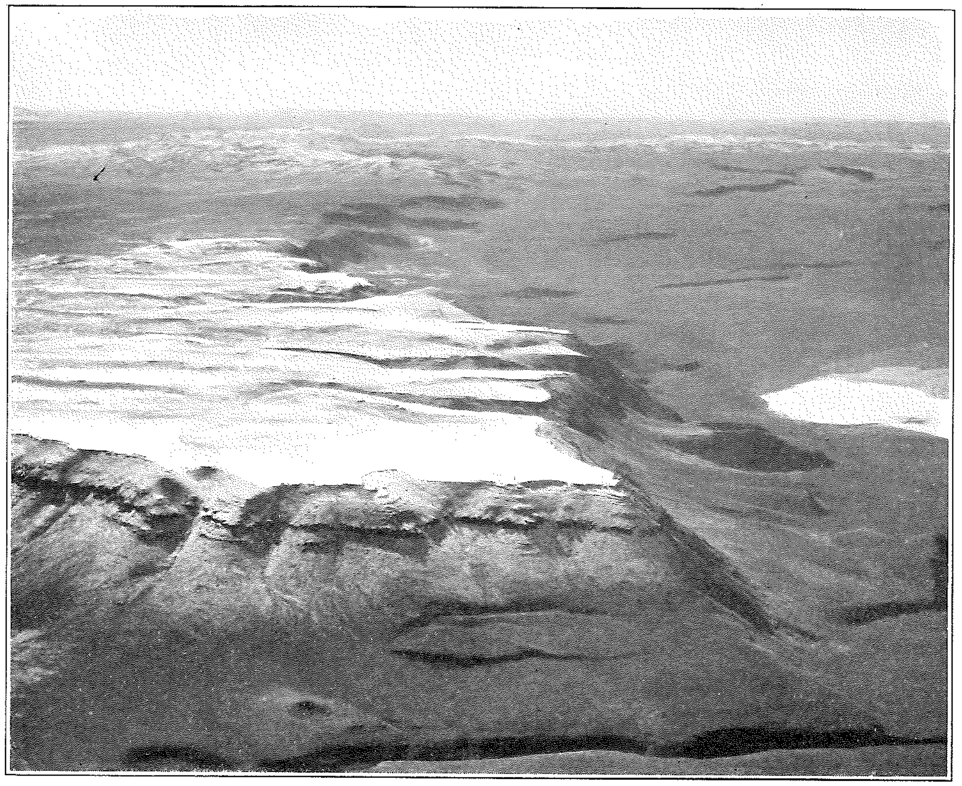

Fig. 10. Aeroplane view from the north of the curving western scarp at the northern end of the Pueblo Mountain block. This scarp is the southern continuation of the one defining Southern Steens. Lone Mountain is visible in the middle distance. R. E. Fuller and A. C. Waters, *op. cit.*, fig. 6, p. 218.

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 a low elevation and have a predominant strike of approximately N. 65° W., and a dip to the southwest of about 10° to 15°.

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.

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.

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).

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

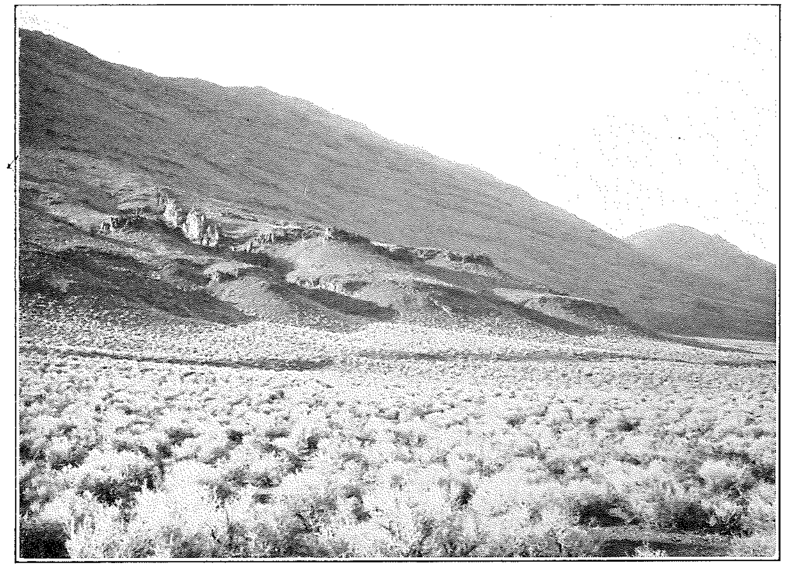

Fig. 12. View of the scarp southwest of Upper Alvord Basin showing in the foreground the displacement caused by a recent fault. The partially dissected miniature scarp, which is about six feet in height, can be traced for at least a mile.

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.

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.

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.

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.

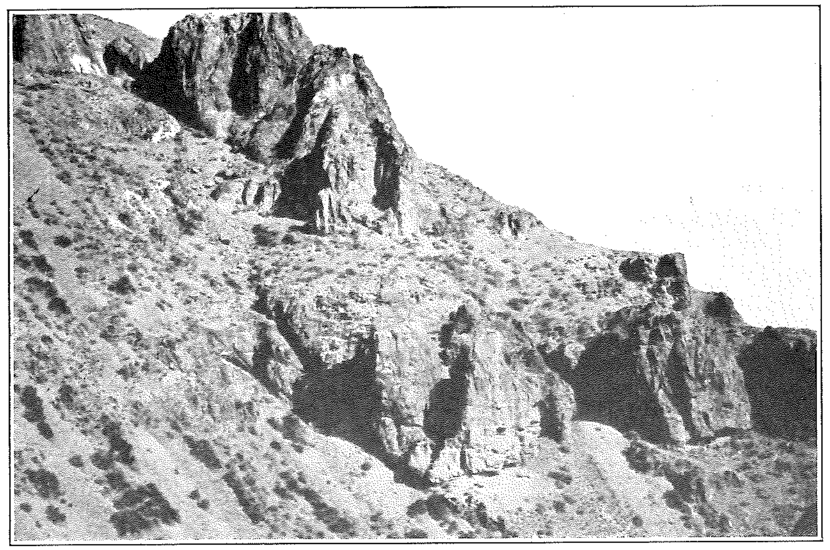

Fig. 14. In Toughey Creek a view of the main scarp shows one of the numerous step faults, which occur in this locality.

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.

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

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

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 tuff 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.

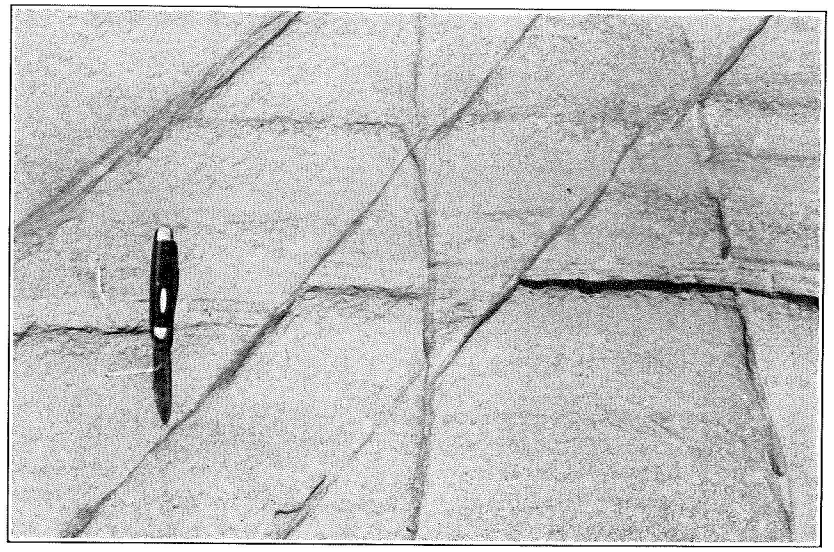

Fig. 15. View of the miniature faults exposed in the bedded tuffaceous sediments on the northern side of the lower cirque in Mosquito Creek. The inclined normal faults dip westward towards the main mass of the mountain. Some of the vertical fractures show a slight displacement, which permits the depression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

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.

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.

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

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

[5] W. 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.

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. 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.

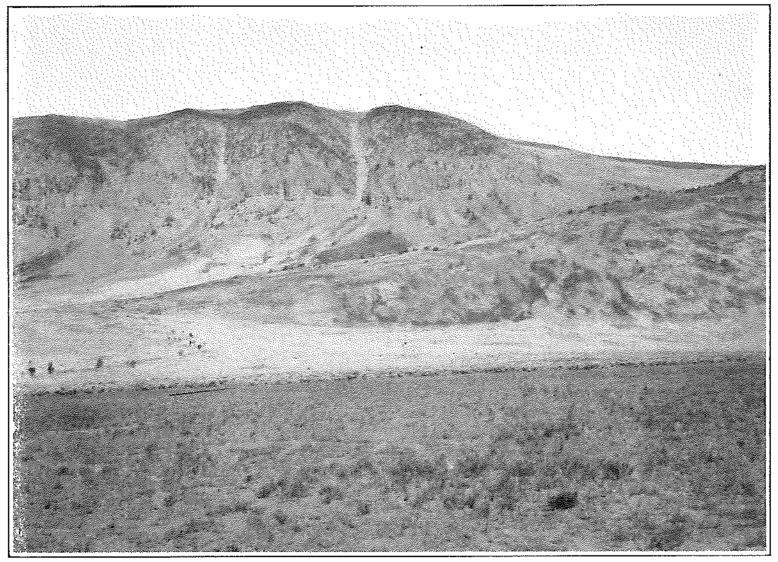

Fig. 18. View of the scarp of Northern Steens about ten miles north of the Mann Lake Ranch. The southern end of the inclined step fault block is clearly defined. This block becomes horizontal after attaining an elevation of about 1000 feet.

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).

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.

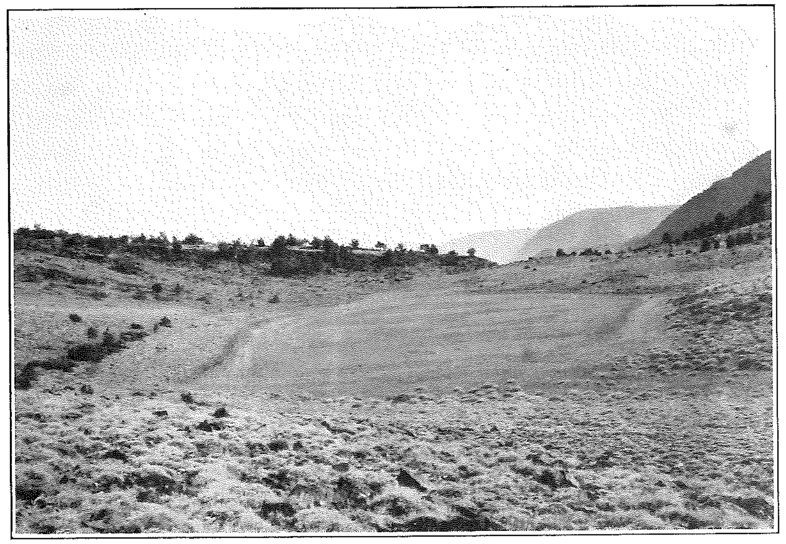

Fig. 19. Looking southward on the top of the above mentioned step fault block. The formation of the playa lake is attributed to the damming of an erosional valley by a landslide.

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.

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.

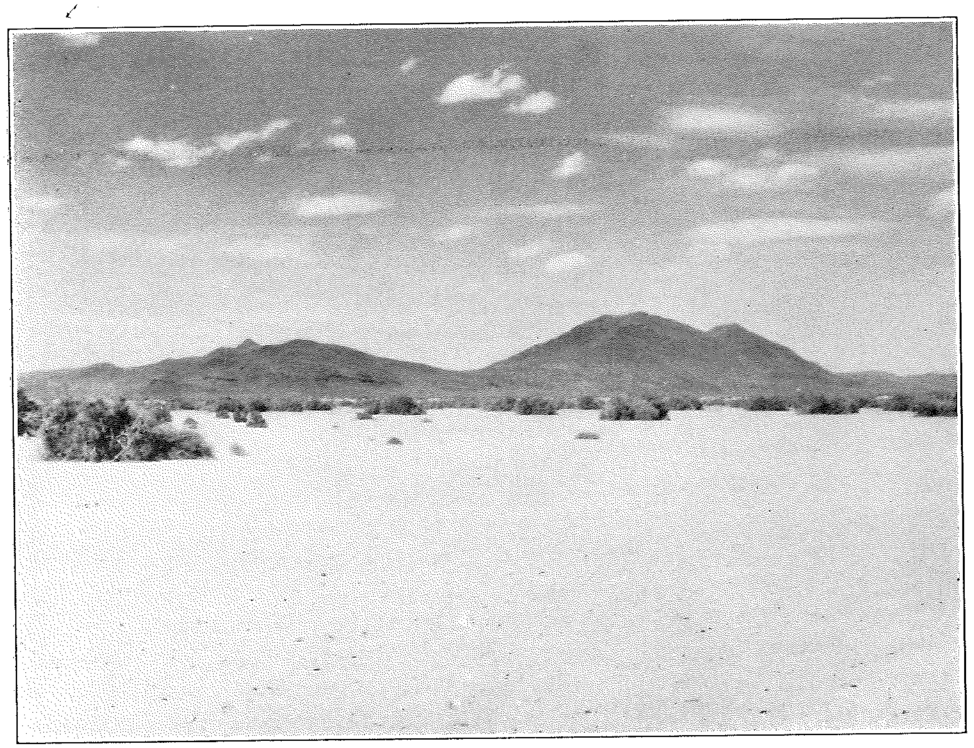

Fig. 20. Isolated fault blocks at the northern end of Alvord Desert viewed from the south. A small recent fault cuts their eastern scarp. Note the encroachment of vegetation at the margin of the playa.

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.

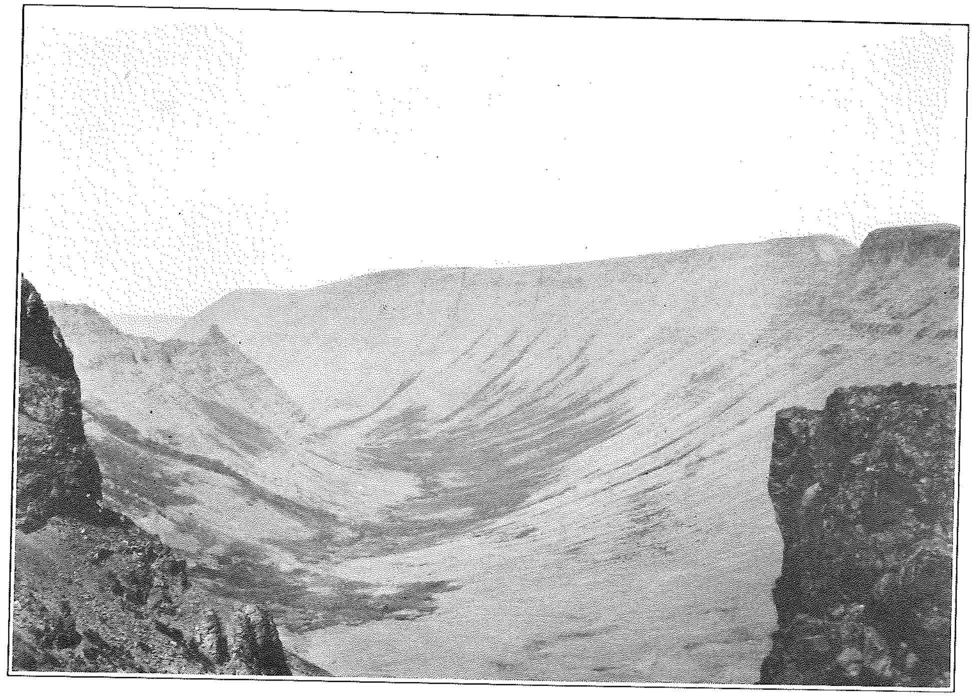

Fig. 21. Looking northward down the U shaped glacial valley of Kieger Canyon from the top of its cirque directly west of the head of Mosquito Creek.[7]

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 Toughey Creek is also locally known as Little Indian.

GLACIATION

I. C. Russell[6] and Waring[7] considered the broad U-shaped valley of Kieger Canyon (fig. 21) to be due to stream action subsequently modified by glacial erosion. Smith[8] later observed the well-marked evidence of glaciation in Wildhorse Canyon. In addition, however, the presence of broad shallow cirques, *roches moutonnées,* 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.

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

[7] Gerald 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.

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. Russell[9] 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.

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 terraine. 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

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[9] I. C. Russell, "Hanging Valleys," *Geol. Soc. America Bull.,* vol. XVI, p. 84, 1905.

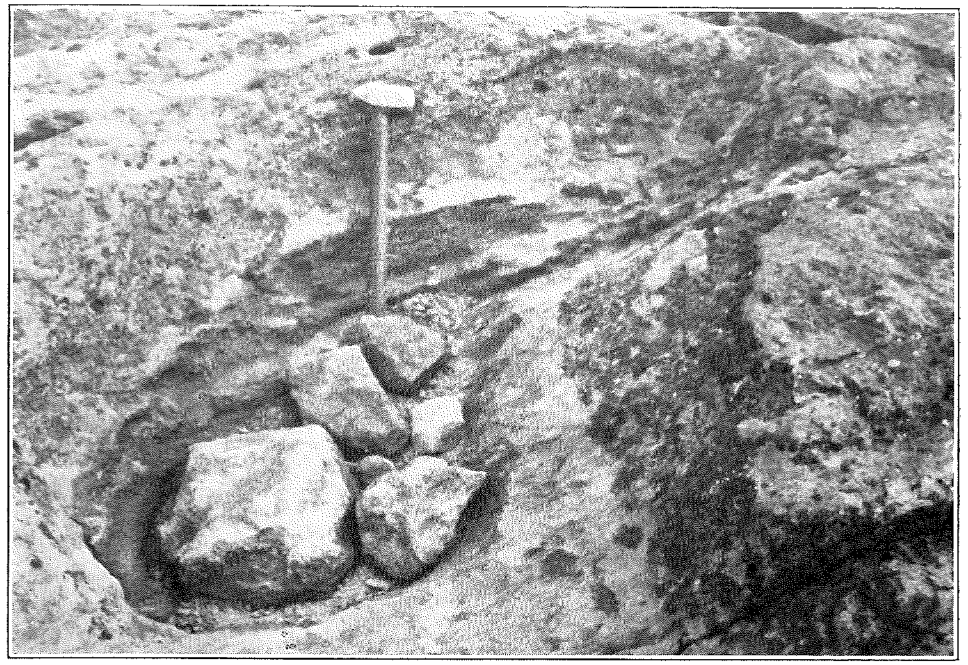

Fig. 22. A pot hole on the surface of the dacite between Toughey Creek and Indian Creek viewed from the north. The angular boulders pointing southward testify to wind erosion from that direction. The orientation of the boulder at the base of the hammer was disturbed.

formed by the disintegration of the dacite, for a minutely hackly jointing causes the latter to break into a fine gravel.

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.

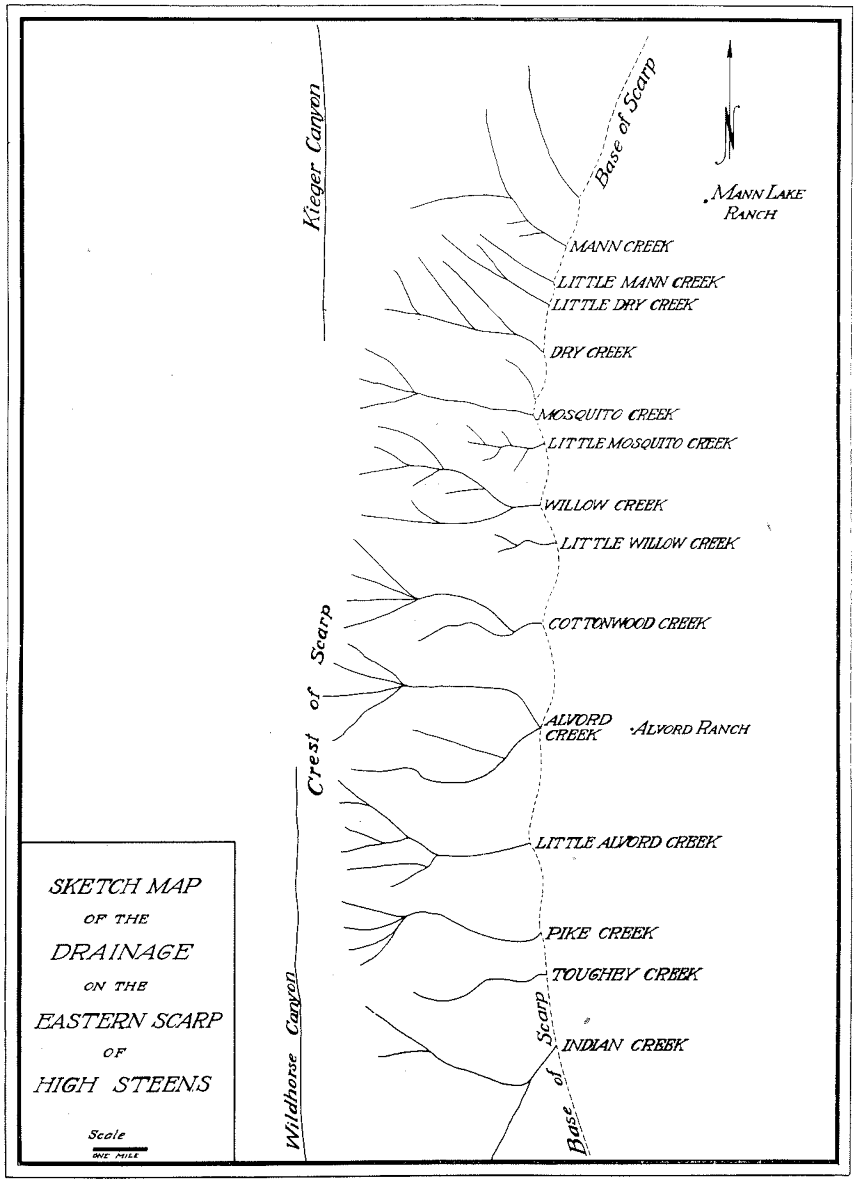

Fig. 23. Sketch map of the drainage on the eastern scarp of High Steens.

THE VOLCANIC SEQUENCE

The great eastern scarp of High Steens presents the most extensive exposures in south central Oregon. Locally outcrops are almost continuous for a height of over 5,000 feet, while across Alvord Desert, on the lower opposing wall of the graben the higher members of the series survive. Except for minor tuffaceous deposits and a few intrusions, the mountain is composed of flows of varying magnitude. The volcanic activity responsible for this lava was predominantly parallel to the potential line of weakness later followed by the great fault. Many of the vents are exposed in the deep valleys that cut the scarp.

Most of the members of this sequence are formed by the thick accumulation of the near vent phase. Owing to high viscosity at the time of extrusion, some of the flows are very local in their distribution. On the other hand, the flows of more fluid types are widely distributed and, if of a characteristic variety, have considerable stratigraphic value. The tuffaceous sediments of this region show such marked lithologic similarity that their correlation must be based largely on a rather meager fossil content.

In piecing together the regional geology of this broad volcanic field, it is necessary to correlate the series exposed in isolated scarps, which are usually 20 or 30 miles apart. Aside from the topography, only the ubiquitous presence of a thick series of basaltic lavas, which were extruded in a highly fluid condition, suggests a definite correlation. Otherwise the rapid changes in the stratigraphic sequence even on a single scarp clearly indicate the impossibility of basing regional correlation on the distribution of viscous lava or on minor variations in the volcanic sequence.

SUMMARY

Near the base of the Steens Mountain scarp, between Cottonwood Creek and Little Alvord Creek, there are scattered exposures of well-stratified tuffs, which are at least 800 feet in thickness. A small flora indicates these beds to be of Middle Miocene age, thus approximately corresponding to the Mascall Formation, which overlies the great series of Columbia River Basalt in the John Day region. For the present, these tuffs are called the Alvord Creek Beds in reference to the location of their major outcrops. Unfortunately, owing to the difficulty in correlating isolated exposures, the complete structure was not conclusively interpreted.

To the north of Alvord Creek, however, the subsequent flows are concordant with these beds, while to the south, the overlying series is nonconformable. Here, the sediments have been intruded by a thick basaltic sill and subsequently uparched by an acidic intrusion, which probably was in the form of a laccolith. The uppermost beds of this uparched structure have been truncated by an elongate acidic vent which parallels the scarp for about a quarter of a mile. The absence of deformation indicates its intrusion to have been subsequent to that of the laccolith. Extrusive material from this vent, however, is not exposed and cannot have been very great.

The southern extent of this laccolith could not be accurately determined, but it may well be responsible for the southern dip of the tuffaceous beds exposed on the northern wall of the valley of Little Alvord Creek. The dip slope of these beds formed the retaining wall for a massive flow of rhyolite about 400 feet in thickness. In this same valley, the vent for this flow is exposed cutting the inclined well-stratified tuffs. Poor exposures render it difficult to trace this rhyolite flow to the south so as to permit an accurate correlation with a complex series of acidic lavas exposed in the adjacent valley.

This valley, which is known as Pike Creek, shows an alternation of stratified tuffs and acidic flows. At the base are exposed about 200 feet of tuffs beneath an equal thickness of platy rhyolite, which locally appears to overlie its vent. On this flow was deposited more tuffaceous material to a depth of almost 300 feet. A well-defined vent crosscuts these beds and wells into another thick flow of platy rhyolite, which is at the same stratigraphic level as the previously mentioned rhyolite at Little Alvord Creek. The two flows, however, appear to be distinct. This lava was followed by another bed of stratified tuffs, about 40 feet in thickness.

Above this are two thick dacitic flows of very similar composition. The upper one is the larger and shows distinct vent characteristics over an extensive region between Pike Creek and Indian Creek. Here the exposures have a thickness of over 500 feet in spite of the erosion of the surface features. Northward the upper dacite thins gradually to almost half that depth, and at its northern extremity appears to abut against the previously mentioned elongate vent exposed above the laccolithic structure.

To the north, in the valleys of both Cottonwood Creek and Willow Creek, other masses of acidic lava outcrop at the base of the scarp. The former locality shows only a fault contact with the later series. Although due to their isolation, it is impossible to determine the relationship of these lavas to the acidic series exposed to the south, they at least have a similar stratigraphic position, in as much as they were both followed by the eruption of andesite.

Between Alvord Creek and Cottonwood Creek, a flow of basic andesite is interbedded in the Alvord Creek Beds at about 100 feet below their top. These same beds are also overlain by another thick andesitic flow of similar composition. This upper flow of basic andesite was capped first by a well-stratified bed of coarse tuffs of intermediate composition, and then by a huge flow of slightly more acidic andesite, which locally shows a visible content of hornblende. Immediately to the north of Alvord Creek, this flow has a thickness of approximately 900 feet, while farther to the north in the valley of Cottonwood Creek it has thinned to about half of that thickness. In the valley of Mann Creek, a similar lava forms the lowermost exposures and shows a thickness of 300 to 400 feet. Presumably it is part of the same flow, although it was not observed in the intervening valleys. Possibly it was derived from a series of contemporaneous vents, but the only discordant relation observed is exposed on the southern side of the valley of Alvord Creek. The presence of another locus of extrusion, however, is also distinct on the northern wall of the valley of Little Alvord Creek. Here the andesite welled above its vent to a sufficient depth to permit a thin extension to cap the upper dacite of the Pike Creek series.

Prior to any obvious erosional interval, the irregular surface of this great flow was capped by the extrusion of thin aphanitic flows of similar chemical composition. This upper series, which shows a maximum thickness of over 1,500 feet, attained a relatively level upper surface, although it locally decreases rapidly towards the west. The flows are remarkable in the fact that they consist predominantly of vesicular breccias, which are locally cut by auto-injections from their own thin platy flows. The basal breccia of each flow, as a rule, merges with the surface of the previous one, so that their contacts are usually imperceptible unless defined by an accumulation of stratified tuffs. This series has been greatly complicated by a discontinuous series of vents, which are scattered through a zone roughly parallel to the scarp. Between Mosquito Creek and the valley of Little Mann Creek, two of these vents gave rise to explosive activity, which formed cinder cones about 400 feet in height near the top of the series. These cones were subsequently almost completely submerged by additional flows, which are similar to the lower ones except for being slightly more vitreous.

Before any marked erosion had taken place the andesite was covered to a depth of at least 3,000 feet by a series of basaltic flows. These flows have marked physical and petrographic characteristics which are largely dependent on their extreme fluidity at the time of extrusion. The identical series can be traced southward to Pueblo Mountain and westward to Warner Valley and Abert Rim.

R. J. Russell[1] refers to the capping basalt in the Warner Mountain region of California as the Warner Basalt and correlates it both with the uppermost basalt exposed to the north near Plush, and also with the great thickness of lava at both Bluejoint and Abert Rims. He did not realize, however, that in the Warner Lake region the capping basalt, which is merely several hundred feet in thickness, rests disconformably on stratified tuffs overlying a far greater series, which is apparently formed by the western continuation of the Steens Mountain flows. In consequence, the writer will follow Russell's nomenclature in referring to the capping flows as the Warner Basalt, while using the name Steens Mountain Basalt for the lower series which forms the great thickness both in Warner Valley and at Abert Rim.

On the lower scarps in the region, which have been subjected to less vigorous erosion, quite a complex later chapter of the volcanic history is still apparent. The series exposed is extremely variable in its sequence. In general it consists of miscellaneous alternation of acidic, intermediate and basic flows with light colored tuffs which may or may not show stratification. The uppermost member both to the east of Alvord Desert and at the northern end of Warner Valley is slightly nonconformable. In the case of the former, however, the series is capped by basalt, while in Warner Valley an acidic flow locally closes the volcanic history. Otherwise the upper sequence appears approximately conformable with irregularities due merely to the viscosity of the lava. This varied series has a thickness of over 500 feet.

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[1] R. J. Russell, *op. cit.*, pp. 416, 427, 439.

ALVORD CREEK BEDS

General Characteristics

Light colored tuffaceous sediments outcrop locally at a number of places (fig. 24) in the lower thousand feet of Steens Mountain between Cottonwood and Toughey Creeks. In this distance, of over five miles, there are only a few good exposures and these for the most part are widely separated. The bedding as a rule is well defined and roughly horizontal, invariably testifying to the absence of compressional forces. The isolated exposures, however, could not be correlated, but owing to their close association they are classed as the Alvord Creek Beds.

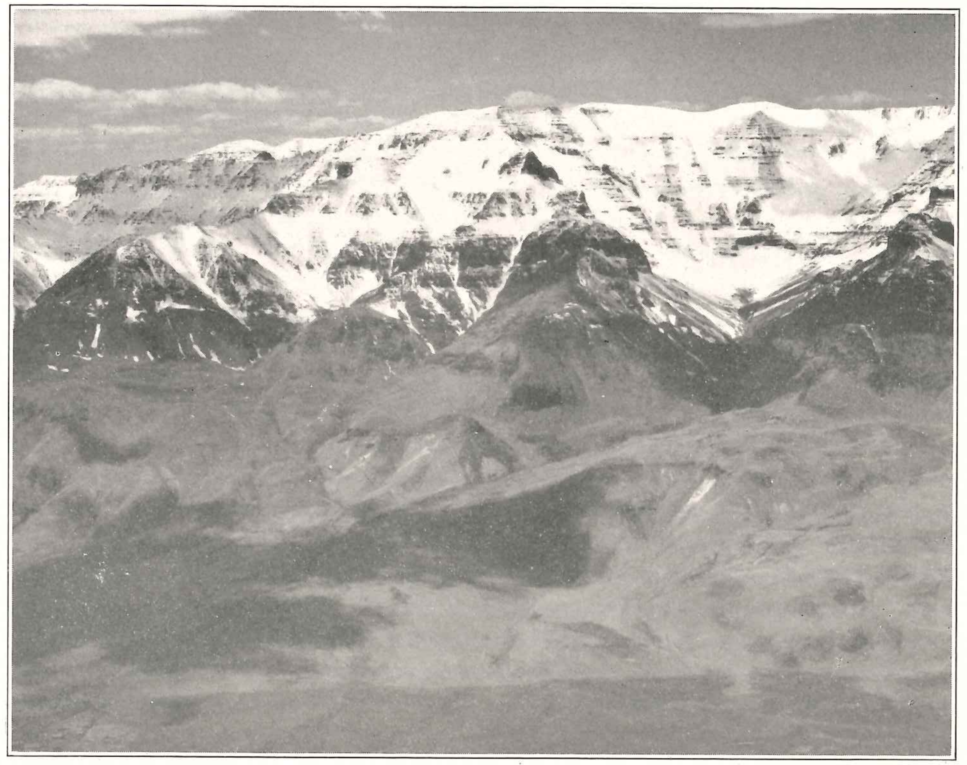

Fig. 24. Aeroplane view of High Steens west of Alvord Ranch, which is in the foreground on the left. On the right the valley of Alvord Creek exhibits a broad cirque with the characteristic glaciated tributaries visible as snow fields just below the crest. The light colored exposures at the base of the mountain are formed by the Alvord Creek beds. These beds on the northern side of the valley may be seen to dip southward. The dark outcrops at the top of the south fork locality are caused by basaltic and andesitic intrusions.

In general, the sediments consist of stratified acidic tuffs, which are predominantly white in color. Owing to the subsequent volcanic activity, these sediments have suffered considerable alteration, which has affected both their color and consolidation. Greenish and brownish varieties are relatively common. The greenish coloration is definitely due to localized alteration, while the brownish shades, at least in one exposure, appear to have an exotic origin. In consequence, in the field, the color does not form a satisfactory criterion for correlation. In two localities, a content of fossil leaves indicates a similar age, but not necessarily the same horizon. Some exposures show small conglomeratic facies composed largely of subangular pebbles of acidic lavas, while others show beds of a very fine shale. These phases are too local in their distribution to permit the correlation of isolated exposures even if the same stratigraphic horizon were exposed. Aside from the local indication of water classification, the coarseness of the material probably depended chiefly on the proximity of the locality to a volcanic vent. In consequence the size of fragments may have varied rapidly in distribution. It is possible that a correlation might be attained by detailed petrographic methods.

North of Alvord Creek

The greatest exposure (fig. 25) occurs on the main scarp a few hundred yards north of the valley of Alvord Creek. Here well-stratified beds dip southward at about 7°. The lowest beds are of brownish tuffs that are exposed continuously for a height of approximately 500 feet. For the most part they are too badly altered to permit the survival of any relict structure. In some fragments, however, the alignment of a few minute feldspathic laths indicates an original trachytic texture and suggests a lava of intermediate com-

Fig. 25. The main exposures of the Alvord Creek beds north of Alvord Creek. A flow of basic andesite about 100 feet in thickness is interbedded in the upper part of the series. The fossil beds are a little over 100 feet below its base. The resistant horizons are due to local opalization.

position. At about 200 feet above the base of the exposure, the tuff is relatively coarse and exhibits dark pumiceous fragments, which are usually not over 1.5 cm. in diameter. Stratification is locally apparent, but as a rule it is rather indistinct. An impregnation with zeolitic material is common. The lower part of this exposure shows a number of displacements. Although the lithologic homogeneity renders it difficult to be sure of the extent of movement, the distance in any instance did not appear to be more than a few feet. This lower brownish facies grades upwards into buff colored stratified tuffs about 50 feet in thickness. These in turn are overlain by about 200 feet of whitish tuffaceous sediments, which contain horizons of opalized shale rich in fossil leaves.

Capping these beds is a flow of rather basic andesite close to 100 feet in thickness. This lava is overlain by less than 100 feet of white tuffs, which are poorly exposed beneath a second far greater andesitic flow of similar composition. This upper flow can be traced northward as a horizontal stratigraphic unit for over a mile to Cottonwood Creek. There it may be seen to be still underlain by well-stratified white tuffs about 100 feet in thickness. As in the section to the south, these sediments cap a lower andesitic flow, which is here cut by a vertical fault roughly parallel to the scarp. The eastern block, consisting of an acidic agglomerate several hundred feet in thickness, has been upthrown, thus hiding the base of the lower andesite.

Judging from these exposures and from the similarity between these two adjacent sections, the andesite that caps the upper tuffs is at least locally conformable. To the south, however, north of Alvord Creek, the tuffaceous sediments dip southward at about 7°. In this locality, the relationship of the capping andesite cannot be accurately determined, but it appears to lack this deformation.

SOUTH FORK OF ALVORD CREEK

About a half a mile further to the south, on the northern side of the south fork of Alvord Creek (fig. 26), there are good exposures of stratified tuffs, which at least superficially resemble the section studied to the north. These tuffs are cut by small elliptical andesitic necks of dark glassy andesite, and by basaltic dikes, one of which is 75 feet in width. The induration from this dike has resulted in the formation of a cliff at the top of the exposure.

The beds, which are roughly horizontal, show a thickness of about 450 feet without exposing either the top or the base of the section. Again the lowermost exposures are of a brownish color (fig. 27), but this phase is eroded to a depth of only about 50 feet. Higher in the section the tuffs are very light colored. In this zone, about 30 feet below the base of the previously mentioned cliff, a partially opalized horizon of shale was found to be rich in fossil leaves. The uppermost phase of the section is rather agglomeratic. The top is close to 200 feet below the massive andesite, which overlies the two previously mentioned andesitic flows to the north of Alvord Creek.

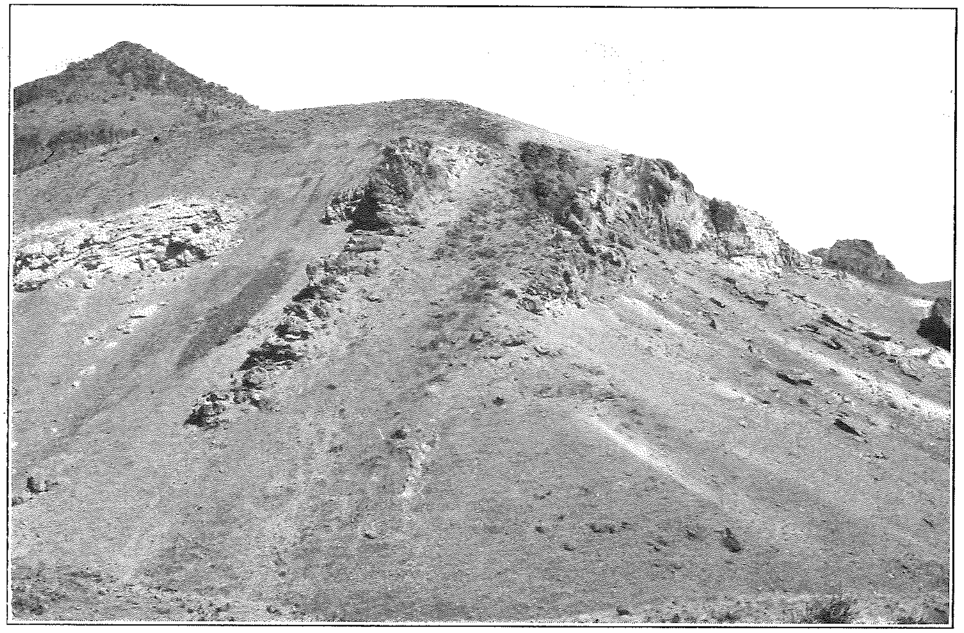

Fig. 26. Looking northward at the Alvord Creek beds north of the south fork of Alvord Creek. The cliff on the right is formed of tuffaceous sediments indurated by a 75 foot basaltic dike, which is visible in the center of the view. The fossil locality is about 50 feet below the base of this cliff near its southern end.

NORTH OF LITTLE ALVORD CREEK

It is also impossible to determine the stratigraphic relationship of the previously mentioned tuffs to those exposed on the scarp southward as far as Little Alvord Creek. In this locality, similar tuffs have been intruded by a basic sill approximately 200 feet in thickness and subsequently uparched by an intrusive mass of rhyolite, which outcrops at the base of the scarp for several hundred yards. Although its base is not exposed, this rhyolite is presumably in the form of a laccolith.

Judging from the inclination both of the contact and of the overlying beds, the exposure is formed by the eastern margin of the intrusive. On the northern limb near the contact, the beds have a strike of N. 30° W. and dip approximately 11° N.E. Adjacent to the southern contact the structure shows a southerly dip of about equal magnitude, but the exposures do not permit an accurate reading. The possible height of this dome is hidden by an elongate acidic vent, which cuts the arch parallel to the scarp at about 1,000 feet above the desert.

For about half a mile to the south, to the valley of Little Alvord Creek, the scarp exhibits a few small outcrops of tuffs, which are either approximately horizontal or dip slightly to the south. Adjacent to the scarp, however, on the northern wall of this valley, the tuffaceous series has a strike of N. 80° E. and dips approximately 15° S. About a quarter of a mile farther to the west, the strike is approximately N. 45° W. and the beds have a slightly greater dip to the southwest. Although no conclusive evidence is available, it is possible that this deformation is due to a southern continuation of the laccolith.

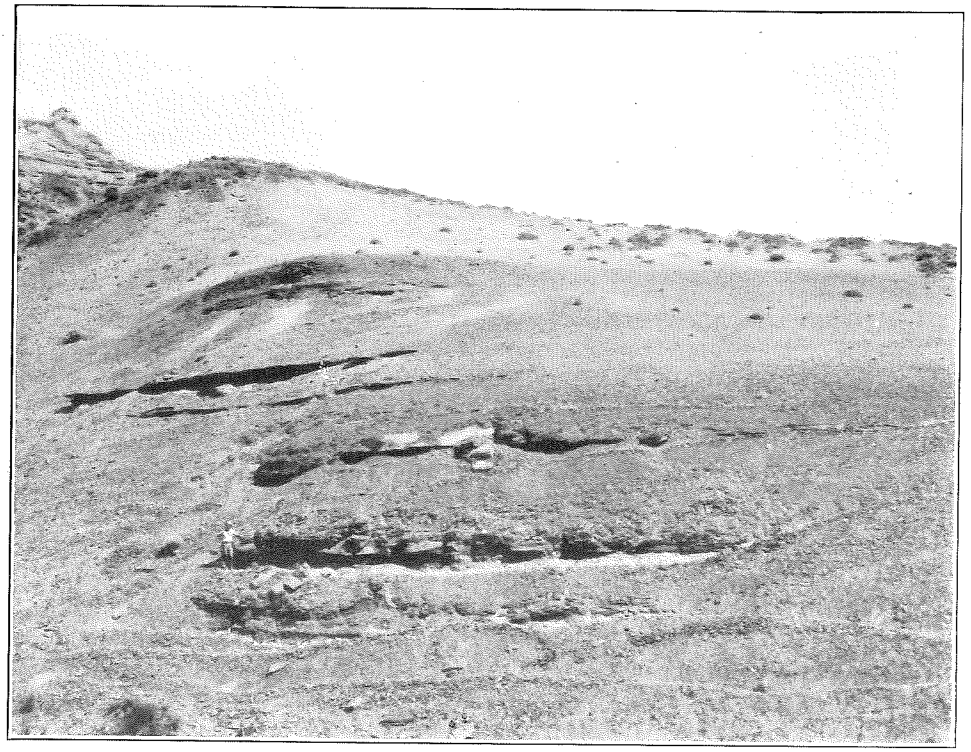

Fig. 27. The lowermost beds to the north of the south fork of Alvord Creek. The undisturbed stratification furnishes strong testimony against compressional faulting.

These inclined beds at Little Alvord Creek form the retaining wall for a thick rhyolite flow extruded from a vent which cuts them. Although tuffaceous material associated with this vent is indistinguishable from some facies of the series, the fine stratification of the latter locally demands aqueous deposition and precludes the possibility of a genetic relationship. Judging from the horizontal exposure formed by the chilled basal phase of this flow, it was extruded to the south on a relatively level surface. The absence of lower outcrops, however, makes it impossible to determine whether this surface was formed by non-conformable deposits resting on the tuffaceous series or by the direct continuation of these beds flattening out away from the margin of the laccolith.

In the valley of Pike Creek, nearly 2 miles to the south, there are exposed beneath the stratigraphic continuation of this flow over 400 feet of stratified tuffs and agglomerates with a lower 200 foot flow of rhyolite interbedded in them. The base of these beds is not exposed. Although they may well correlate with the uppermost Alvord Creek Beds, the relationship at the best is only hypothetical.

FOSSIL CONTENT

North of Alvord Creek the fossil leaves were found in partially opalized thin bedded shales. This horizon, which is about four feet in thickness, occurs approximately 100 feet below the interbedded flow of basic andesite. Owing to its hackly fracture, the highly opalized rock, which is confined to a layer about six inches thick, is not very productive. Fortunately the weathered phase of the upper and lower margins, which were possibly less silicified, split readily.

The other locality was found near the southern margin of the main exposure north of the south fork of Alvord Creek. It is about 50 feet below a wall formed by the induration of the great basaltic dike, which cuts about N. 10° E. Here the fossils were again confined to an opalized thin bedded shale. The specimens were more satisfactory owing to the fact that the horizon is exposed in a shallow prospect hole.

After a preliminary examination, Dr. Ralph W. Chaney considered these fossils to demand a direct correlation of the beds with the Mascall Formation,[2] which is exposed in the John Day Valley above the Columbia River Basalt. In submitting the following list of the fossils (table 1) he stated,[3] "There are a number of specimens represented by incomplete material or at present unknown to me which will increase the list somewhat. But it seems unlikely that the resemblance to the Mascall will be greatly affected by such additions. In a list of this length the percentage figures have no great importance, but I have put them in for what they are worth. Rosa hilliae is a typical Florissant species, and is commonly considered to be a Miocene species, although I have found it to be in the Upper Oligocene as well."

TABLE I

	South Fork Alvord Creek	North of Alvord Creek	Mascall Formation
Abies magnifica, var. shastensis	+	+	+
Acer bandirei	+	+	+
Acer oregonianum	+	+	+
Alnus sp.	—	+	+
Celastruss dignatus	+	+	+
Cercocarpus antiquus	+	+	+
Cyperacites sp.	+	+	+
Prunus merriami	+	—	+
Rosa hilliae	—	+	—
Rhus sp.	+	+	—
Sequoia langsdorfii	+	—	+
Total species	9	9	
Per cent common to both floras	78	—	
Per cent common to Mascall	89	78	

Preliminary comparison by Dr. Ralph W. Chaney of the flora from the Alvord Creek Beds with that from the Mascall Formation.

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[2] J. C. Merriam, "A Contribution to the Geology of The John Day Valley," *Univ. Calif. Publ., Bull. Dept. Geol. Sci.*, vol. 2, no. 9, 1901. R. W. Chaney, "The Mascall Flora; its Distribution and Climatic Relation," *Carnegie Inst. Washington Publ.*, no. 349, 1925.

[3] R. W. Chaney, personal communication.

About five miles east of the southern end of Alvord Desert there are some well-stratified tuffaceous deposits rich in fossil leaves and diatomite. These beds, which are known as the Trout Creek Formation,[4] have been considered to be of Eocene age and to occur at the base of the volcanic series.[5] Vertebrate remains, however, recently collected by Stock "indicated quite clearly that the beds were not earlier than the Middle Miocene."[6] Although this evidence permits the Trout Creek Formation to be tenatively correlated with the Alvord Creek Beds, its stratigraphic relation to the adjacent flows suggests a far later origin. No definite statement can be made, however, for the flows observed in association with it have no resemblance to any members of the Steens Mountain series exposed on the opposite side of the desert.

EARLY INTRUSIONS IN THE ALVORD CREEK BEDS

Basaltic Sill

About a mile to the north of the mouth of Little Alvord Creek, a large basaltic sill is exposed where the Alvord Creek Beds are uparched by the rhyolitic laccolith. Viewed from the desert, its brownish outcrops cause the domed structure to be apparent. The basic intrusive, which is over 200 feet in thickness, is separated from the rhyolite by only about 100 feet of tuffaceous sediments. Above the laccolith, this basalt has suffered such marked alteration that from a megascopic examination it is almost indistinguishable from a basic tuff. In fact, to the north where the alteration is less extreme and the upper portion of the intrusion is relatively fresh, it requires very careful observation to determine even the approximate contact with the underlying tuffs. This greenish brown contact zone has been partially silicified and impregnated with calcite.

The upper contact of this igneous mass is best exposed in the extremely altered zone above the acidic intrusion. Here the determination of its position and relationship also requires minute examination, for the stratified beds for the next 25 feet above are of approximately the same light brownish color. The upper part of the basalt is distinguishable from its high content of minute vesicles averaging about 1 mm. in diameter. These are filled with a dark powdery substance which appears to be formed of decomposed chlorophaeite. The actual contact is demarked by a thin layer of soft black material which is considered to be devitrified tachylite. This contact fluctuates slightly without causing any appreciable disturbance in the overlying beds.

A thin section of the less altered rock, from one of the most northerly exposures about 50 feet above the base, shows the sill to be formed of a feldspathic basalt. About 50 per cent of the rock is composed of roughly aligned labradorite laths which show a seriate development ranging from .1 mm. to 2 mm. in length. The rock also contains a few grains of augite, which are usually about .5 mm. in diameter. The ground is formed of a brownish white semi-opaque substance, which shows locally a faint suggestion of spherulitic structure, due possibly to an incipient development of variolites in a glass. Throughout this ground there are irregular patches of yellowish brown chlorophaeite, which locally exhibits minute fibres of indeterminable birefringence. The formation of this basic magmatic residual depends largely on the retention of volatiles and is, therefore, quite commonly developed in basic intrusives. In this instance, it is not derived from the decomposition of the pyroxene, for the latter is unaltered. This colloidal residual, which in the past has been confused with palagonite,[7] characteristically occurs both as thin impregnations and as rounded or amoebaform segregations.[8]

Rhyolitic Laccolith

The acidic intrusion, which is responsible for the local deformation of the Alvord Creek Beds and the alteration of the previously mentioned sill, is exposed at about a mile north of Little Alvord Creek. At the base of the scarp for several hundred yards there are scattered outcrops of light grey rhyolite, which exhibits marked cavernous weathering because of the erosion of locally kaolinized areas.

In the more resistant rock, phenocrysts of quartz and dull white feldspar are easily distinguished in a felsitic ground that is usually kaolinized to a whitish grey. The quartz, which composes about 20 per cent of the rock, attains a maximum diameter of about 4 mm., although the grains average less than half that size. In thin section, many of the individuals show a good crystal outline, which is locally modified by numerous sinuous embayments. The feldspar phenocrysts that constitute probably an equal percentage, are as an average decidedly larger. They were invariably found to be highly altered, but judging from their remnants they appear to consist wholly of orthoclase. The rock also contains a number of angular inclusions of a kaolinized iron stained material that is indeterminable, but probably represents fragments of the intruded tuffs.

At the northern margin of the intrusive, the adjacent tuffs have been highly brecciated and altered to a dense pale greenish rock. At about 200 feet above the basal exposures, the contact of the intrusion with the white tuffs may still be observed curving upwards into the hill, as if forming a small segment of a dome. The actual contact is very sharp, but the adjacent rhyolite contains

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[4] W. D. Smith, *op. cit.,* p. 206.

[5] Gerald A. Waring, "Geology and Water Resources of the Harney Basin Region," *U.S. Geol. Sur., Water Supply Paper* 231, p. 20, 1909.

[6] Chester Stock, personal communication.

[7] L.L. Fermor, "On the Composition and Nomenclature of Chlorophaeite and Palagonite, and on the Chlorophaeite Series," *Rec. Geol. Surv. India,* vol. LX, pp. 411-430, 1930. Martin A. Peacock, "The Distinction between Chlorophaeite and Palagonite," *Geol. Mag.,* vol. LXVII, pp. 170-178, 1930.

[8] Robert Campbell and James W. Lunn, "Chlorophaeite in the Dolerites (tholeiites) of Dalmahoy and Kaimes Hills, Edinburgh," *Min. Mag.,* vol. XX, pp. 435-440, 1925. "The Tholeiites and Dolerites of the Dalmahoy Syncline," *Trans. Roy. Soc. Edinburgh,* vol. LV, pp. 496-500, 1927. M. A. Peacock and R. E. Fuller, "Chlorophaeite, Sideromelane and Palagonite from the Columbia River Plateau," *Am. Mineralogist,* vol. 13, pp. 361-369, 1928. D. N. Wadia, "Palagonite-bearing Dolerite from Nagpur: Suggestion regarding the Nature and Origin of Palagonite," *Rec. Geol. Surv. India,* vol. LVII, pp. 338-343, 1925.

small fragments of the indurated tuffs. Most of these fragments are angular and do not suggest resorption. The massive tuffs near the intrusion are highly shattered and locally injected by small apophyses a few inches wide and extending for merely a few feet.

About 50 feet higher on the slope, the rhyolite is again exposed, possibly in some measure on account of a small fault, but more probably it is caused chiefly by the slope of the contact being greater than that of the scarp. At these uppermost exposures, the intrusive is greatly kaolinized and, in part, streaked with bands formed of decomposed white spherulites. Near the contact, massive white quartz occurs in a few irregular veins, which are 2 or 3 inches in thickness.

Just below this uppermost exposure of the intrusive, a well slickensided surface in the tuffs marks a vertical fault trending roughly N. 70° E. From an examination of this surface, the side towards the center of the laccolith was found to form the downthrow. The displacement was undetermined, but apparently small. Possibly only by chance its direction almost corresponds with that of some highly silicified lines of brecciation that cut the overlying series. These lines are approximately N. 60° E. Owing to differential erosion, these zones of silicification, on cutting the badly decomposed basalt, outcrop as resistant dikelike masses, one to two feet thick. The orientation of these lines of fracture furnishes an additional suggestion that the major axis of the laccolith continues to the southwest, thereby causing the deformation observed in the valley of Little Alvord Creek.

ELONGATE ACIDIC VENT

Above the sill, at the center of the laccolith, stratified tuffs exhibit a thickness of about 250 feet. Their exposure ceases with the outcrop of a light grey rhyolite which superficially suggests a flow, for it can be traced horizontally to the north for possibly 100 yards before it is covered by a landslide. To the south, however, the rhyolite grades into a perlitic phase which has intruded the tuffs and locally has upturned the uppermost beds.

About 50 feet above this intrusive contact more perlite is exposed, apparently as the northern margin of a well-defined vent that forms an elongate exposure continuing southward for over a quarter of a mile. At its northern end this volcanic neck is marked by a series of exposures trending approximately east and west. Traced downwards they swing southward as if defining a curving margin.

To the south of the perlitic margin and immediately parallel to it there is a wall-like exposure about 50 feet wide, which weathers out as a series of thin partitions about one to four inches in width. These partitions are covered with rounded excrescences, which are the surface expression of a solid mosaic of conflicting spherulites, ranging approximately from 1 to 10 cm. in diameter. As a whole, the surface usually attains an irregular reniform structure. Some of the rounded nodes exhibit a crater-like depression in the center, due apparently to the collapse of a hollow spherulite. The easily eroded material between these thin partitions usually is of a soft pale greenish substance, which, where less altered, is found to be formed by the decomposition of perlitic glass.

To the south of this marginal phase there are continuous exposures of a lava that appears identical to the grey rhyolite except for a brick red color and highly inclined flow structure. This phase ends abruptly at a distance of over a quarter of a mile to the south in a steep cliff about 300 feet high (fig. 28). Approximately a hundred yards farther, across a soil covered slope, there is another precipitous exposure at slightly higher elevation. This is formed by the southernmost limit of the great flow of biotite-dacite that caps the series to the south. Although the surface of this flow is comparatively level, the base, showing a fairly fresh perlitic phase, increases rapidly in elevation as if it were abutting on the marginal accumulation of an earlier vent. In consequence, it is considered by the writer to be of later origin.

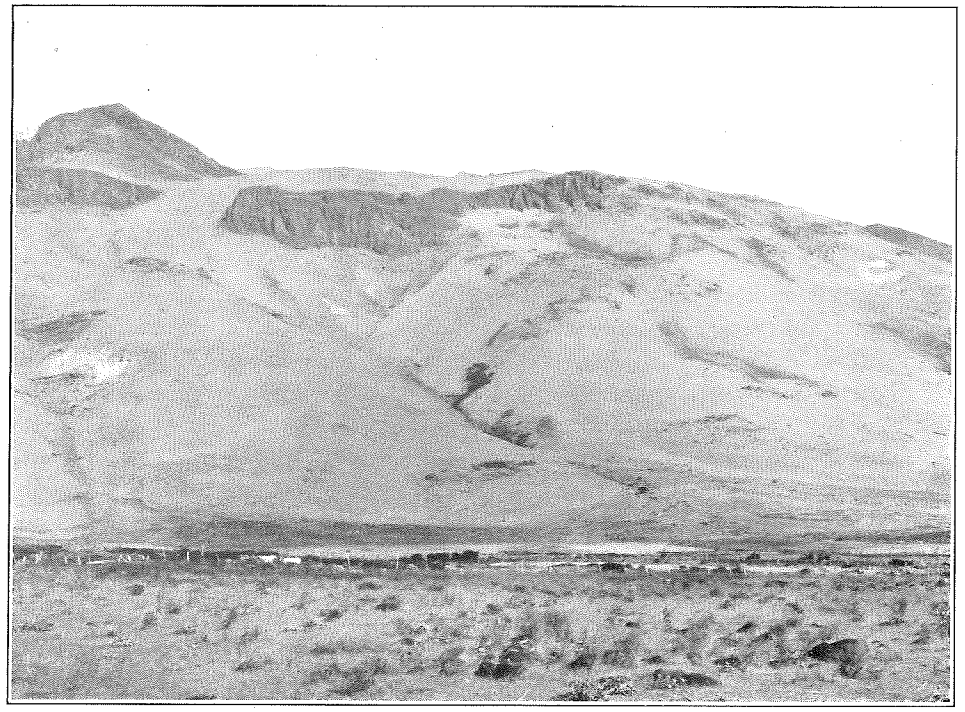

Fig. 28. The lower thousand feet of the main scarp about a half mile north of Little Alvord Creek. The rhyolite vent forms the large horizontal exposure in the center of the picture. To the left of it is the upper flow of biotite-dacite. The principal outcrops directly beneath the northern part of the vent are attributed to landslides. In the center at the southern margin, inclined tuffaceous beds are visible.

The elongate exposure to the north appears to consist of the elliptical neck of a vent with no obvious extrusive material. The western margin is not exposed, but the outcrops and flowage suggest a trend slightly west of north. The lava shows pronounced near-surface characteristics, and, therefore, cannot have suffered extensive erosion, although its glassy features have been removed. At the time of activity it probably was surrounded by tuffs.

On the shoulder of the scarp below the steep cliff formed by the southern end of this vent there are scattered exposures of a similar lava of the same near-surface type. Immediately above this exposure, there is a re-entrant in the upper escarpment. The position of the lower outcrops is, therefore, attributed to landslide, although the primary irregularity in the steeply inclined lines of flowage renders it difficult to be sure of the reverse rotation of the block.

This volcanic vent and its satellitic intrusion to the north show no indication of deformation and are considered to be of later origin than the laccolith. In spite of their close association, these elongate volcanic necks show no petrographic evidence of a genetic relationship to the underlying intrusion. On the other hand, both the rock forming the rhyolite vent and the upper flow of biotite-dacite, with which it is almost in contact on the south, appear to be somewhat similar petrographically, although they are both very variable in their phases. Judging from chemical analyses, however, at least the satellitic intrusion to the north is definitely rhyolitic and distinct from the biotite-dacite. The rhyolite is higher both in silica and potash and decidedly lower in its content of soda, lime, iron, and magnesia (table II).

Petrographically the rhyolite and the dacite both contain oligoclase and orthoclase. In each, the feldspar shows a glomeroporphyritic tendency and usually exhibits many glassy inclusions. In the rhyolite, the phenocrysts as a rule appear to be far more complex, for a number of the larger crystals, which range from 2 to 3 mm. in diameter, contain aggregates of smaller grains. Biotite, although it usually constitutes less than one per cent, is common to both of them, but the flakes in the rhyolite are seldom visible megascopically. They are generally less than 1 mm. in length, while those in the dacite are several times that size. In addition, the felsitic groundmass in the rhyolite is less altered and locally shows well-developed spherulites. In both types the contents of feldspathic phenocrysts varies from about 10 to 20 per cent of the rock.

TABLE II

PART 1

	I	II
Silica	73.00	67.05
Alumina	14.23	14.91
Ferrous Oxide	1.28	1.48
Ferric Oxide	.28	.92
Magnesia	.24	.65
Lime	1.25	2.44
Soda	2.96	4.15
Potash	4.86	3.04
Water above 105° C.	1.00	4.35
Water at 105° C.	.60	.50
Carbon Dioxide	none	none
Titanium Dioxide	.18	.34
Phosphorus Pentoxide	trace	.12
Sulphur	none	trace
Manganese Dioxide	none	trace
	99.88	99.95

I. Northern extension of rhyolite vent above laccolith north of Little Alvord Creek. Analysts W. H. and F. Herdsman.

II. Basal perlite of the upper biotite-dacite flow on the south side of Pike Creek. Analysts W. H. and F. Herdsman.

PART 2

	I	II
Quartz	33.24	24.84
Orthoclase	28.91	17.79
Albite	25.15	35.11
Anorthite	6.12	11.40
Corundum	1.73	.61
Hypersthene	2.32	3.05
Magnetite	.46	1.39
Ilmenite	.46	.61
Apatite	....	.34
Water	1.60	4.85
	99.99	99.99

Norms calculated from the analyses in Part I:
I. Toscanose, C. I. P. W. symbol, I. "4."2.(2)3.
II. Toscanose, C. I. P. W. symbol, I.4.2". 3".

PIKE CREEK VOLCANIC SERIES

As previously mentioned the dip slope of the southern limb of the laccolithic dome in part forms the northern wall of the valley of Little Alvord Creek. To the south of the creek for about three miles there is a great series of acidic flows and stratified tuffs, in all more than 1500 feet in thickness (fig. 29).

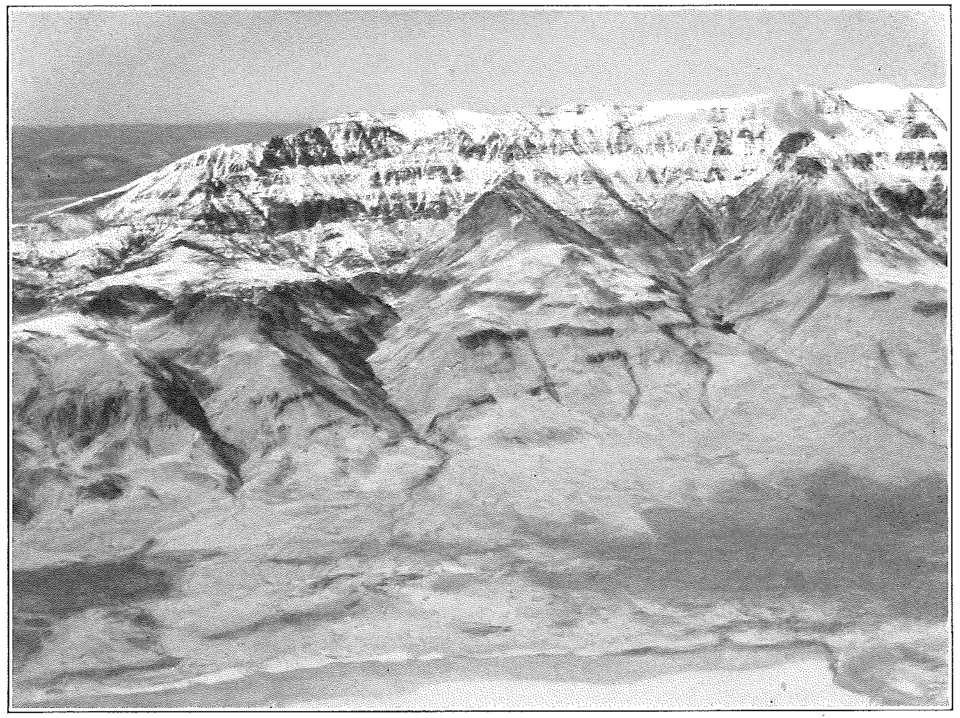

Fig. 29. Aeroplane view of the southern end of High Steens from the east. The volcanic series of Pike Creek, which lies in the center, is prominently exposed. On the right the andesitic vent on the northern side of Little Alvord Creek is visible. Farther northward at the margin of the picture, the rhyolite vent above the laccolith may be seen just to the north of the most northerly exposure of the upper flow of biotite-dacite. At the base the playa formed by Alvord Desert is partially flooded.

Aside from the gentle westward dip of the fault block this series is flat lying. The flows composing its upper 1000 feet abut against the inclined strata forming the southern margin of the dome. The lowermost beds of this southern series, exposed in Pike Creek, about two miles to the south, consist of an acidic flow interbedded in stratified tuffs. Each of the three members thus formed is about 200 feet in thickness, although the base of the lower tuffs is not exposed. Locally these lower beds are conformable to the upper series, but if they could be traced northward they might be found either to be, like the upper members, nonconformable to the southern limb of the laccolith or to be the direct stratigraphic continuation of its domed beds, with which a local viscous flow is interbedded.

Since the stratigraphic relationship of these acidic tuffs and lavas is best exposed in the valley of Pike Creek, that name is given to the series (fig. 30). To follow the chronology of events as well as the origin of its different members, it is necessary, however, to digress geographically both to the north to Little Alvord Creek and southward to Indian Creek.

In the valleys of both Pike Creek and Toughey Creek, the geology is greatly complicated by the previously mentioned step faults which roughly parallel the scarp as it extends towards Wildhorse Spur. These step faults are rarely more than 100 yards from the main scarp.

LOWER TUFFS

To the west of this zone, on the northern side of the deep valley of Pike Creek, the lowermost outcrops are formed by about 200 feet of stratified tuffs, the base of which is not exposed. These beds are chiefly of a pronounced greenish hue, due presumably to the alteration of the normal white acidic tuffs by the contact effect of the adjacent acidic vents.

Locally these beds are cut by five basaltic sills varying in thickness from a few inches to about 15 feet. The smallest of these, at its western extremity, diminishes to a thickness of only half an inch. The two larger ones, which are approximately of equal size, have both resulted in the induration of the adjacent sediments to a dark grey. This contact effect dies out within about five feet. The largest of the three smaller sills is less than four feet in thickness. The induration caused by these minor intrusions is almost negligible.

LOWER LAMINATED RHYOLITE

Directly above these tuffs in the valley of Pike Creek and extending westward for several hundred yards, there is some extremely laminated felsitic rhyolite (table III) of a reddish brown color. This acidic lava is about 200 feet in thickness. Overlying the tuffs, the laminations are largely horizontal and the mass is definitely a flow, but farther to the west it develops marked vent characteristics. These characteristics consist of highly inclined features such as lines of flowage, and bands of spherulites and lithophysae. At the surface, additional evidence is furnished by the presence of perlitic spines, surrounded by white tuffaceous material, which presumably is of contemporaneous origin. Unfortunately a crosscutting relationship of this rhyolite with the underlying highly altered tuffs is not exposed. Its only other exposure occurs immediately to the south in the valley of Toughey Creek, where it forms the base of the section.

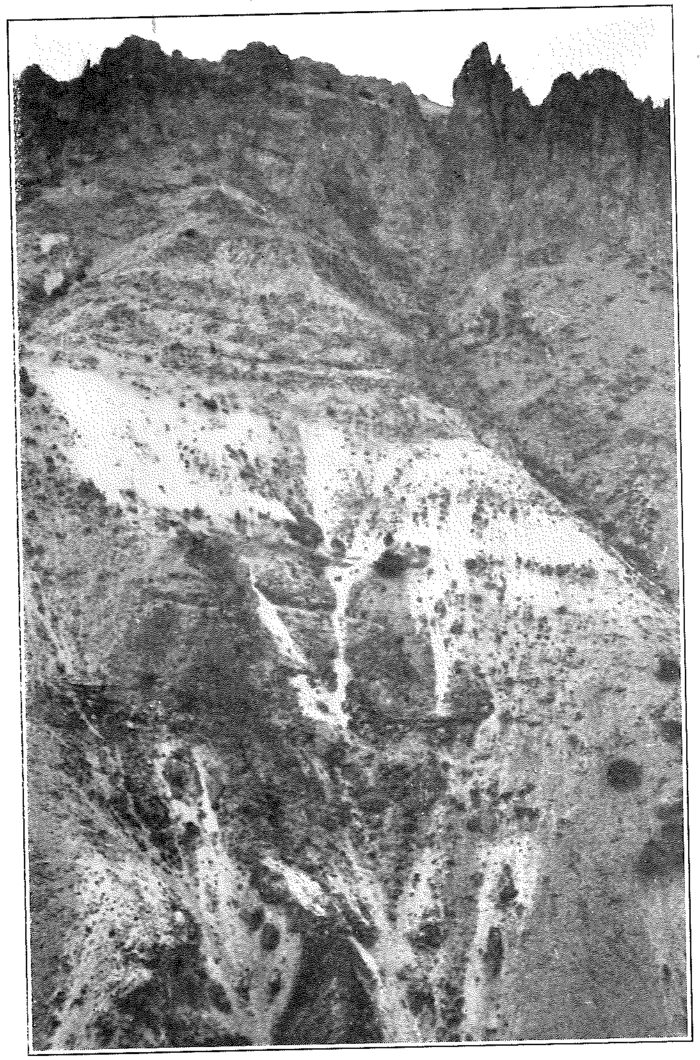

Fig. 30. The volcanic series disclosed in an exposure about 1500 feet in height on the southern side of Pike Creek valley. At the base the lower platy rhyolite may be seen. Above it the dark exposures are formed by the middle tuffs. These are overlain by the upper platy rhyolite, which is shown by the light colored exposures in the center of the series. Above this are the upper tuffs and the lower biotite-dacite, which is not clearly defined. The upper flow of biotite-dacite forms the pinnacles at the summit.

TABLE III

Part 1

	I	II	III
Silica	73.60	75.62	74.50
Alumina	12.96	11.52	12.45
Ferrous Oxide	1.19	1.19	.83
Ferric Oxide	.82	.82	.85
Magnesia	.20	.26	.28
Lime	.64	.62	1.82
Soda	1.71	1.80	3.88
Potash	7.27	6.50	4.27
Water above 105° C.	.80	.90	.66
Water at 105° C.	.40	.33	.30
Carbon Dioxide	none	trace	none
Titanium Dioxide	.30	.34	trace
Phosphorus Pentoxide	trace	trace	.07
Sulphur	none	trace	.04
Manganese Dioxide	none	none	trace
	99.89	99.90	99.95

I. Lower flow of platy rhyolite in the valley of Pike Creek. Analysts W. H. and F. Herdsman.

II. Spherulite in the upper flow of platy rhyolite in the valley of Toughey Creek. Analysts W. H. and F. Herdsman.

III. Rhyolite flow in the valley of Little Alvord Creek. Analyst W. H. Herdsman.

Part 2

	I	II	III
Quartz	33.60	38.16	31.98
Orthoclase	43.37	38.36	25.58
Albite	14.15	15.20	33.01
Anorthite	3.34	3.06	3.61
Corundum	1.02	.41	.....
Diopside	.....	.....	3.00
Wollastonite	.....	.....	.35
Hypersthene	1.56	1.66	.....
Ilmenite	.61	.61	.....
Magnetite	1.16	1.16	1.16
Apatite	.....	.....	.34
Water	1.20	1.23	.96
Sulphur	.....	.....	.04
	100.01	99.85	100.03

Norms calculated from the analyses in Part 1:
I. Omeose, C. I. P. W. symbol, I.″4.1.″2.
II. Magdeburgose, C. I. P. W. symbol, 1.3(4).1.2.
III. Toscanose, C. I. P. W. symbol, I.″4.2.3.

In the valley of Pike Creek, the most striking feature of this lava is the extreme regularity of the parallel laminations. Although some of the banding is remarkably straight, much of it is slightly wavy (fig. 31) or even contorted. In the latter instance the extreme viscosity locally resulted in brecciation. When fresh, the rock shows an alternation of fine streaks of dark grey and reddish brown felsite. With kaolinization, the banding is more apparent, for the alteration is localized in certain streaks. With weathering following the lines of flowage, this rhyolite splits into paperlike laminations of a pale pinkish shade. Crystalline quartz is locally visible as minute segregations between the felsitic bands as well as in a network of transverse veinlets, which are chiefly apparent on the weathered plates.

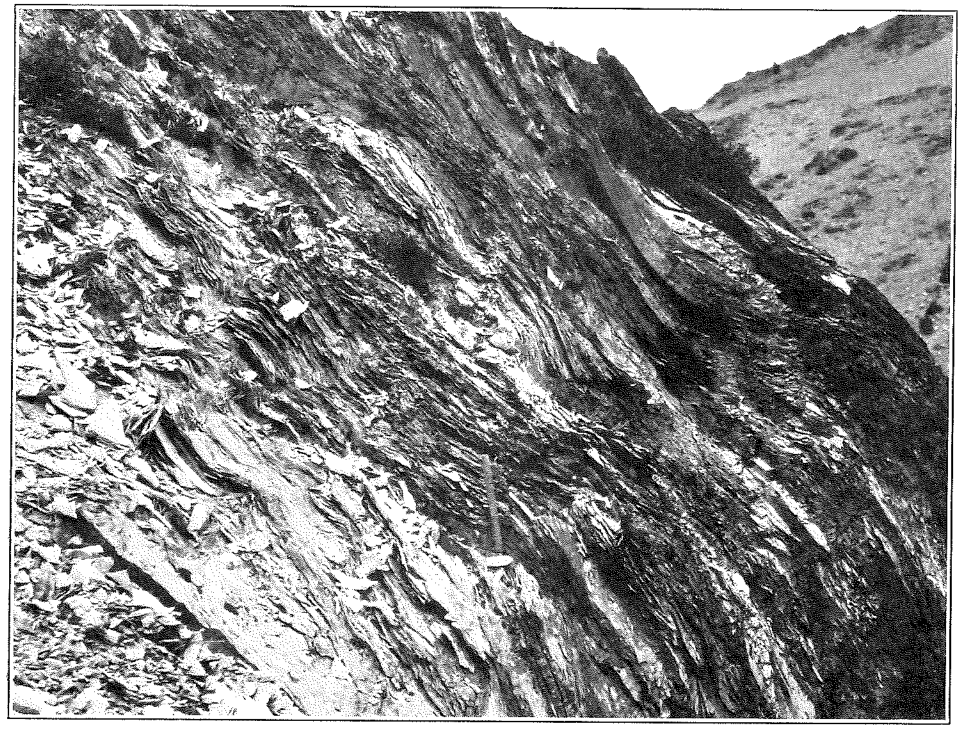

Fig. 31. Typical exposure of the lower flow of platy rhyolite in the Pike Creek series.

In thin section the rock is cryptocrystalline, but the different laminations vary in coarseness. The quartz occurs in the center of thin, rather opaque streaks, which are of finer texture and of a darker shade of reddish brown. Many of these segregations of quartz are lenticular in shape. One of the largest observed, which is about .3 mm. in width, contains individual quartz grains over 1 mm. in length. Others consist of idiomorphic crystals separated largely by opaque iron stained material, but with their crystal faces projecting into the felsitic matrix. The major axes of these crystals parallel the lines of flowage.

The formation of the quartz apparently preceded the complete solidification of the lava. The network of veinlets also appears to be endogenetic, for the overlying stratified beds lack the silicification exhibited by the perlite and its associated tuffaceous material. Both here and higher in the series, the silicification of perlite has been rendered apparent by differential erosion. In extreme cases a whitish, honeycombed structure is formed, on account of the resistance of a network of siliceous veinlets, which roughly follow the mesh formed by the curving cracks. The glass, which has been at least partially devitrified by the solutions, is easily altered and subsequently eroded.

MIDDLE TUFFS AND THEIR STRATIGRAPHIC EQUIVALENT TO THE SOUTH

Capping this lower rhyolite are well-bedded tuffaceous sediments close to 300 feet in thickness. These beds, which dip predominantly to the northwest at about 15°, are exposed on the south side of Pike Creek at about a half mile from its mouth and also to the south in Toughey Creek. They were not observed in Indian Creek. Instead, in this locality a badly altered acidic lava outcrops at approximately the same stratigraphic horizon.

The beds consist chiefly of whitish material that appears to be wholly of tuffaceous origin, but they also contain a number of horizons, usually two to three feet in thickness, which are formed principally of angular to subangular fragments of acidic lava. Although the fragments are predominantly less than an inch in diameter, they were found locally to be even a foot across. The angular fragments consist chiefly of platy lava resembling the rhyolitic flow immediately below.

Although these beds show no marked alteration at their base, which is in contact with a reddish, soil-like layer capping the underlying perlite, they have been highly silicified at a number of horizons. Perhaps because of their initial porosity, this action usually has been confined principally to the horizons containing the coarse fragmental material. Immediately beneath the capping flow of rhyolite, however, the silicification is more general and so extreme that the rock resembles a glassy acidic lava, but it grades into more normal tuff when traced downward about five feet. This alteration is invariably accompanied by the greenish coloration of the rock.

The localization of the alteration at scattered horizons, which probably were originally porous, suggests that the beds have been subjected to the horizontal access of altering solutions. These would have advanced along well-defined stratification and would have been concentrated in the more porous beds, especially when in contact with a relatively impervious layer. These solutions are easily explained by the presence of the vent for the overlying flow only a few hundred yards to the west.

In the valley of Indian Creek, local exposures apparently corresponding with this horizon are formed by a lava which is too badly altered to permit petrographic determination. In a felsitic ground with a marked spherulitic tendency, it shows a high content of thick feldspathic crystals about 5 mm. in length. This rock is cut by vertical lines of brecciation, which are highly silicified and locally impregnated with a low concentration of cinnabar. These zones of brecciation were not observed higher in the section. At what appears to be the approximate base of the flow, they are truncated by a thick diabasic sill which forms the lowest member of the local section. This basic rock is extremely fresh and shows no possible relation to the ore. The latter is therefore thought to have been deposited by the exhalations which accompanied earlier volcanic activity and to have been subsequently truncated by the sill.

UPPER LAMINATED RHYOLITE

The middle tuffs are capped by another flow of laminated rhyolite. Although the banding of this lava lacks the extreme regularity that characterizes the lower flow, it causes the rock to split into pinkish plates which strongly resemble those of the lower rhyolite even to the presence of minute siliceous veinlets. The felsitic flow structure is usually apparent from an alternation of greyish or reddish colors varying from a dark to a light shade. The lighter bands are usually completely kaolinized, while the dark constituent is found in thin section to be composed of cryptocrystalline quartz. This quartz as a rule occurs either in very irregular anastomosing bands that are roughly parallel, or in small segregations that may show slight alignment. Some specimens contain a few feldspathic phenocrysts that consist of orthoclase and highly sodic plagioclase.

In the main section, on the south side of Pike Creek, the thickness of this flow is approximately 250 feet, including both the upper and lower perlitic margins. The upper perlite, which shows near surface features, is over 30 feet in thickness. Its contact with the underlying platy phase is not exposed, but towards its base it develops horizontal bands of spherulites which suggest a transition. The lower perlitic selvage is about 15 feet in thickness.

Traced less than 200 yards to the west, this rhyolite loses its horizontal banding and merges into an irregular mass of lava which crosscuts the underlying tuff. Here unfortunately the actual contact is not exposed. Owing to the gradient of the stream, the width of the vent cannot be determined, but to the west the characteristic vertical jointing is well defined for at least 100 yards. In this lava, 100 feet or more above the stream, there are many irregular breccias formed of light colored aphanitic rock, which was presumably derived from the tuffaceous sediments at the time of extrusion. These fragments, which have locally suffered a brownish discoloration, prove in thin section to be so completely silicified and kaolinized that their origin cannot be determined.

This rhyolite thickens greatly to the south, and on the northern side of Toughey Creek, at a distance of only about a quarter of a mile, it is close to 500 feet in thickness, even disregarding the step faults, which cause a repetition of the flow at the face of the scarp.[9] The increased thickness is due largely to the position of these exposures directly over the southern continuation of the vent or immediately adjacent to it. Although subject to considerable irregularity, the platy jointing of this lava in Toughey Creek is in general steeply inclined. On erosion it forms steep cliffs (fig. 32) and pinnacles that rise from a fine platy talus.

On the northern wall of the valley, west of the step faults exposed on the scarp, the middle tuffaceous beds outcrop beneath the rhyolite. To the west, however, the rhyolite curves downward in an even arc, crosscutting this strata.

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[9] Although there are innumerable minor faults on the scarp, the major displacement previously mentioned by the author is incorrect, owing to the fact that the presence of two rather similar platy flows was not realized. R. E. Fuller and A. C. Waters, *op. cit.*, fig. 10, p. 222.

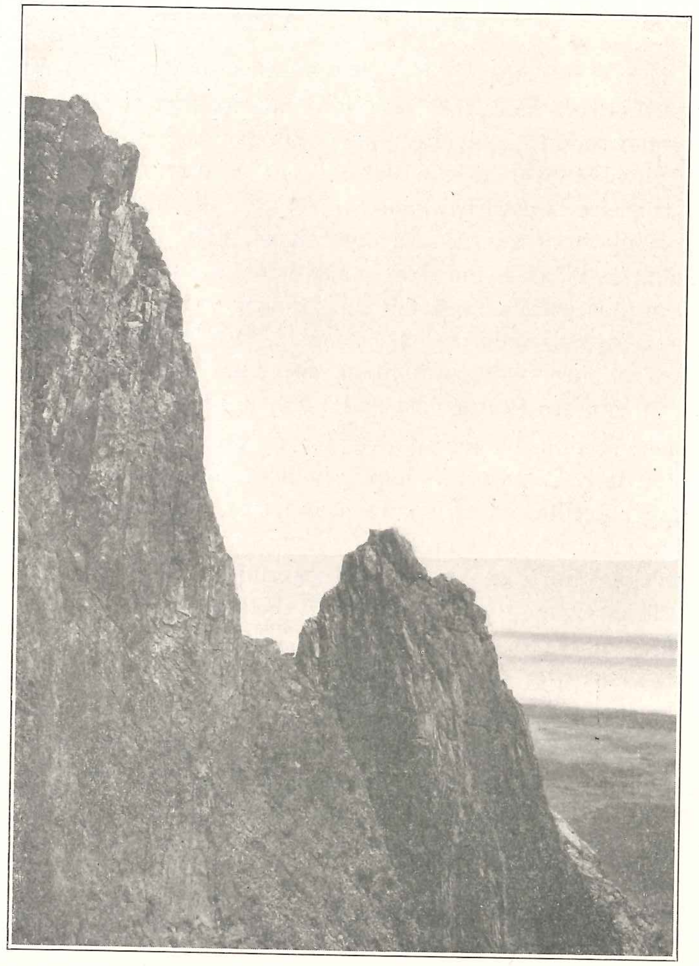

Fig. 32. Vertical jointing in the upper platy rhyolite on the northern wall of Toughey Creek. The cliff on the left is about 100 feet in height.

Defining this basal contact, a dark mass of vitrophyre about 30 feet in thickness outcrops for almost 100 yards (fig. 33). Again the gradient of the stream prevents the determination of the width of the vent, but its occurrence to the north in the valley of Pike Creek suggests that both valleys intersect an elongate volcanic neck which has an approximate north and south axis.

Both the vitrophyre and the overlying felsite, near its lower contact, develop spherulites which are concentrated in zones approximately parallel to the flowage. At the margin of the vent, directly above the steeply inclined phase of the vitrophyre, some spherulites surrounded by altered glass attain a diameter of about 3 feet. These show a slightly reniform surface of pale greenish shade, while the inner part, which is free from alteration, is reddish brown. The center of some of the masses consists of a single spherulite. The outer zone, however, in thin section shows a succession of conflicting segments of spherulites which radiate roughly from the center of the mass. Except for a microscopic band of quartz delineating these segments, the component minerals of the spherulites were not determined. Their birefringence, however, is low, and the fibrous constituent shows a positive elongation. The extinction is roughly parallel, although mottled. The rock is rather opaque, partly because of the presence of minute crystallites.

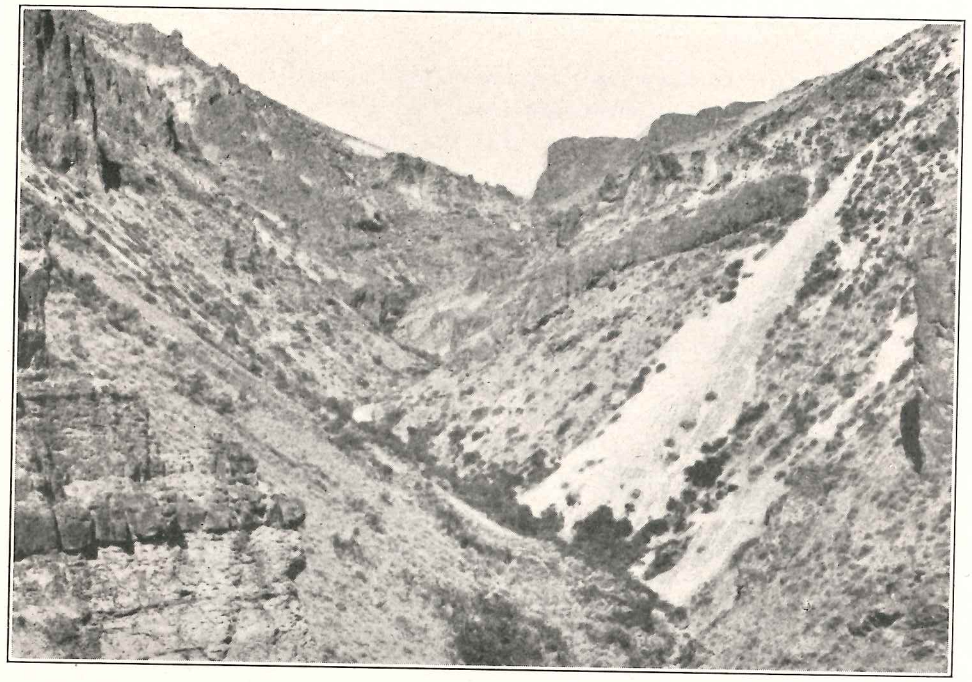

Fig. 33. View of Toughey Creek showing the middle tuffaceous beds in the foreground. On the right wall of the valley the dark sheet of vitrophyre defines the curving contact of the upper platy rhyolite, which forms the precipitous exposures both above and to the west. The cliff on the right in the distance is formed by the upper flow of biotite-dacite.

The classification of this lava as a rhyolite depends chiefly on a chemical analysis of one of these large spherulites. With a high potash content, its composition coincided very closely with that of the lower platy flow (table III). At least a large part of the plagioclase in the norm may be attributed to the presence of embayed phenocrysts of sodic oligoclase.

This lava may be traced to the south into the valley of Indian Creek. In the southern part of the valley, as it swings northward, the platy rhyolite appears to be divided into two flows by an irregular horizontal perlitic zone, but farther to the north, the glassy lava cuts through both phases, possibly because of some type of auto-intrusion. In the same locality, however, vertical flowage and highly inclined spherulitic zones suggest a locus of extrusion, which may possibly be caused by another intersection of the fissure-like vent exposed to the north. All the varied facies appeared to be definitely syngenetic, but the exposures did not permit a conclusive interpretation of the relationship.

Little Alvord Creek Rhyolite

The exposures on the main scarp are not sufficient to permit the upper platy rhyolite flow to be traced northward from Pike Creek. Where last exposed it appears to be thinning rapidly towards the north. In Little Alvord Creek, however, another mile and a half to the north, a very thick flow of rhyolite occurs at the same horizon. The vent from which this lava was extruded is also exposed. It lies at least approximately in line with the two just described to the south, but the lava does not closely resemble the upper platy rhyolite in either its physical or its chemical characteristics (table III).

This lava, like the upper platy rhyolite, contains a few small phenocrysts of oligoclase and orthoclase, and also exhibits some felsitic flow structure, but not sufficient to cause it to split into plates. It lacks the irregular segregations of cryptocrystalline quartz that characterize the Pike Creek flow. Chemically, however, the distinction appears to be more definite. Although the silica content is almost equally high in both flows, there is marked difference in the oxides. In the Little Alvord Creek rhyolite, the potash is far lower, while the content of soda and lime is decidedly higher.

On the south side of Little Alvord Creek, at about a quarter of a mile from the scarp, there is a steep cliff about 400 feet high formed by this flow of rhyolite (fig. 34). In marked contrast, the north side of the valley is formed by the partially dissected dip slope of the tuffaceous sediments composing the southern limb of the laccolith. This slope, as previously mentioned, formed the retaining wall for the rhyolitic flow, but farther to the west it is cut by the vent from which the lava was extruded. The base of the flow is not exposed. Since it shows a basal margin of perlite that is approximately level, it presumably was extruded on a relatively flat surface, which should occur close to the level of the stream.

This basal perlite is exposed for only about 100 yards and ceases with the development of vent characteristics, which consist in the presence of vertical lines of flowage in the rhyolite and in the intrusive relationship of the perlite on the north side of the valley. These exposures of the latter extend up the northern slope for several hundred feet and appear to define part of the rounded northern end of the rhyolitic vent.

To the east of this margin lie the inclined, well-stratified tuffs, which dip to the southwest at over 15°. The inclination of these beds towards the vent suggests a genetic relationship, but the marked classification of the clastics demands an aqueous stratification. The slope may be explained by the deformation induced by the rhyolitic laccolith.

To the west, the perlite develops steeply inclined bands of spherulites. Some of these radiating masses attain a diameter of 18 inches. As usual, they mark the transition to the felsitic phase, which shows pronounced vertical flowage. This phase locally exhibits partitions covered with small nodes formed by conflicting spherulites.

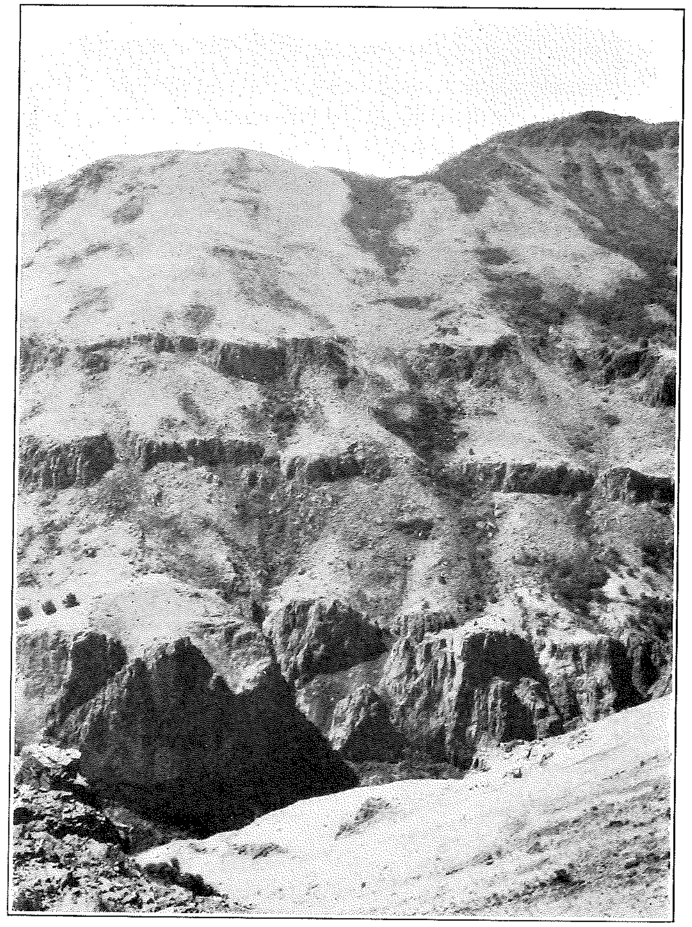

Fig. 34. A view of the southern wall of the valley of Little Alvord Creek showing the 400 foot flow of rhyolite overlain by the two flows of biotite-dacite.

Near the center of the vent, a breccia, formed of perlitic fragments in a light colored tuff, rises about 200 feet above the surface of the flow. This tuff is thought to be formed both by the local explosive activity and by the comminution of the perlite, which injects it extensively. These injections rise steeply and then tend to curve into horizontal sheets which are usually but four or five feet in thickness, although some range up to 15 feet or more (fig. 35). As a rule these injections, which are considered to be near surface features of the rhyolitic vent, cannot be traced for more than 30 or 40 feet. They appear to end rather bluntly.

About 100 yards to the west at a lower elevation there is an exposure near the stream of massive black perlite showing irregular zones of coloration to brownish and reddish shades. This vitreous lava presumably formed the surface of the flow. As in the case of varicolored obsidians previously described by the writer[10] the variations in color are due to the oxidation of the glass adjacent to the lines of fracture in a flow breccia. The fragments were thus partially altered to a brownish or reddish shade. The hot gasses following these brecciated zones subsequently caused the refusion of the glass. With additional flowage the clean-cut outline of the breccia was locally destroyed.

Fig. 35. Perlitic injections curving to a horizontal position in the tuffaceous breccias above the rhyolite vent on the northern side of Little Alvord Creek. An 18 inch hammer is beneath the center of the lower injection. The basal exposure of the andesitic vent is visible at the top.

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[10] R. E. Fuller, "The Mode of Origin of the Color of Certain Varicolored Obsidians," *Jour. Geol.*, vol. XXXV, p. 570, 1927.

UPPER TUFFS

The next stratigraphic unit of this volcanic series outcrops only in the exposure of the main sequence on the south side of the valley of Pike Creek (fig. 30). Here well-stratified tuffs about 40 feet in thickness are exposed overlying the irregular perlitic phase that caps the upper platy rhyolite. This bed is quite green towards the top, but shows some brownish shades in the lower part. Near the top there are two conglomeratic beds less than three feet in thickness. The fragments are of acidic lava and vary in shape from round to angular. Possibly owing to their original porosity these beds have suffered extreme silicification similar to that observed lower in the series. The alteration is probably due to the proximity of an adjacent vent, which will be described later.

It is impossible to establish the horizontal extent of these sediments. Owing to the thickening of the underlying platy rhyolite to the south, they do not occur in Toughey Creek. The strata, however, may continue to the north, but unfortunately there is no exposure in which this may be determined.

BIOTITE-DACITE

Above these sediments are two great flows of biotite-dacite, which are very similar both petrographically and chemically (table IV). They show feldspar and biotite in a dense ground that varies from light grey to brownish or reddish shades. As a rule the ground shows no flowage. The percentage of feldspar is somewhat variable, but it appears to be distinctly more plentiful in the upper flow, where it forms as much as 30 per cent of the rock. In the lower flow it probably does not attain half that figure.

The size of the crystals is about the same in both flows, although the individuals in each are very variable. The larger masses are usually glomeroporphyritic feldspathic intergrowths 4 to 6 mm. in diameter. These as a rule contain glassy inclusions. Most of the feldspar, however, occurs in small angular fragments or in irregular grains, whose rounded outline indicates partial resorption. These smaller individuals average less than 1 mm. in length. Some of the feldspar is a sodic plagioclase, but many of the fragments show no twinning or zoning and appear to be orthoclase.

Flakes of biotite are relatively common and range up to 2 mm. in width. Locally, in the vicinity of Pike Creek, the biotite in the lower flow is distinctly aligned in an aphanitic ground that exhibits irregular flowage by an alternation of pinkish and whitish bands. In this phase, the feldspar is completely altered to a cryptocrystalline aggregate that consists partly of quartz.

TABLE IV

PART 1

	I	II
Silica	68.66	67.05
Alumina	14.44	14.91
Ferrous Oxide	1.28	1.48
Ferric Oxide	.80	.92
Magnesia	.18	.65
Lime	1.96	2.44
Soda	3.86	4.15
Potash	3.28	3.04
Water above 105° C.	4.80	4.35
Water at 105° C.	.40	.50
Carbon Dioxide	none	none
Titanium Dioxide	.25	.34
Phosphorus Pentoxide	trace	.12
Sulphur	none	trace
Manganese Dioxide	none	trace
	99.91	99.95

I. Basal perlite of the lower flow of biotite-dacite on the south side of Pike Creek valley. Analysts W. H. and F. Herdsman.

II. Basal perlite of the upper flow of biotite-dacite on the south side of Pike Creek valley. Analysts W. H. and F. Herdsman.

PART 2

	I	II
Quartz	28.68	24.84
Orthoclase	19.46	17.79
Albite	32.49	35.11
Anorthite	9.73	11.40
Corundum	.92	.61
Hypersthene	1.72	3.05
Magnetite	1.16	1.39
Ilmenite	.46	.61
Apatite	.....	.34
Water	5.20	4.85
	99.82	99.99

Norms calculated from the analyses in Part 1:
I. Toscanose, C. I. P. W. symbol, I.″4.2.3.
II. Toscanose, C. I. P. W. symbol, I.4.2″.3″.

Both flows appear to have been erupted from the same vent after the intervention of an insignificant time interval. The lower flow is exposed in the valleys of Pike Creek and Little Alvord Creek with a relatively uniform thickness of about 200 feet. The upper flow shows a similar thickness in Little Alvord Creek valley, but increases gradually to the south reaching a maximum between Pike Creek and Indian Creek, where presumably at the center of its vent, it forms exposures over 500 feet in height. In this region, the two flows appear to have merged into one.

In the main Pike Creek section (fig. 30), the lower biotite-dacite shows, above the upper tuffs, a basal perlitic phase about 50 feet in thickness. Adjacent to the sediments, the glass is altered to a pale greenish shade resembling the color of the altered beds with which it is in contact. This lower perlite shows some highly inclined bands of spherulites. Above it, the massive lava shows almost vertical flow structure, which is very marked in the coarse perlitic spines at the upper surface. The lower flow of dacite is here close to 300 feet in thickness, although it decreases greatly within 100 yards to the west. These facts suggest that it is the locus of extrusion, but a crosscutting relationship is not visible. This locality is at the margin of the vent, from which the great overlying mass of the upper dacite was largely extruded, and its peculiar characteristics may be due to an earlier phase of the same volcanic center.

On the divide between Pike Creek and Little Alvord, the biotite-dacite outcrops persistently and is clearly defined by perlitic facies as two separate flows. In the valley of Little Alvord Creek, at about a mile from the scarp, these exposures end. A few hundred yards to the west, similar rock forms a large outcrop that intersects both horizons and suggests that they merge. The flowage in this exposure is irregular, but predominantly highly inclined. Two interpretations of its relationship appear possible; the exposure might be formed by a vent from which both flows were extruded, or the lower flow being highly viscous might have ended abruptly with a steep margin, over which the upper flow would have advanced and would thus have acquired irregularly inclined jointing. The margin of the thick flow of Little Alvord Creek Rhyolite may also have contributed to this rapid increase in gradient. Although the latter explanation is favored, the exposures are not of sufficient depth to offer conclusive proof.

Between Pike and Indian Creeks, the upper biotite-dacite has been stripped of its overlying rocks, and forms the surface of an irregular broad shoulder which is at least a mile in width. Here the rock is considerably altered and exhibits a minute hackly jointing, which causes it to erode in this interfluvial region like a coarsely granular rock. The shape of the wind eroded exposures, however, is largely controlled by highly inclined flow structure which gives rise to steep pinnacles and cliffs (fig. 36). Between the irregular prominences a gently rolling terrain supports a scattered growth of junipers (fig. 37). On the west, the precipitous exposures formed by the overlying basaltic flows rise abruptly over 2000 feet above this relatively level shoulder.

The flow structure is very persistent in the eastern part of this broad area, but it is best exposed at the western end of Toughey Creek where it can be traced vertically for about 500 feet. In spite of the depth of erosion, the base of the mass is not exposed. Northward, however, at the margin of the Pike Creek valley, and southward at Indian Creek the lines of flowage are inclined as if emerging from a large vent centered near the head of Toughey Creek. The lava is, therefore, considered to have been extruded from an extensive vent lying beneath the broad divide between Pike and Toughey Creeks, and continuing southward to the northern part of Indian Creek.

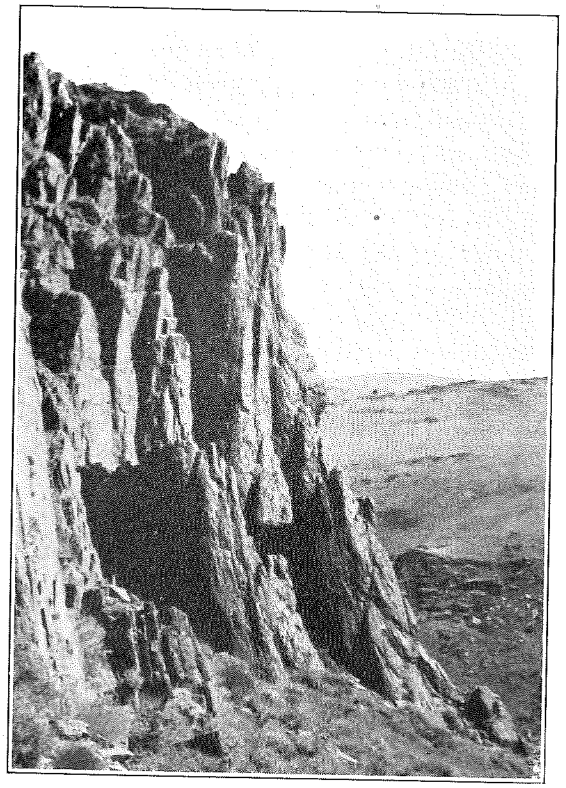

Fig. 36. Vertical jointing in the vent for the upper biotite-dacite north of Toughey Creek. The exposure on the left is approximately 75 feet in height.

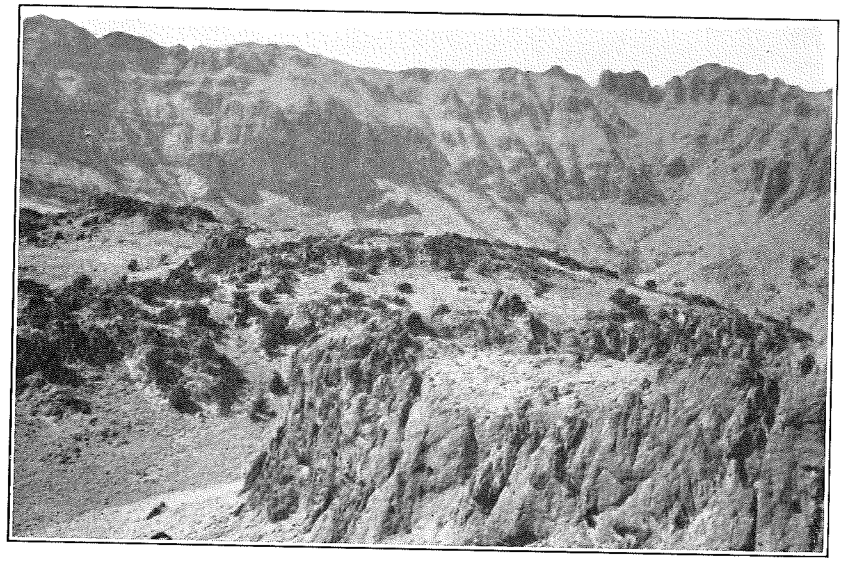

Fig. 37. The broad divide between Toughey Creek and Pike Creek exposing the upper biotite-dacite. The basalt forms the precipitous exposures in the background.

RHYOLITIC ROCKS OF COTTONWOOD CREEK AND WILLOW CREEK

Rhyolitic rocks, which appear to be unrelated to those previously described, are exposed at the foot of the mountain in the valleys of Willow Creek and Cottonwood Creek. In the latter, a rather homogeneous massive light grey rock outcrops for several hundred yards with a maximum thickness of about 300 feet.

This rock is high in angular fragments, but it is so altered that the writer has been unable to determine whether it is a lava filled with inclusions or a remarkably homogeneous agglomerate partially silicified. The fact that no surface features were observed and that the mass, which is apparently continuous, shows a high quartz content in its upper part and a high orthoclase content towards the base of the exposure, suggests a tuffaceous origin. On the other hand in thin section it appears to show slight traces of flowage and no indications of palimpsest structure of volcanic ejectamenta. Its high content of quartz and orthoclase, however, definitely prove a rhyolitic composition.

This rhyolitic rock is separated from the northern continuation of the uppermost Alvord Creek Beds and the interbedded andesite by a vertical fault which parallels the scarp. No precise evidence on the direction of movement was observed. The fault zone, however, is small and does not suggest great displacement. In the upper exposures of the mountain there is no rhyolite, although the series may locally have been capped by acidic flows now eroded. In consequence, the downthrow of an hypothetical acidic cap would demand a displacement of at least 4000 feet, which would hardly be expected on a narrow, almost vertical fault zone. An interpretation of minor upthrow of the eastern block coincides with the exposures in Willow Creek valley about 2 miles to the north. There, rhyolite is definitely overlain by the later andesite and yet near the contact it has been upraised by a minor almost vertical fault.

Near the mouth of the Willow Creek valley there are scattered exposures of a light grey rhyolite, which for the most part is highly altered. These exposures, which continue for about a quarter of a mile, show a thickness of approximately 500 feet. They appear to be formed by the accumulation of lava above a vent which is close to the present fault line. Near the western margin of the exposure a poorly defined vertical fault has permitted the uplift of the eastern wall. The displacement cannot be much more than 100 feet, for the upper surface of the rhyolite sloping westward at about 20° is exposed beneath the overlying andesite. This fault presumably is the northern continuation of the one previously mentioned in Cottonwood Creek. The displacement is the reverse of that occurring in the customary step faults.

This rhyolite in Willow Creek shows a few scattered feldspathic phenocrysts, up to 4 mm. in length, in a cryptocrystalline ground, which exhibits very irregular flowage. The phenocrysts show no twinning and appear to be wholly of orthoclase. The flowage in part is defined by sinuous lenticular segregations of relatively coarsely crystalline quartz. Coinciding with this evidence, a chemical analysis (table V) proved the rock to be a rhyolite, but its composition did not closely correspond with any of those previously described. Probably, however, it is genetically connected with the rhyolitic agglomerate in Cottonwood Creek.

TABLE V

Part 1

	I	II	III	IV
Silica	72.65	73.00	74.50	75.62
Alumina	13.64	14.23	12.45	11.52
Ferrous Oxide	.68	1.28	.83	1.19
Ferric Oxide	.70	.28	.85	.82
Magnesia	.60	.24	.28	.26
Lime	.55	1.25	1.82	.62
Soda	2.54	2.96	3.88	1.80
Potash	5.70	4.86	4.27	6.50
Water above 105° C	1.50	1.00	.66	.90
Water at 105° C	1.50	.60	.30	.33
Carbon Dioxide	none	none	none	trace
Titanium Dioxide	.10	.18	trace	.34
Phosphorus Pentoxide	trace	trace	.07	trace
Sulphur	none	none	.04	trace
Manganese Dioxide	trace	none	trace	none
	100.16	99.88	99.95	99.90

I. Rhyolite from the valley of Willow Creek. Analysts W. H. and F. Herdsman.

II. Northern extension of rhyolite vent above laccolith north of Little Alvord Creek. Analysts W. H. and F. Herdsman.

III. Rhyolite from the valley of Little Alvord Creek. Analysts W. H. and F. Herdsman.

IV. Spherulite in the upper platy rhyolite in Toughey Creek. Analysts W. H. and F. Herdsman.

Part 2

	I	II	III	IV
Quartz	33.72	33.24	31.98	38.16
Orthoclase	33.92	28.91	25.58	38.36
Albite	21.48	25.15	33.01	15.20
Anorthite	2.78	6.12	3.61	3.06
Corundum	2.14	1.73	.....	.41
Diopside	.....	.....	3.00	.....
Wollastonite	.....	.....	.35	.....
Hypersthene	1.86	2.32	.....	1.66
Magnetite	.93	.46	1.16	1.16
Ilmenite	.15	.46	.....	.61
Apatite	.....	.....	.34	.....
Water	3.00	1.60	.96	1.23
Sulphur	.....	.....	.04	.....
	99.98	99.99	100.03	99.85

Norms calculated from the analyses in Part 1:

I. Omeose C. I. P. W. symbol, I.(3)4.1.2″.
II. Toscanose, C. I. P. W. symbol, I.″4.″2.(2)3.
III. Toscanose, C. I. P. W. symbol, I.″4.2.3.
IV. Magdeburgose, C. I. P. W. symbol, I.3(4).1.2.

STEENS MOUNTAIN ANDESITIC SERIES

Basic Andesite

To the north of Alvord Creek, as previously mentioned, a flow of basic andesite, about 100 feet in thickness, is interbedded near the top of the Alvord Creek Beds. Above the uppermost tuffs, there is another flow of similar andesite (table VI), which is well exposed in both forks of Cottonwood Creek (fig. 47). This flow can be traced a short distance southward and then found again with similar relationship about another mile to the south on the northern side of Alvord Creek (fig. 46). Here it is exposed for several hundred yards. In the valley of Cottonwood Creek, the flow is over 200 feet thick, but to the south, it appears to be less than half that figure, although the base is not exposed.

Chemically the two flows are almost identical. Petrographically the resemblance is equally strong. The rock, in both cases, is a dark grey aphanitic andesite that resembles megascopically a chilled basalt. In thin section, they both show a seriate development of andesine laths exhibiting marked flow alignment. In most specimens, the feldspar forms about 60 per cent of the rock. The size of the laths, in the lower flow especially, varies considerably. The largest observed is about 3 mm. in length, although the average in both flows is close to .2 mm. One specimen of the lower flow contains isolated grains of ophitic augite with individuals up to .8 mm. in length. The maximum dimension of this mafic as a rule is transverse to the alignment of the laths, which it encloses. In another specimen of the same flow, there are minute intersertal grains of a mafic that is presumably augite. In addition, a brownish glass and an orange colored deuteric residual form a common minor constituent. In the upper flow, the ground is a dark, rather opaque substance that is considered to be formed of partially decomposed glass. Small grains of magnetite are distributed throughout the rock.

TABLE VI

Part 1

	I	II	III
Silica	55.30	56.90	62.28
Alumina	17.80	17.55	17.17
Ferrous Oxide	5.28	6.05	2.04
Ferric Oxide	1.98	.27	2.56
Magnesia	3.38	3.82	1.64
Lime	7.40	7.05	5.45
Soda	3.92	3.36	3.62
Potash	1.78	1.75	2.44
Water above 105° C	.70	1.56	1.40
Water at 105° C	1.10	.30	.90
Carbon Dioxide	none	none	none
Titanium Dioxide	.92	.98	.15
Phosphorus Pentoxide	.36	.18	.14
Sulphur	none	none	trace
Manganese Dioxide	.13	.20	trace
	100.05	99.97	99.79

I. Lower andesitic flow interbedded with tuffs north of Alvord Creek. Analysts W. H. and F. Herdsman.

II. Middle andesitic flow capping the Alvord Creek beds in Cottonwood Creek. Analysts W. H. and F. Herdsman.

III. Base of homogeneous phase of the Upper Andesite on the northern side of Alvord Creek valley. Analysts W. H. and F. Herdsman.

Part 2

	I	II	III
Quartz	4.68	7.86	18.00
Orthoclase	10.56	10.01	14.46
Albite	33.01	28.30	30.92
Anorthite	25.85	27.80	23.35
Diopside	6.58	5.07	2.22
Hypersthene	12.04	16.22	4.36
Magnetite	3.02	.46	3.71
Ilmenite	1.67	1.98	.30
Apatite	1.01	.34	.34
Water	1.80	1.86	2.30
	100.22	99.90	99.96

Norms calculated from the analyses in Part 1:
I. Andose, C. I. P. W. symbol, II."5.3"."4.
II. Andose, C. I. P. W. symbol, II.(4)5.3"."4.
III. Amiatose, C. I. P. W. symbol, I(II).4.3.3".

The upper of these two flows is capped by a thin bed of coarse andesitic tuffs. These deposits, which locally show well-defined stratification, vary from a thickness of about 20 feet in Cottonwood Creek to less than half that figure in the exposures on the northern side of Alvord Creek valley. In this locality, they exhibit many peculiarities that are difficult to explain conclusively. They rest on the vesicular flow breccia of the underlying andesite. At their base, they grade into similar tuffaceous material that is interstitial to these coarser blocks. Examination proves that these tuffs, at least in part, have been formed by the comminution of the margins of these extremely fragile vesicular andesitic blocks (fig. 38). In numerous instances, this interstitial tuffaceous material shows marked stratification roughly parallel to the irregular surface of the adjacent block.

Fig. 38. Interstitial tuffaceous material in the breccia capping the upper flow of basic andesite north of Alvord Creek.

In this same locality, several small lava domes project above the flow and rise a few feet higher than the erosional surface of the tuffs (fig. 39). The beds, although truncated, curve upwards at the steep contacts of the domes and suggest that they have been intruded by the viscous lava, on which they rest. On closer examination, however, the relation may be seen to be definitely due to deposition on an irregular surface. The step contacts may be explained by the fact that the viscosity of the lava, which intruded its flow breccia, resulted in a slope greater than the angle of repose of the pyroclastics. The inclination may subsequently have been augmented by compacting, which would have increased in amount with the thickness of the bed. The perfection of the bedding locally demands aqueous agencies, but much of the stratification may be attributed to variations in the ejectamenta. The transition from the tuffaceous deposits to the interstitial material in the flow breccia may be due to the initiation of deposition while the flow was still advancing.

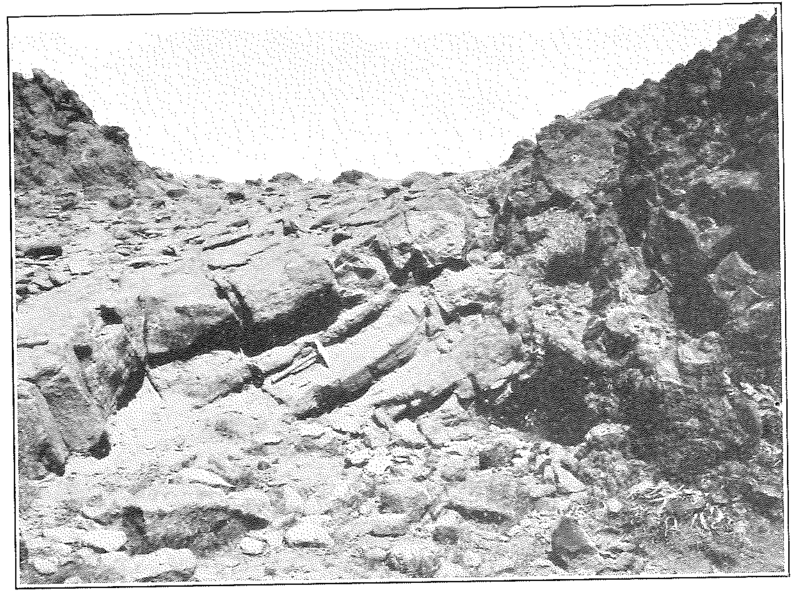

Fig. 39. A local irregularity in the contact of the tuffaceous beds overlying the upper flow of basic andesite. To the left, the surface of the flow also protrudes above the tuffs.

The Great Flow

GENERAL FEATURES

In the valley of Cottonwood Creek and to the south on the northern wall of Alvord Creek valley, a tremendous flow of andesite caps the stratified tuffs which overlie the upper flow of basic andesite. In the Alvord Creek locality, the flow shows a thickness of about 900 feet (fig. 40), but within a mile to the

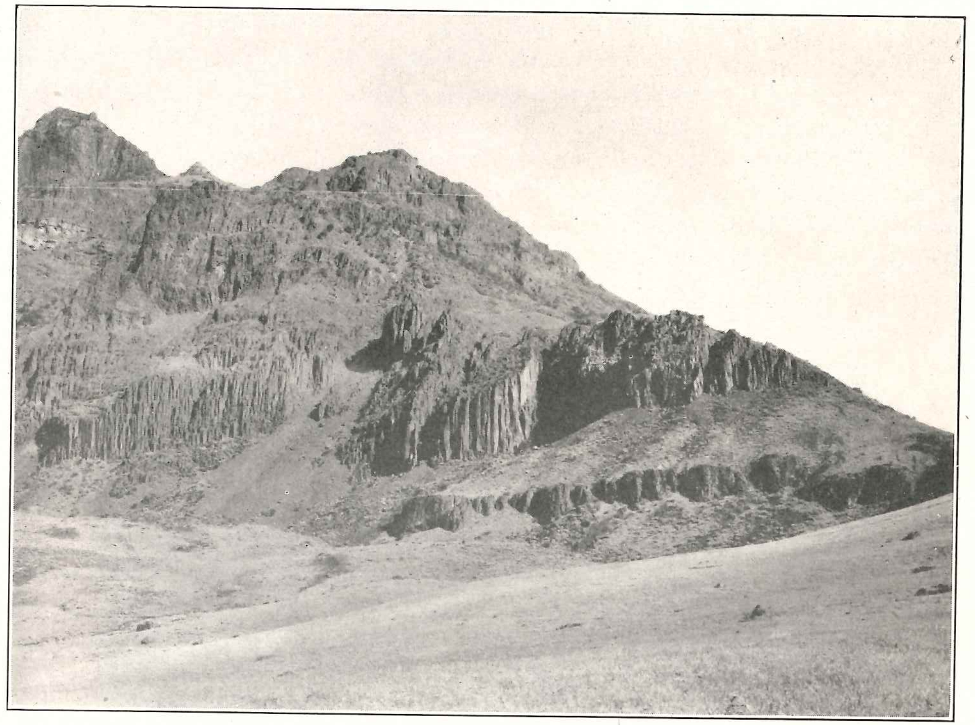

Fig. 40. Northern side of the Alvord Creek valley adjacent to the scarp. At the base on the right the upper flow of basic andesite is exposed. Above it in the center of the view the great andesitic flow rises about 900 feet.

north, in the valley of Cottonwood Creek, it was found to have thinned to about 500 feet (fig. 41). Northward from that point it is not exposed, although stratigraphically at least the upper part should outcrop in the valley of Willow Creek. In the valley of Mann Creek, however, about seven miles farther north, a similar lava shows a thickness of about 400 feet. Although here the base is not visible, an adjacent cinder cone, at the base of the scarp at the mouth of Little Mann Creek, suggests that the bottom of the flow is not far distant (fig. 58).

With increasing thickness, the flow shows coarser jointing and on the northern wall of the valley of Alvord Creek it exhibits coarse rectangular columns that are approximately ten feet in diameter (fig. 42). These great columns are cut locally by irregular platy jointing, which towards the base is roughly horizontal, while higher in the exposure it is usually somewhat inclined. In both the valley of Cottonwood Creek and that of Mann Creek, the jointing is fairly uniform, but in the upper part of the exposure north of Alvord Creek it becomes lost to a great measure in irregular zones of alteration.

The upper surface of the flow is invariably characterized by a well-defined shoulder, which usually supports a scattered growth of junipers. This topographic break is due to the erosion of a soft grayish clay-like material, which appears to have been derived from the devitrification of a glass, probably owing in part to the effect of volcanic emanations. Although the minor vesicularity of unaltered vitreous remnants forms the only indication of the top of the great flow, its extrusive origin is more conclusively indicated by the relation of the overlying thin andesitic flows, which lap against its inclined surface. These flows lack any indication of marked induration, and also fail to contain the hornblende which characterizes the upper surface of the great flow. To the south of Alvord Creek, the relation of the great extruded mass is not so clearly defined, partly owing to the fact that it is, at least locally, overlying one of the vents from which it welled.

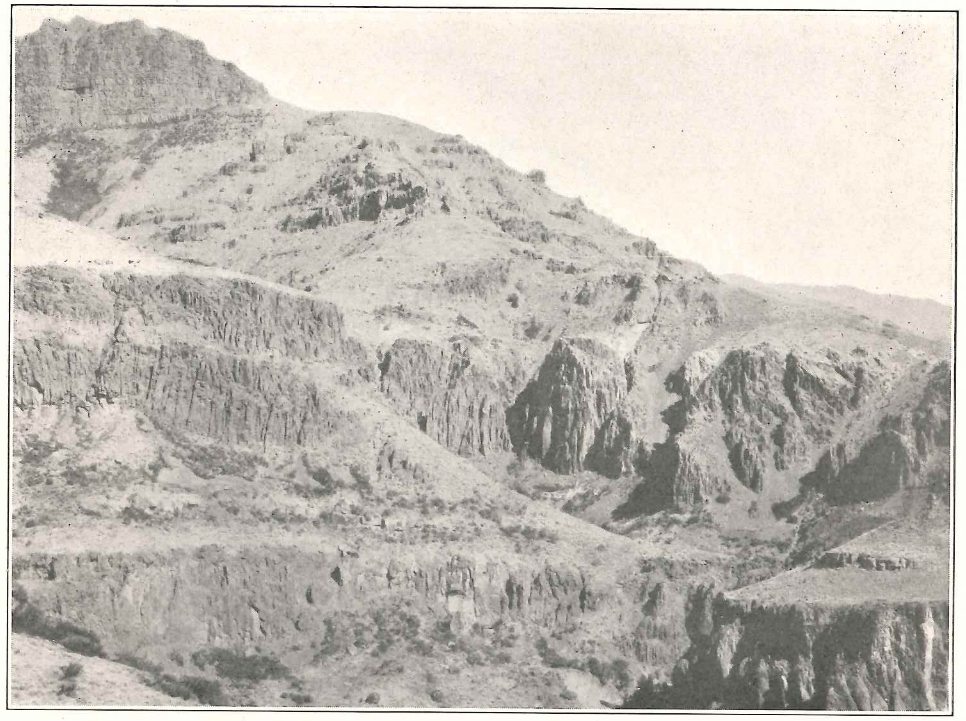

Fig. 41. View of the northern fork of Cottonwood Creek, showing at its base the upper flow of basic andesite. Above it, the tuffaceous bed is visible beneath the northern extension of the great flow. The poorly defined exposures in the upper center are formed by the subsequent thin andesitic flows. On the left, the basaltic series forms the cliff at the top.

On the southern wall of the valley of Alvord Creek, towards the scarp, the jointing becomes more symmetrical and the lava exhibits magnificent hexagonal columns that tower more than 300 feet above the talus slope (fig. 43). Although the upper exposures are not so distinct, the columns appear to extend upwards for at least twice that height. At the eastern margin of the exposure, they curve eastward and become progressively reduced in size from over five feet to approximately six inches in diameter. In like manner, immediately to the north, at an elevation several hundred feet lower and considerably below the base of the great flow, a waterfall in Alvord Creek has been formed by similar curving columns which dip northward to an unexposed cooling surface (fig. 44). These

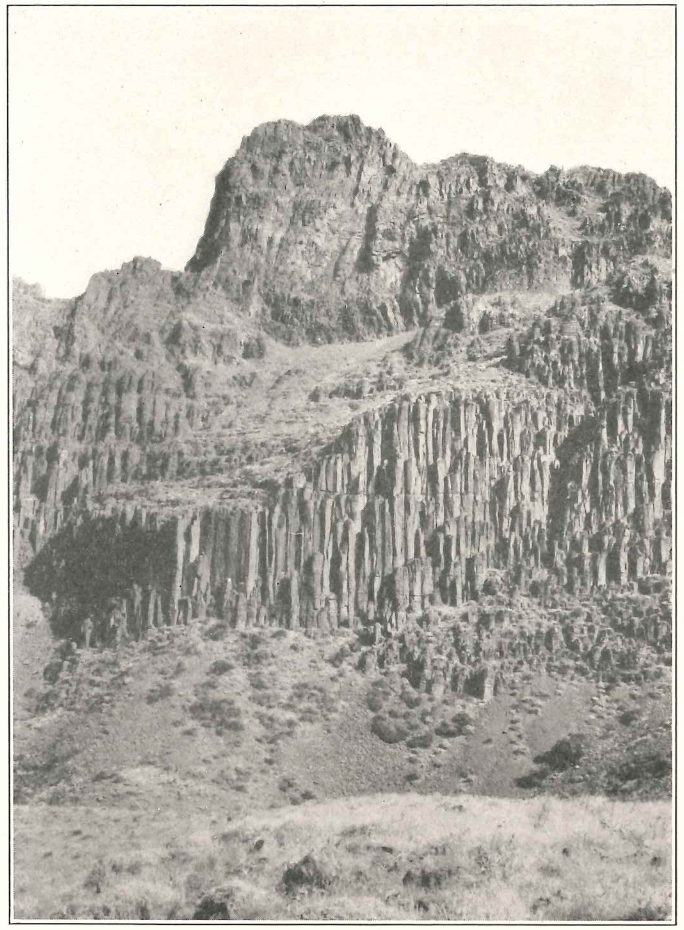

Fig. 42. View of the northern wall of the valley of Alvord Creek showing the maximum exposure of the great andesitic flow, which here has a thickness of about 900 feet. The columns average approximately 10 feet in diameter. The local absence of columnar jointing in the upper part may be explained by deuteric alteration.

two localities, showing curving columns, mark points adjacent to the rounded margin of a vent, which is directly in line with one exposed to the south in the valley of Little Alvord Creek. The wall rock presumably was formed by the Alvord Creek Beds, which are exposed to the east.

Within about 200 yards to the east of the main exposure, a small elliptical intrusion of dark aphanitic andesite cuts the tuffs. The outline is roughly about 100 by 150 feet across (fig. 45). Two similar, far smaller intrusions cut the stratified tuffs a few hundred yards to the south. These three volcanic necks lie almost precisely on a common north-south line, which parallels their major axes. In like manner, both the great flow and the upper andesitic series, which will be subsequently described, may have been extruded from a series of vents distributed at intervals along one main line of tensional weakness.

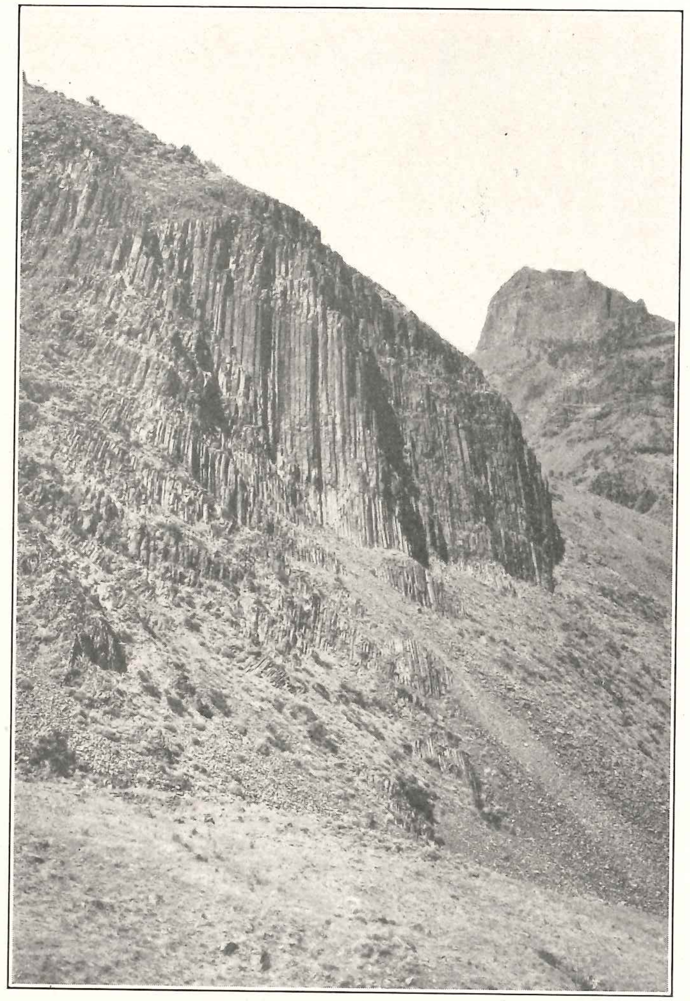

Fig. 43. Columnar andesite forming the great neck on the southern wall of Alvord Creek valley. The columns are at least 300 feet in height. At the basal margin they curve until normal to a roughly vertical contact.

Farther to the south on the northern side of the valley of the south fork of Alvord Creek, the inclination of the columns at the base of the great exposure suggests that it again approaches the eastern margin of the vent, but erosion is not sufficient to disclose a crosscutting relation. Here and immediately to the north, the andesite appears to have welled quietly from a broad elongate vent. To the south, the surface of the flow locally decreases in elevation, forming a depression which is filled with later andesitic flows. Poor exposures prevent the great flow from being traced continuously southward, but scattered outcrops

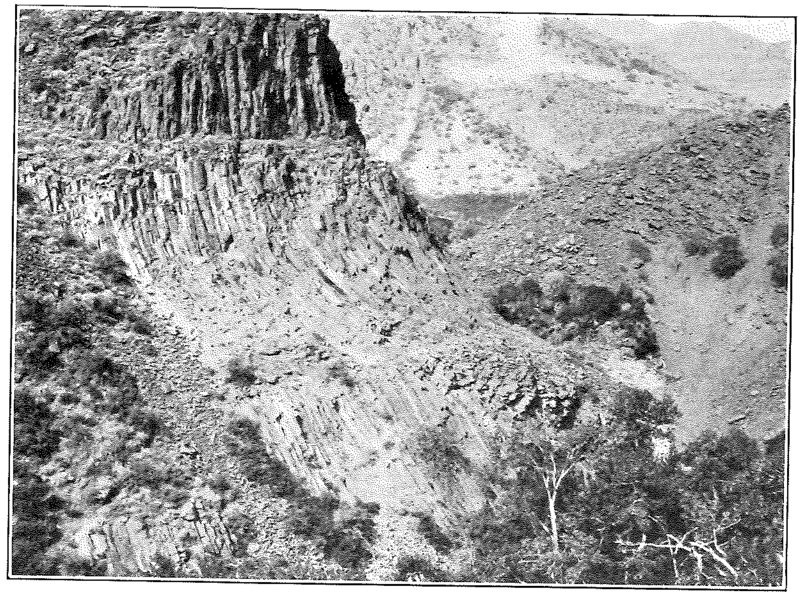

Fig. 44. The curving columns at the northern margin of the andesitic vent in Alvord Creek.

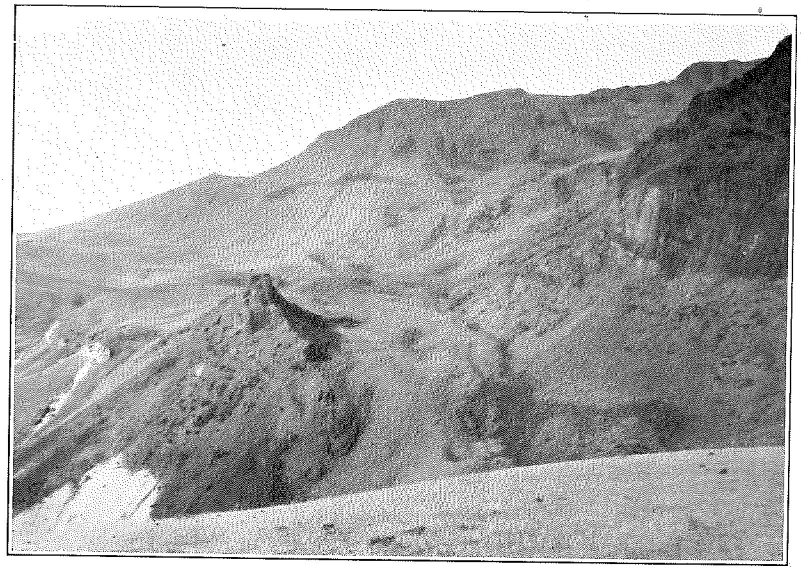

Fig. 45. View of the southern wall of Alvord Creek valley, showing the great andesite vent on the right and the largest of the series of smaller intrusions on the left.

indicate that it gradually develops explosive characteristics. Perhaps merely by chance, these are best defined where the underlying vent cuts the previous eminence formed by the uparched Alvord Creek Beds and the Pike Creek Volcanic Series, which abuts against the southern dip slope of the tuffaceous sediments.

On the northern side of the valley of Little Alvord Creek, directly above the vent for the rhyolite of that name, the southern continuation of the great flow of andesite forms a large exposure about 250 yards across with a semicircular lower margin which reaches to within 50 feet of the uppermost rhyolite tuff (fig. 46). About 100 yards to the east, a small outcrop shows the andesite in contact with the capping perlitic phase of the lower biotite-dacite flow of the Pike Creek series. This contact appears to be crosscutting, although it is not very conclusive.

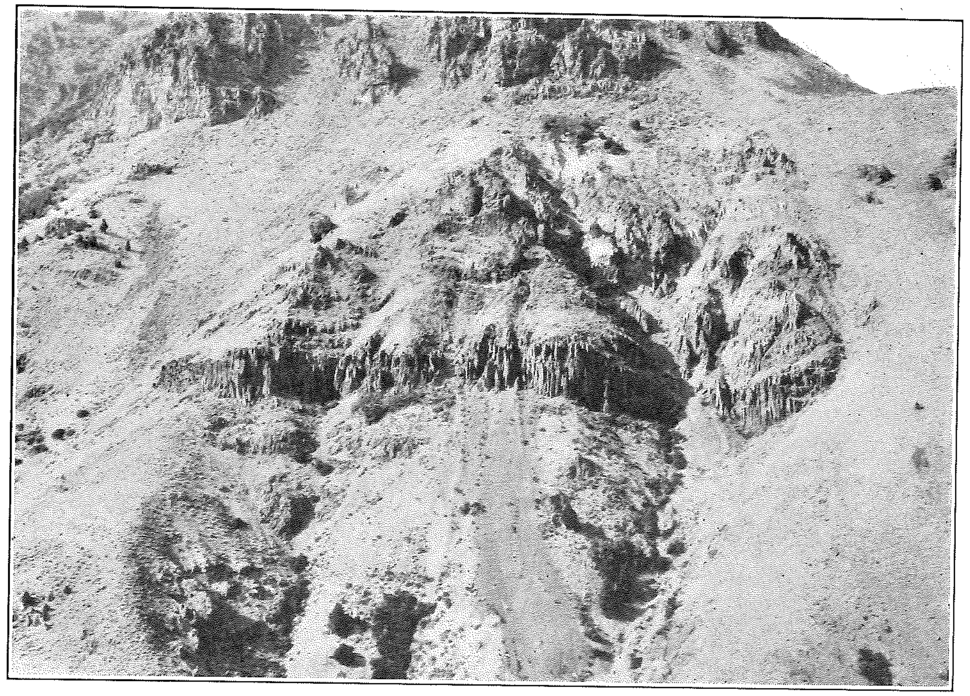

Fig. 46. The rounded exposure in the center is formed by the southern margin of the great andesitic vent on the northern side of the valley of Little Alvord Creek. The upper part of the rhyolitic vent outcrops on the lower left at about 800 feet below the basaltic flows which form the cliff at the top.

The great exposure of andesite with its rounded lower margin extends upwards for over 700 feet. In its lower part, it shows coarse columnar jointing. Upwards it grades into a vertical platy rock, which is associated with great masses of reddish vesicular breccias (fig. 47). The uppermost facies, beneath the basalt, is largely decomposed to a soft grayish rock which is identical to that capping the great flow farther to the north and which is also presumably derived from devitrified glass. In this zone there were also observed a few scattered blocks of unaltered hornblende-free andesite, which may be of pyroclastic origin.

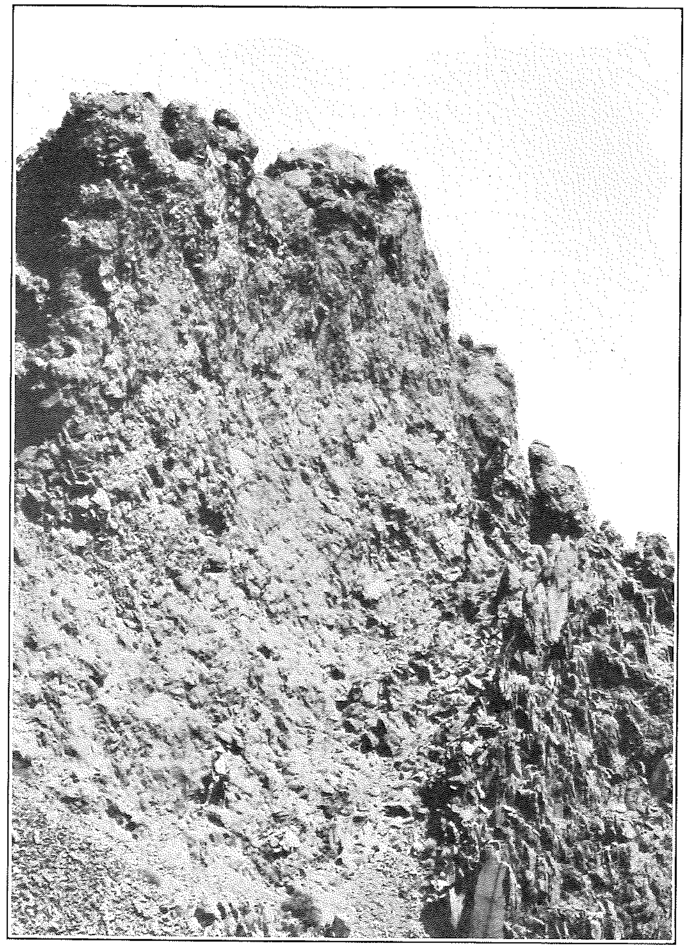

Fig. 47. Reddish breccias in the center of the andesitic vent north of Alvord Creek. On the right is a platy injection with vertical jointing. A figure in the foreground on the left furnishes the scale.

In the valley of Little Alvord Creek, some of the vesicular breccias, towards the western portion of the rounded exposure exhibit locally a horizontal distribution. This fact, together with the horizontal platy jointing, which here is especially distinct near the base of the exposure, suggests that the andesite welled out as a flow far below the one which caps the series to the south. In the center of the exposure, however, the broad zones of breccia, which parallel the highly inclined platy structure, testify to an underlying locus of extrusion and suggest a relatively late stage of explosive activity. It is possible that the discordant relation with the biotite-dacite may also be explained by a volcanic explosion, but no supporting evidence was observed. On the other hand, to the west in the valley of Little Alvord Creek, both the lateral extent of the andesite and its horizontal structures suggest a flow, the relation of which would be more easily accounted for, at least in part, by the abrupt ending of one of the viscous dacitic flows.

Where Little Alvord Creek cuts this horizon at about a quarter of a mile to the west of the large semicircular exposure, it discloses such irregular platy jointing as to suggest another locus of extrusion. This locality is about a mile and a half due north of some small intrusions of dark glassy andesite in the western part of the valley of Pike Creek. It is possible that together they mark the position of another series of vents on a north-south line of weakness. If so they are contemporaneous in their activity with the main ones to the east. It is more probable, however, that the irregularity in the jointing has been caused by the same rapid increase in gradient that appears to have been responsible for the steep flow structure in the dacite immediately to the east.

PETROLOGY OF THE GREAT FLOW

In spite of its thickness, the great andesitic flow is predominantly aphanitic. Locally, however, small phenocrysts of both feldspar and amphibole are visible megascopically in a dark gray groundmass, which exhibits a fairly smooth fractured surface. The phenocrystic facies was observed invariably in the upper part of this massive lava. In the valley of Alvord Creek it also forms the horizontal columns that indicate the margin of the crosscutting andesite. To the south of Little Alvord Creek, a similar lava forms the flow capping the Pike Creek series. Towards the center of the main exposures, the porphyritic texture gradually disappears. The rock assumes a greenish or reddish shade and simultaneously develops a far rougher surface when fractured. The massive type invariably grades upwards into a light gray, highly altered facies containing small irregular cavities. Unfortunately, this light gray porous rock is so easily eroded that the surface of the flow is invariably masked by soil. The local survival of unaltered remnants indicates, however, that it has been derived from the devitrification of a glass.

In thin sections of the porphyritic type, the andesine commonly shows a marked seriate development with individual crystals ranging up to 2 or 3 mm. in length, but with the average more nearly .1 or .15 mm. These laths usually show irregular alignment. Locally the larger ones are chiefly fragmental. Although the presence of glassy inclusions in the coarser crystals frequently renders their zonal growth apparent, they are relatively homogeneous in composition. The plagioclase as a rule forms about 60 per cent of the rock. The texture is characteristically hyalopilitic. It can seldom be classed as pilotaxitic, for there is usually a cryptocrystalline semi-opaque ground, which is probably derived from a decomposed glass. It consists largely of indistinct feldspathic material filled with opaque dust which is thought to be formed of magnetite and kaolin.

With greater depth, the texture in some specimens becomes slightly coarser and the smaller laths average approximately .2 mm. in length. As a rule in this phase, however, the feldspar shows no marked increase in size, but instead of exhibiting a clean cut outline it is irregular and ill-defined. The fine groundmass thus formed may appear blotchy in thin section on account of localized alteration, which does not otherwise affect the texture.

The needles of hornblende range up to 5 mm. in length and locally form about five per cent of the rock. This mineral is variable in its optical properties. Some appears definitely to be of a basaltic variety, with a dark brown pleochroism, a very low extinction and a high index of refraction. In other specimens, the pleochroism of crystals of similar magnitude varies to a decided green, while the extinction angle ranges as high as 14°. Since similar variations have been artificially induced in hornblende,[11] it is possible that physical conditions may have locally affected the properties of the mineral. Commonly the dark brown crystals are partially replaced by a marginal rim of magnetite or of brownish opaque iron oxides. In many sections only pseudomorphs survive. The elongate concentrations of magnetite, thus formed, may be observed in various stages of disintegration. Even the remnants are lacking in the central altered zone where the individual crystals of plagioclase are most poorly defined.

Pale greenish augite appears invariably to be present as a minor constituent. It was observed as irregular grains less than .5 mm. in diameter. A few thin sections show scattered, well-shaped crystals of hypersthene with a maximum length of about .8 mm. In contrast to the amphibole, these pyroxenes are unaltered. Aside from the hornblende, no regularity was detected in the distribution of these mafics, which form the only accessory minerals observed.

TABLE VII

PART 1

	I	II	III	IV
Silica	62.28	62.26	61.60	60.03
Alumina	17.17	16.65	16.23	18.37
Ferrous Oxide	2.04	3.58	2.27	4.05
Ferric Oxide	2.56	1.73	3.54	1.64
Magnesia	1.64	2.34	3.00	2.84
Lime	5.45	5.30	5.40	5.25
Soda	3.62	3.22	3.70	3.45
Potash	2.44	2.52	2.32	2.72
Water above 105° C.	1.40	1.60	1.00	.88
Water at 105° C.	.90	.30	.30	.58
Carbon Dioxide	none	none	none	none
Titanium Dioxide	.15	.14	.52	trace
Phosphorus Pentoxide	.14	.13	.16	.29
Sulphur	trace	trace	none	trace
Manganese Dioxide	trace	.15	trace	trace
	99.79	99.92	100.04	100.10

Specimens I, II, and III are from the andesitic exposures on the northern side of Alvord Creek valley. Analysts W. H. and F. Herdsman.

I. The base of the great flow.
II. Unaltered andesite from the top of the great flow.
III. Platy andesite associated with the breccias at the uppermost andesitic exposures.
IV. Andesite from the summit of the divide between Little Mann Creek and Little Dry Creek. Analyst W. H. Herdsman.

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[11] Virgil E. Barnes, "Changes in Hornblende at about 800° C.", *Am. Mineralogist*, vol. 15, pp. 393-417, 1930.

PART 2

	I	II	III	IV
Quartz	18.00	17.64	16.74	11.94
Orthoclase	14.46	15.01	13.34	16.12
Albite	30.92	27.25	31.44	29.34
Anorthite	23.35	23.35	20.85	24.19
Corundum	.....	.....	.....	.82
Diopside	2.22	1.14	3.27	.....
Hypersthene	4.36	10.25	6.50	13.30
Magnetite	3.71	2.55	5.10	2.32
Ilmenite	.30	.15	.91	.....
Apatite	.34	.67	.67	.67
Water	2.30	1.90	1.30	1.46
	99.96	99.91	100.12	100.16

Norms calculated from the analyses in Part 1:

I. Amiatose, C. I. P. W. symbol, I(II).4.3.3".
II. Harzose, C. I. P. W. symbol, "II.4.3.3".
III. Harzose, C. I. P. W. symbol, "II.4.3.3".
IV. Harzose, C. I. P. W. symbol, "II.4"."3.3".

In spite of the small variations, an analysis of a remarkably fresh specimen from the uppermost hornblendic zone coincides almost exactly with that of a hornblende-free rock from the base of the columns about 900 feet below (table VII). A comparison of these analyses with those of the basic andesite, however, indicates that the lava became progressively more salic (table VI).

UPPER ANDESITIC SERIES

GENERAL FEATURES

Following the extrusion of the great flow, there is no evidence of an erosional interval prior to its submergence beneath a number of thin andesitic flows, which have been locally complicated by the close association with their vents. At a few horizons, accumulations of ejectamenta testify to explosive activity, which has given rise to several small, well-defined cinder cones. The lower part of this upper series consists predominantly of flows which vary rapidly in their physical characteristics, and yet are so uniform in their variations that they can be described as a unit. Some of the more distinctive local peculiarities observed in the series will, however, be subsequently mentioned in a brief description of the andesite in each valley.

Most of this upper series consists of a horizontal alternation of vesicular andesitic breccias and dark gray aphanitic platy lava, which as a rule follows a slightly sinuous course (fig. 48). At a few localities, interbedded stratified tuffs indicate occasional intervals in the extrusion of the series and testify to the fact that it has been formed by the advance of successive flows. The individual members, however, are poorly defined, for the basal breccia of one merges with the irregular surface breccia of that which locally preceded it. The contact as a rule is therefore imperceptible if it is not defined by the accumulation of ejectamenta.

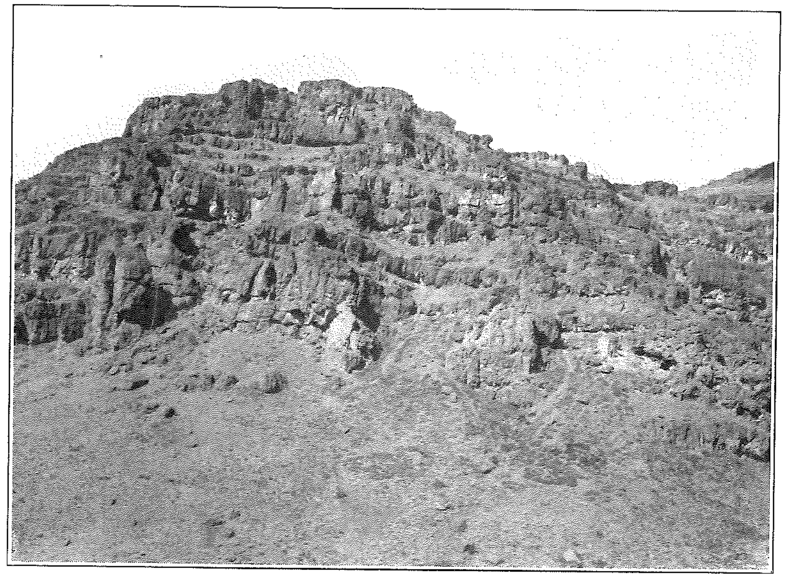

Fig. 48. View of the andesitic flows exposed at the base of the scarp south of Little Dry Creek. The resistant horizons are formed principally of extensive flow breccias.

As in the case of all blocky lavas, the margin of each flow presumably ended in a relatively steep wall with a slope depending on the angle of repose of the fragmental material. Since the successive sheets were apparently derived from a series of adjacent vents and not from a central one, it is obvious that the steep margin of one might have locally curtailed the advance of the succeeding flow. This possible merging of successive marginal flow breccias may explain the vertical zones of brecciation that are both underlain and overlain by the normal horizontal alternation of breccia and platy lava (fig. 49). Some more extensive vertical zones of brecciation, however, mark loci of extrusion.

The breccias, almost invariably, form the bulk of the series. Their predominance is emphasized, however, by the fact that their consolidation renders them sufficiently resistant to erosion to cause them to stand out prominently, while the platy horizons, which are usually less than a third as thick, are deeply eroded (fig. 50). The resistant members, consisting largely of roughly rounded vesicular fragments that range from 2 to 10 inches in diameter, show as a rule a thickness of from 10 to 40 feet. Many of the individual lines of platy lava can not be traced more than a few hundred yards before they are found either to lense out, or to blend into the breccia, leaving no obvious break to separate the upper and lower members.

Locally, however, far thicker horizontal masses of lava occur in the breccia. Some of these are very irregular, both in outline and jointing. Others show curving jointing roughly parallel to an elliptical outline, which may be 20 by 40 feet or more across. Some minor injections can be traced from these larger masses. Some of these curve into a roughly horizontal sinuous course, usually

Fig. 49. View of the northern wall of the valley of Dry Creek, showing the local merging of breccias presumably at the conflicting steep margins of flows.

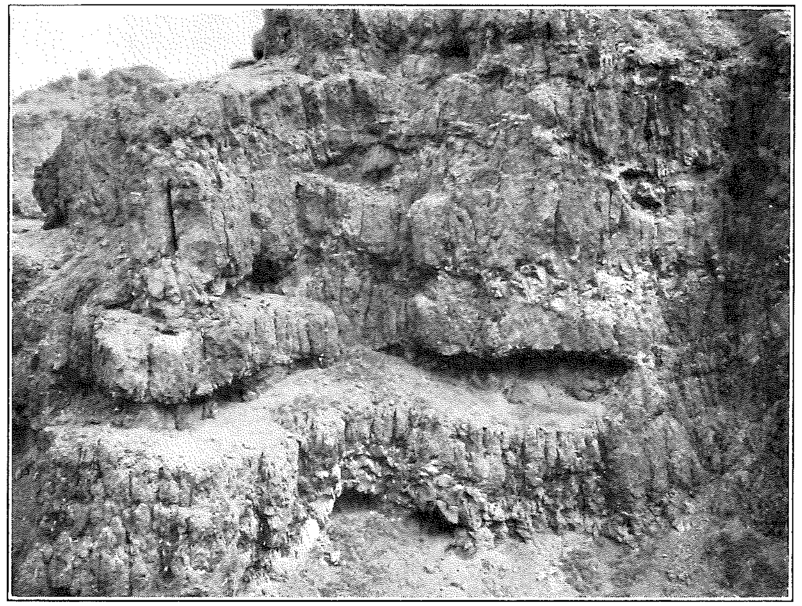

Fig. 50. View of the valley of Dry Creek, showing the typical alternation of breccia and platy lava formed by the merging of successive flows. The slight vertical structure of the breccia is caused by erosion. The area shown has an estimated height of about 100 feet.

showing a thickness of from one to three feet and a lateral extent of from 10 to 50 feet. Although their orientation probably depended on the direction of flowage, no uniformity was observed in their inclination. In fact, in a number of exposures, the injections were observed to spread laterally in both directions and to develop a pronounced fan shape, which flares upwards (fig. 51). Many of these small injections show well-defined platy structure, but as a rule the more glassy ones exhibit an irregular spinelike jointing. These minor extensions of the larger masses are considered to have been formed as auto-injections, caused by tongues of the still fluid lava intruding and squeezing upwards or laterally into vesicular breccias that either capped or defined the margin of an advancing flow.

Fig. 51. Fan-shaped injection intruding its own flow breccia directly above the shoulder at the top of the great flow north of Alvord Creek.

The contact of the upper part of these auto-intrusions appears invariably to be clean cut, but traced downward their margins as a rule become gradually vesicular and develop more irregular and coarser jointing. At these lower contacts, the injections even exhibit a rough reddish surface identical to that of the adjacent fragments. Locally either a surface of this type or fractured vesicular lava appears to truncate the injections actually normal to the direction of their flowage, as indicated both by the jointing and the elongation of the vesicles.

The lava advancing beneath its breccia would obviously have been more chilled and viscous at its margin. If hydrostatic pressure caused the local advance of auto-intrusions into its own breccia, the viscous marginal lava would have been forced outward in the front of the injection, but it would have been followed by lava that became more and more fluid as it was derived from the central portion of the flow. The porosity of the breccia would have permitted a relief of pressure and a consequent development of vesicles, which would have become progressively more marked as the gradual downward increase in fluidity permitted the volatiles to expand. The chilling induced by this expansion would have caused the vesicular lava to solidify and the injection thus to be truncated. With the further advance of the flow the injection might have been completely brecciated. In the flow breccias, the linear distribution of fragments of platy rock locally testifies to the former presence of injections.

These flows resemble the aa variety of basalt more closely than they do the slightly more acidic type of blocky lava observed by Washington at Fouqué Kameni.[12] In these Santorini flows, the upper breccias are formed of loose angular glassy blocks, which, as well as the underlying lava, are practically free from vesicularity. In marked contrast to this type, the breccias of the upper andesitic flows on Steens Mountain are highly vesicular, although far more minutely so than the typical basaltic ones. The primary surface of some of the vesicular blocks is very rough and jagged and closely similar to that frequently developed by basalt. Unlike typical aa basalt, however, the andesite is always aphanitic and as a rule relatively glassy, rather than showing the characteristic coarse crystallinity of the more basic lava. Although the breccias are not very compact, they are for the most part firmly consolidated. In contrast to the aa type, this agglutination appears to be due to later agencies and not to the adhesion of still viscous fragments of slag-like lava.

DISTRIBUTION

Although these flows appear to have been very viscous and as a rule to have advanced predominantly as unconsolidated flow breccias, they accumulated with sufficient uniformity to give the andesite a relatively level surface throughout its entire extent from Little Alvord Creek northward to Mann Creek, where it is truncated by a transverse fault. For this distance of about 11 miles the uppermost member of the andesitic series is, as a rule, 2,000 to 2,500 feet above the base of the scarp. Owing to the irregularity of the surface on which they were extruded, however, the thickness of this upper series of andesitic flows is very variable.

These upper flows are not present above the vent in the valley of Little Alvord Creek. Here the later activity is merely suggested by isolated blocks of hornblende-free andesite scattered throughout the capping zone of soft altered glass with its obvious content of hornblende. It was not determined if the blocks were derived from pyroclastics. It is possible, however, that some of the previ-

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[12] Henry S. Washington, "Santorini Eruption of 1925," *Bull, Geol. Soc. Am.*, vol 37, p. 367, 1926.

ously mentioned explosive characteristics at this locality may indicate a transition to the later phase of activity. A little farther to the north in the southern part of the valley of the south fork of Alvord Creek, a number of poorly defined flows of andesite fill the local depression in the surface of the great flow to a depth of about 400 feet. Although their jointing is predominantly horizontal, it locally is very irregular, and in a few horizons is associated with vesicular breccias which here form a minor constituent.

Northward this upper series of flows decreases in thickness as the surface of the great andesitic flow increases in height above the vent south of Alvord Creek. In this region, vesicular andesitic breccias may be seen to be locally cut by injections, but the outcrops are not of sufficient magnitude to permit an interpretation. It is only in this vicinity, however, that the basal contact of the overlying basalt was observed. The basaltic flows were invariably found to have lapped against a slightly irregular surface that sloped gently westward. The andesite is covered with a thin layer of tuff that shows only a slight tendency to stratification. There is no indication of erosional agencies. Immediately below this upper contact, blocks of glassy andesite outcrop. Some of these appear to represent the surface of an exceptionally vitreous flow, while others may have been distributed as coarse pyroclastics.

On the northern side of the valley of Alvord Creek, the upper series of andesitic flows is excellently exposed above the great flow (fig. 52). At this locality the upper andesite shows a minimum thickness of about 600 feet. A succession of flows accompanied by extensive breccias form the lower half (fig. 53). These rapidly increase in number to the west with the thinning of the underlying extrusive mass. In the upper part of the exposure, there are several thick irregular masses of platy lava that definitely crosscut and indurate the breccia. These appear to have welled into a thick flow. Farther to the west along the divide between the Alvord Creek and the Cottonwood Creek drainage, there are additional indications of small loci of extrusion. The surface of these is characteristically formed of a dark dull glass which breaks into spinelike fragments. This vitreous lava is extensive throughout the upper part of the series. It appears to indicate an increase in the viscosity of the magma, for the composition remains approximately uniform (table VII).

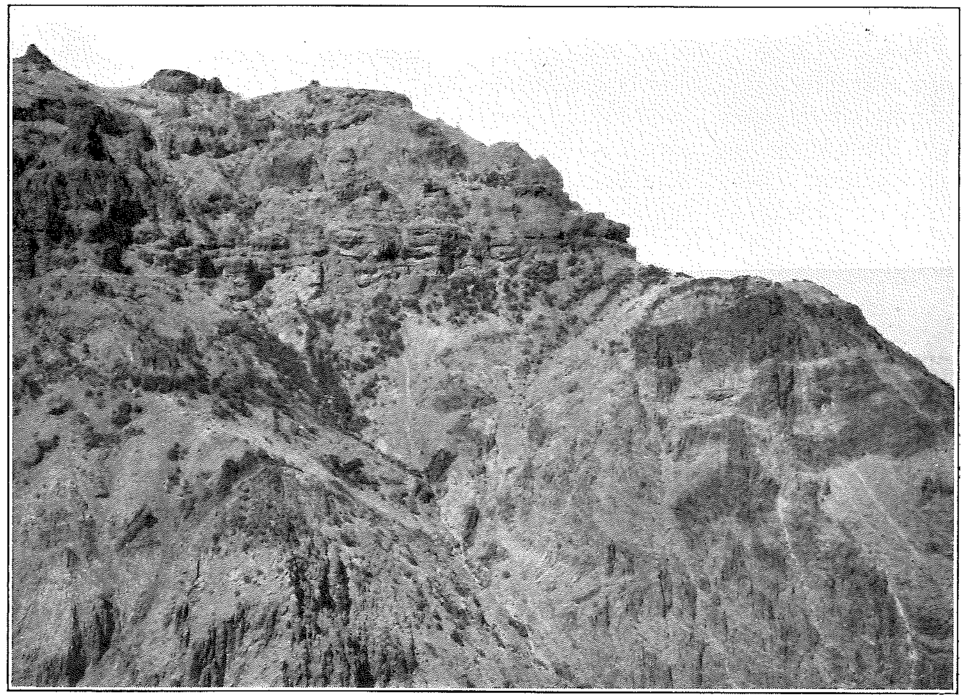

Fig. 52. View of the andesite exposed on the northern wall of Alvord Creek showing the upper portion of the great flow overlain by the later series. The lava forming the massive exposure in the upper center appears in part to overlie the minor vent or vents from which it was derived. Here the upper andesitic series shows a minimum thickness of about 600 feet, but it increases rapidly to the west.

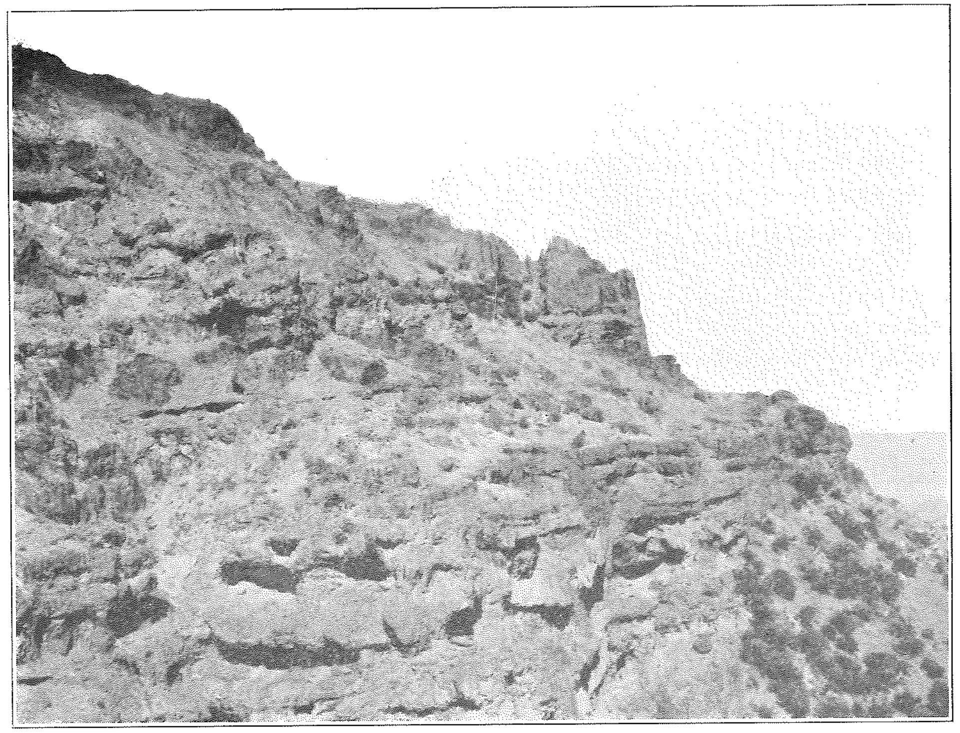

Fig. 53. View of the upper andesitic series capping the great flow north of Alvord Creek (*cf.* fig. 52). The resistant horizons in the foreground are formed predominantly of flow breccias. Above them is a near-vent accumulation of lava. The exposures on the skyline show a total height of about 500 feet.

Both here and to the north there is evidence of a discontinuous series of vents, which as a rule are a half mile or more to the west of the base of the scarp. To the east, the upper andesite appears like a fairly normal series of blocky flows, but when the exposures are followed westward, the local variations accompanying the near vent facies render them far more irregular. The horizontal alternation, which usually defines the series, becomes locally no longer apparent. The actual mechanism can seldom be conclusively interpreted, for as a rule such criteria as the orientation of the platy jointing are too variable to be relied upon.

Near the head of the south fork of Cottonwood Creek, there is additional evidence of a vent, which was active at an horizon several hundred feet below the uppermost members. To the east on the northern wall of the north fork, a homogeneous breccia of dark vesicular glass forms a vertical zone that is over 500 feet in height. Immediately adjacent to this zone, the platy lava forming the horizontal flows is far more extensive than usual. The inclination of their jointing suggests that several consecutive flows have been derived from this vent, which subsequently gave rise to explosive activity.

The other noteworthy feature observed in the valley of the north fork is the occurrence of a large inclined block of acidic stratified tuffs at the bottom of the canyon to the south of the vertical zone of brecciation, and only about 100 feet above the top of the great flow. This block, which shows dimensions of about 70 by 30 feet, rests directly on andesitic breccias. Locally it is indurated at its contact with the lava. The content of quartz and biotite in these sediments proves the block to be of exotic origin. An explanation of their presence appears to demand that it has been carried upwards in a vent from the Alvord Creek Beds, the uppermost horizon of which is 600 or 700 feet below.

Northward in the valley of Willow Creek, the andesitic flows are continuously exposed. Although the breccias are very marked, they are locally less predominant than usual. In the eastern portion of the valley, they appear to form a normal series, but to the west, at the head of the lower cirques, there are indications of a vent of indeterminable dimensions midway between the two forks. Here dark vitreous injections protrude from the summit of the divide. The vertical structures may be traced downward on either side for several hundred feet. At this locality, the discordant relation of the basalt is more marked than observed elsewhere and the contact has an inclination of at least 30°.

Mosquito Creek forms the next valley to the north. Its walls are less precipitous and its exposures therefore less distinct, but isolated outcrops permit the andesitic series to be traced continuously as a normal succession of flows. Immediately to the north, the narrow gorges of four closely spaced valleys show magnificent exposures, which permit more detailed observation. Although each of these valleys exhibit distinctive features, they disclose principally a repetition of flows of the blocky type, which have been previously described. At several horizons, these valleys show evidence of explosive activity, either as interbedded tuffs or as well-defined cinder cones. The center of activity appears to have moved progressively westward. Higher in the valleys, the series is cut by elongate intrusions from which at least some of the uppermost members have been derived.

The most southerly of these four creeks is known as Dry Creek, although it is usually well supplied with water. Near its mouth, several large flows are exceptionally distinct in their relation. They are separated by typical flow breccias, which, however, form a relatively minor constituent. At two of the lower

horizons an otherwise imperceptible contact of a basal and a surface breccia is rendered apparent by an accumulation of tuffs. In one of these localities, on the northern wall at about 300 feet above the lowermost exposures, a small bed of well-stratified tuffs testifies to the water deposition of tuffaceous sediments in a minor depression on the surface of a flow.

To the south, a dissected cinder cone, at least 400 feet in height, caps the divide between Dry Creek and Mosquito Creek (fig. 54). On both its western and northern sides, the pyroclastics are excellently exposed and show a distinct slope of about 30°. To the south and east of these main tuffaceous deposits, the center of the crater has been removed by erosion, but the position of the neck is indicated both by vertical platy lava and by extensive agglomerates, which are so highly indurated that their structure is apparent only on the weathered surface.

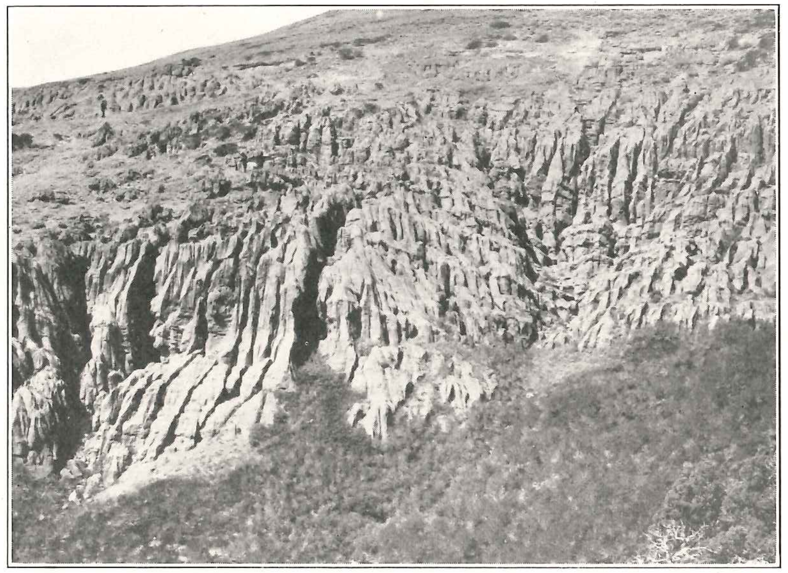

Fig. 54. The western part of the southern cinder cone viewed from the intrusion which cuts its western slope presumably near the crater.

The cone is also cut by several extensive intrusions, which have resulted in similar induration. To the east at its base, one of the largest of these has altered the flow breccias immediately beneath the cone. Adjacent to the major intrusion, the series shows an alternation of horizontal platy lava and irregularly jointed breccias, which are completely indurated. Locally it is impossible to distinguish the platy lava of the flows from lateral extensions of the intrusion. To the south, the transition to the unaltered rock, however, renders the original relation apparent (fig. 55). The uppermost exposure of the western limb of the cone is also cut by an elongate intrusion, which trends a little west of north (fig. 56). This dike-like intrusion has also resulted in extensive alteration. The northern limb of this cone is cut by at least two additional minor andesitic dikes.

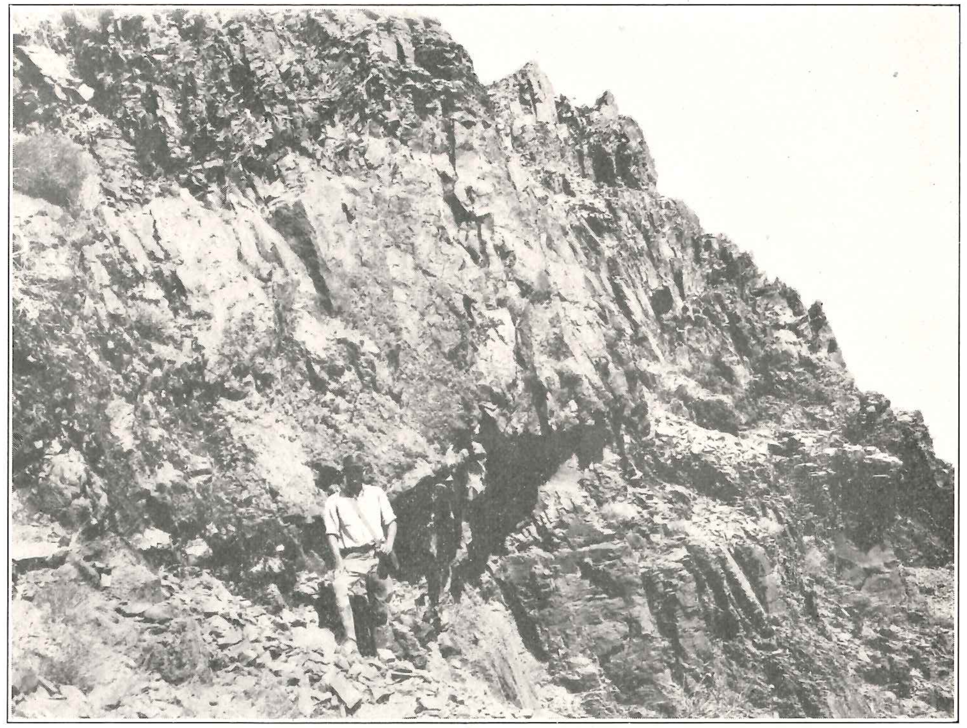

Fig. 55. The margin of the zone of induration in the flow breccias beneath the northeastern margin of the southern cinder zone. To the left, away from the intrusion, the agglomerates grade into a poorly consolidated breccia.

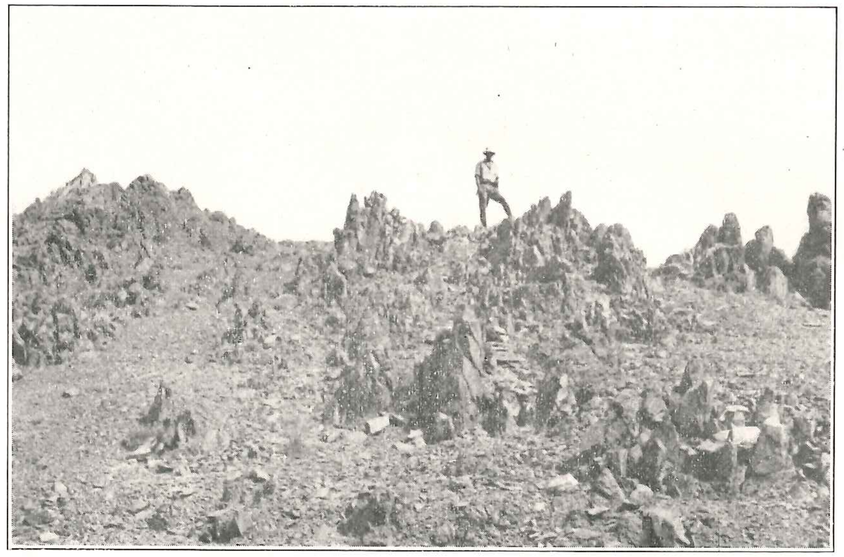

Fig. 56. View of the main elongate intrusion cutting the southern cinder cone. The jointing of the platy intrusive and the associated indurated agglomerates are both predominantly vertical.

North of Dry Creek, another cinder cone is so close to the one just described that their pyroclastics almost coincide at the bottom of the valley. This northern one, which is at approximately the same horizon, may have originally been more extensive, but now its remnants are widely scattered. Its southern limb, which is formed of buff colored tuffs and angular glassy fragments, is exposed on the northern wall of Dry Creek. To the south, near the summit of the divide separating it from Little Dry Creek, a tuffaceous pinnacle has been sufficiently indurated by an andesitic intrusion to survive erosion (fig. 57). This pinnacle exhibits irregular masses of lava that are inclined northward and suggest an accumulation of viscous splashes of lava on the inner slope of a crater. To the east, remnants of the eastern limb survive, but to the north the pyroclastics have been almost completely stripped from a continuous surface that appears to be formed by a flow breccia that slopes northward gently. On the northern wall of Little Dry Creek, the northern limb of a cinder cone shows a thickness of over 100 feet. Presumably it is part of the same cone, but if such is the case, the accumulation of ejectamenta must have been very assymetrical, and the cone must have had a far longer and more gentle slope to the north. In the valley of

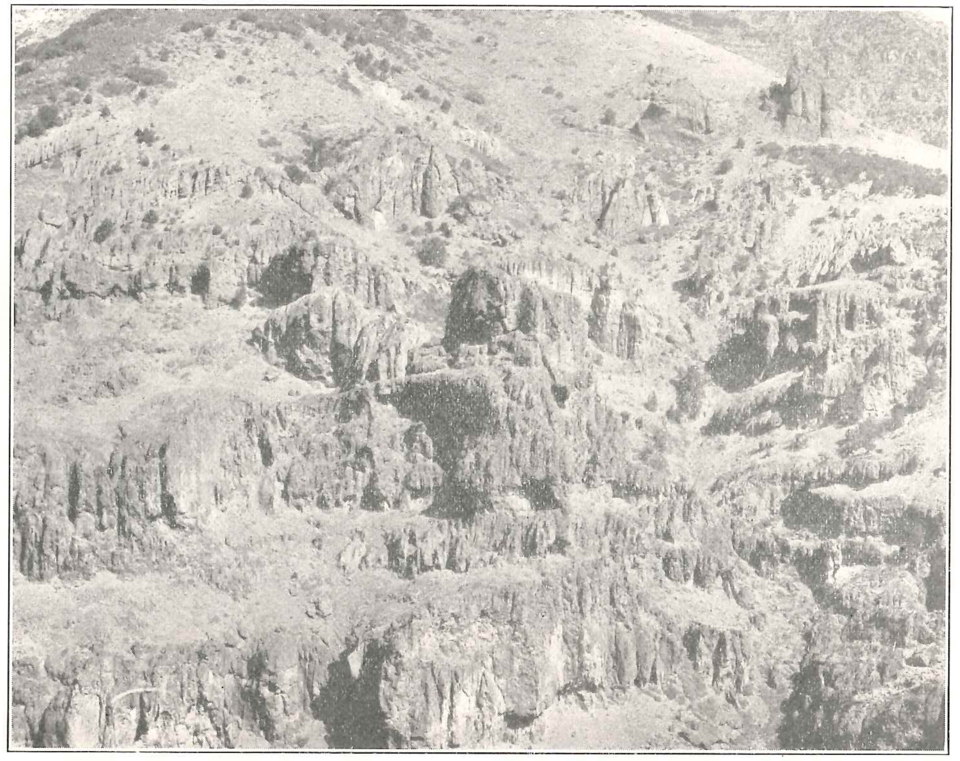

Fig. 57. The northern fork of Dry Creek is on the right. To the left of it, the inclined beds of the northern cinder cone are visible above the flow breccias. As a result of the induration of an elongate andesitic dike, a remnant of the inner lip of the crater forms a red pinnacle on the divide to the north.

Dry Creek, thin andesitic flows are exposed between these two cones, indicating that they were subsequently just submerged. These flows appear identical to the lower series, except that the lava forming them is slightly more vitreous.

A little to the north of this locality, there is also evidence of explosive activity in the lower part of the series. At the mouth of Little Mann Creek, part of a small andesitic cone forms the lowermost exposures (fig. 58). The only other break observed in the extensive flow breccias is near the top of the main series. The thick flow, on the surface of which the northern cone accumulated, shows at its base a persistent thin bed of tuffs, which varies from 2 to 5 feet in thickness (fig. 59). This ejectamenta apparently settled as a relatively uniform coating on an irregular surface. The sharper projections locally failed to be covered. The bed at present follows a sinuous course, which in places may be due to later slumping.

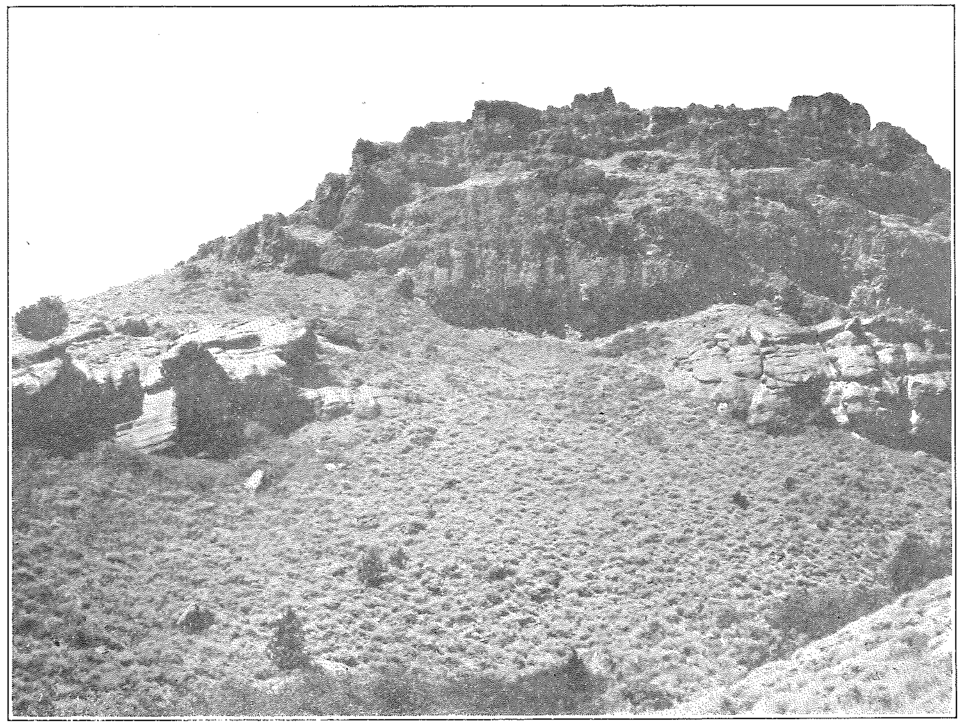

Fig. 58. View of the base of the scarp at Little Mann Creek showing the inclined tuffaceous deposits that underlie the thin flows. To the right, just beyond the margin of the picture, the beds dip in the opposite direction, presumably because of their deposition on the inner slope of a crater.

To the north in the valley of Mann Creek, at several hundred feet higher than the top of the great flow, exposures of tuffs appear to indicate remnants of another smaller cone. Here an outcrop showing platy vertical jointing suggests the position of the neck. Higher in this valley, elongate intrusions form pronounced exposures with a general north-south trend. Like the intrusions cutting the southern cinder cone they are associated with highly indurated agglomerates.

Fig. 59. An exposure on the scarp north of Dry Creek showing a persistent bed of stratified tuffs, which demarks the contact of two flows in the upper part of the series. To the right of the center, a typical auto-injection projects above the surface breccia of the flow.

PETROLOGY OF THE UPPER ANDESITIC SERIES

The vesicular flow breccias, which form such a large bulk of the upper andesitic series, have already been briefly described. As previously stated, most of its blocks range from 2 to 10 inches in diameter. Many of these have been roughly rounded by the breaking of their fragile margins during the advance of the flow, but where the primary surface may be observed, it is found either to be smoothly fractured or extremely jagged and so roughly pitted by the disruption of its vesicles, while still viscous, that it appears almost granular. These vesicles are seldom over 1 mm. in diameter, but they are usually greatly elongated and distorted by flowage.

During the advance of a flow, the grinding of the fragile margins of the blocks has resulted in the interstitial accumulation of tuffaceous material. Evidence of this disintegration may be observed at numerous localities. The disrupted particles, together with the margins of the dark gray blocks, are locally more or less altered to a dull red, or more rarely to a pale buff. Probably owing to fluxion, the finest of this material locally exhibits irregular stratification, which roughly parallels the margins of the enclosing blocks. Somewhat similar results are also attained by the deposition of ejectamenta on the surface of a flow breccia. Beneath the thin interstratified beds of tuff, the fine particles fill the spaces between the upper blocks.

The rock forming the breccia as a rule is completely aphanitic. Minute feldspathic laths, however, are visible megascopically in some of the platy lava, which for the most part is of a slightly lighter shade of gray. The planes of flowage, along which it splits, occur usually at intervals of from 2 to 7 mm. Some of the more vitreous auto-injections are almost black, and break into irregular splinters of various sizes. The major axes of these are parallel to the flowage. Locally this spinous jointing results in the formation of cigar-shaped fragments.

The larger fragments in the ejectamenta show a dull vitreous surface, which also is nearly black. As a rule, they are completely free from vesicles. Some of the blocks have a conchoidal fracture. In others, planes of weakness, which were probably formed by contraction during cooling, cause them to break roughly parallel to the surface and thus to form rounded residuals. Many of the smaller fragments, which compose the light buff or gray matrix, may be seen to have been pumiceous. Although most of the blocks and lapilli exhibit fractured surfaces, the rounded chilled margins of some testify to their extrusion while still plastic.

Petrographically these various facies are so uniform that they may be treated as a unit. The most vitreous types show scattered minute feldspathic microlites averaging about .05 mm. in length in a dark opaque ground. In other very aphanitic types, an ill-defined feldspathic crystallization gives the rock in thin section a slightly mottled appearance. The more crystalline specimens, however, usually exhibit a seriate development of clean cut andesine laths, which show no zoning. The largest of these crystals seldom exceeds 1 mm. in length, while in the main mass of the ground they range from .05 to .2 mm. As a rule these show an irregular alignment. In these more crystalline types, the ground may be formed largely of a fairly light colored glass or it may be cryptocrystalline. It usually has a high content of black dust, which presumably consists of magnetite. In some specimens the ground is clouded with the opaque white dust. Indeterminable mafic grains less than .02 mm. in diameter locally form a marked constituent. Aside from these, a few sections exhibit scattered small crystals of hypersthene and of pale greenish augite. Neither of these minerals exceeds .5 mm. in length.

In no specimen was observed either the coarser andesine crystals or the hornblende phenocrysts, which locally form a marked constituent of the great flow. Some types, however, are very similar to its altered facies both in their indistinct feldspathic crystallization and in their mafic content. A chemical analysis of one of the uppermost vitreous injections cutting the breccia north of Alvord Creek emphasizes the resemblance. It proved the composition of the rock to be practically identical to that of both the upper and the lower portion of the great flow in that locality (table VII). The extreme monotony in both the megascopic and the petrographic characteristics of the rock, forming the upper andesitic series, suggests that it is relatively uniform in composition.

Only slight variations in appearance are shown even by the indurated agglomerates, adjacent to the later andesitic intrusions in the northern valleys. Megascopically their structure is hardly visible except on the weathered surface, but as a rule their irregular jointing contrasts strongly with that of the platy intrusions. Most of the fragments are angular, but some are distinctly distorted. Petrographically their fragmental origin is distinct. The finer particles and usually at least the margins of the larger fragments have been rendered almost opaque by kaolinitic alteration, which locally is very blotchy. The minute feldspathic laths, however, appear to be unaltered. The alignment of some of the feldspar of the interstitial material suggests subsequent flowage. The refusion of the breccia is potentially possible, since the heat of crystallization would not have had to be overcome in the alteration of the glassy fragments.

STEENS MOUNTAIN BASALT

The Upper Andesite is capped by an extensive series of thin basaltic flows (figs. 6 and 60) that extend to the summit of the mountain, about 3000 feet above. This great thickness, however, is far from a maximum figure inasmuch as the near-vent phases of the earlier volcanic rocks, on which the basalt rests, probably formed a marked topographic feature at the time of this later extrusion.

Although the uppermost surface of the underlying andesite fluctuates as it is traced from divide to divide, it retains in general a relatively uniform height. To the south, the top of the Pike Creek volcanic series is almost at the same level. Traced westward into the glacial cirgues, the elevation of the upper surface of the andesite decreases gradually with an inclination, which is locally over 15° (fig. 61). The thin basaltic flows lap against this inclined surface.

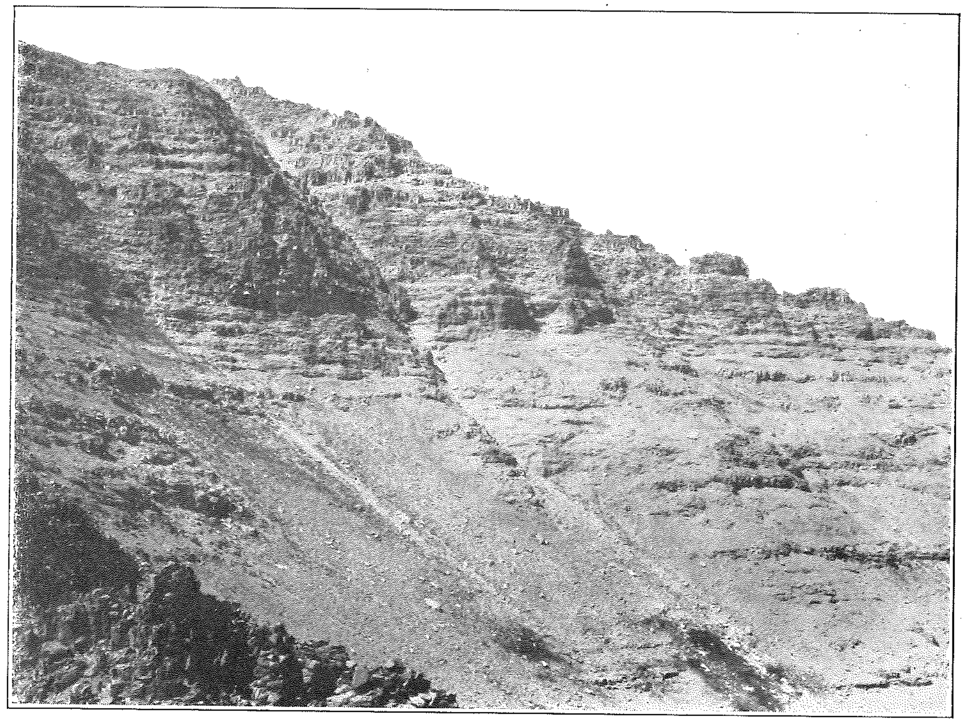

Fig. 60. View of the basaltic flows exposed above the cirque of the south fork of Alvord Creek. On the left the cliff rises nearly 1000 feet.

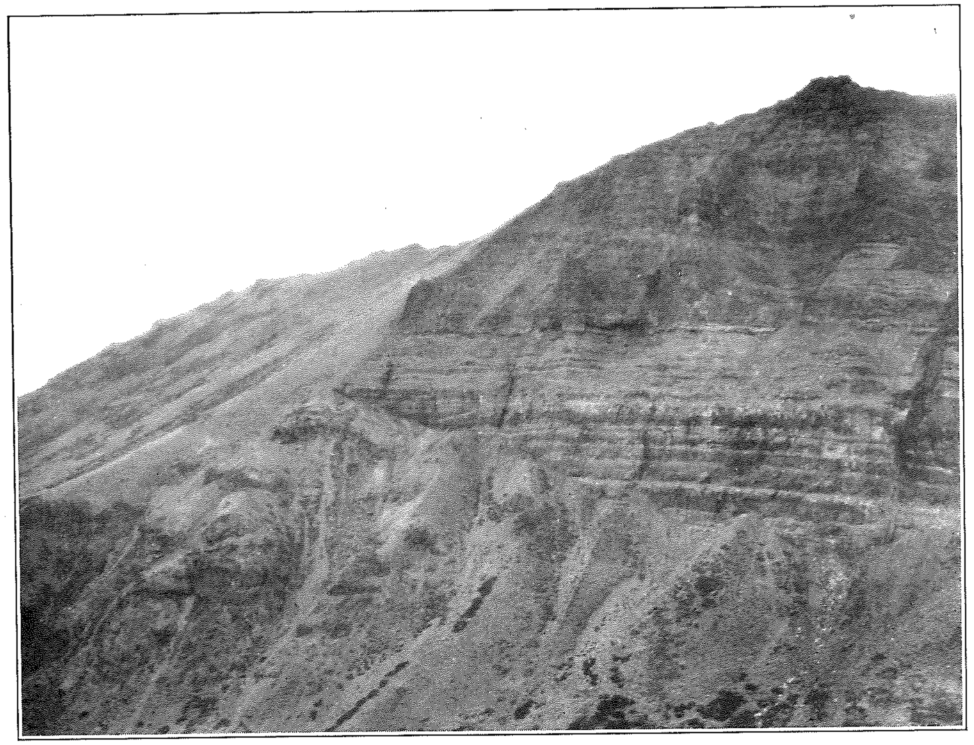

Fig. 61. The basaltic flows abutting against the surface of the andesite on the southern side of the south fork of Willow Creek.

Only to the south of Alvord Creek was the actual basal contact of the basalt observed. There, the surface of the andesite, sloping westward, is capped by a slight thickness of poorly stratified andesitic tuffs, which show no marked indication of erosion. Elsewhere, distant views of the gently undulating contact, demarking the base of the basalt as it abuts against the andesite, suggest that the domed structure, formed by the accumulation of viscous lava, had been relatively unmodified at the time of the basaltic extrusion.

General Description

This series consists chiefly of thin flows of coarsely holocrystalline olivine basalt of a rather light gray color. The rock is distinctive in the field both from a peculiar porous texture, which is quite characteristic, and from its local content both of labradorite phenocrysts ranging from 1 to 4 cm. in length, and of olivine grains, which are predominantly under 2 mm. in diameter. These flows have been found to vary in thickness from less than one foot to over 70, but they average approximately 10 feet. Although most of them retain their thickness, at least locally, without any marked variations, some of the thinner ones end in contortions.

The vesicular upper surface of each sheet is usually remarkably level, while the base as a rule is defined by the development of pipelike vesicles, which are presumably caused by the rising of air imprisoned beneath an advancing flow. At a number of localities well-defined contacts have been found to disappear on being traced laterally, although the physical characteristics such as vesicles, phenocrysts or jointing may still render the two sheets apparent (fig. 62). This merging of successive sheets is attributed to the advance of very fluid lava prior to the complete solidification of the surface of a lower flow, which had become approximately stationary.

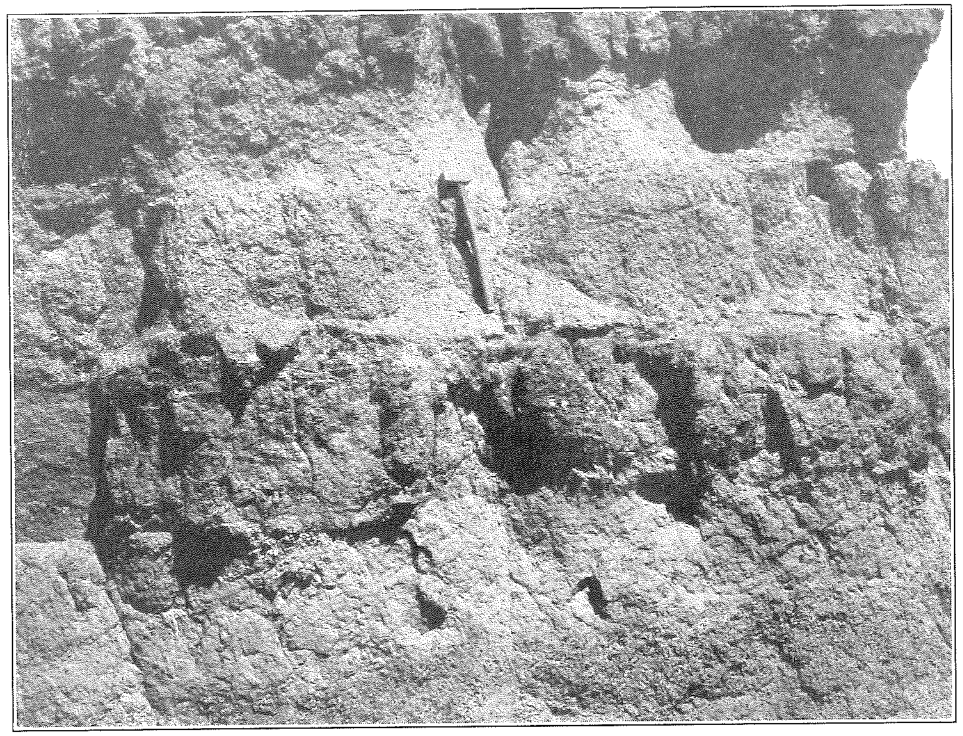

Fig. 62. Near the base of the scarp of Northern Steens about a mile to the south of the main fault spur. Thin flows of basalt may be seen partially merging.

In the valleys of both Little Alvord and Pike Creeks, the contacts of many of the lower flows of the series are irregular and indistinct. As a rule they are defined by a fairly well consolidated zone of finely brecciated scoria, which more rarely exhibits large tilted blocks of thin scoraceous layers. Into this roughly horizontal zone, the base of the overlying flow forms irregular embayments. Presumably the weight of the advancing sheet brecciated the superficially solidified surface of the underlying lava. Beneath this breccia, the basalt has locally developed a peculiar vertical spinous jointing, which the writer attributes to this minor deformation during the process of solidification.

In the lower cirque of Mosquito Creek, at the base of the series, there is a bed of well-stratified grey tuffs about 10 feet in thickness. Higher in the section there are at least two still smaller beds of buff colored tuffs that are very local in their distribution. In the valley of Alvord Creek almost in the center of the basaltic series, there is interbedded a thin mass formed of a black rather vitreous rock which contains thick laths of andesine about 2 mm. in length. Chemical analysis proves this rock to be an andesite of intermediate composition (table IX). Owing both to poor and to inaccessible exposures it has not yet been determined if this mass is a flow or a concordant intrusive. Aside from these small units, which probably comprise no more than 30 feet of an entire section, the consecutive flows on High Steens appear to be in perfect continuity, for flow breccias and basaltic ejectamenta are practically negligible.

Local variations, however, may be found in the series. To the north, vesicular flow breccias are more prevalent. Southwest of Andrews on the broad shoulder at the base of the scarp, there are exposures of extensive palagonitic tuffs containing an irregular distribution of chilled masses of typical porphyritic basalt. The evidence obtained did not permit an interpretation of the origin of this facies, although the chilling suggests aqueous agencies. In adjacent regions, other variations are due to the fact that more acidic lavas of various types are interbedded in the series.

Unlike the Columbia River Basalt, these flows do not show columnar structure, although they are cut by roughly vertical joints, which form broad, gently curving surfaces. These intersect irregularly and bound blocks, which, even in thin flows, are frequently found to be four or five feet in diameter. In general, in spite of the thinness of the flows, the jointing from its coarseness superficially resembles that of a plutonic rock more than that of a lava. Some of the major joints have also smaller systems normal to their surface.

On steep cliffs and pinnacles, the jointing causes each flow to stand out distinctly, but on the slopes where the rock has been subjected to the abrasion of sliding talus, the flows are bevelled to a fairly smooth surface and usually show no topographic expression although continuously exposed (fig. 74). This uniform bevelling is due to the relative softness of the rock. The variations in erosion may thus cause the character of an exposure to change so sharply as to suggest erroneously the presence of a fault.

DISTRIBUTION

Owing to their exceptional fluidity these basaltic flows have developed very distinctive textural peculiarities, although both their mineralogical and chemical composition is for the most part normal. These characteristics, which will be described later, distinguish the rock easily from flows of the Columbia River Basalt. Unfortunately some of the textural peculiarities appear to have persisted in the region over a considerable span of time, for similar flows in a number of instances are widely separated stratigraphically. As a whole, however, the occurrence of a rather thick series, showing the more distinctive characteristics, permits a fairly definite correlation, which is especially justified since a wide distribution may be expected from the fluidity of the lava.

On the eastern scarp of Steens and Pueblo Mountains, these flows are exposed almost continuously for a distance of about a hundred miles. Only on High Steens is the base of the series well defined, although on Pueblo Mountain its position is strongly suggested. At the southern end of this persistent scarp the flows dip to the south beneath the alluvium of the Thousand Creek valley. Farther to the south, the fault block mountains expose the older crystalline rocks with apparently the total absence of the series. The possible relationship of these flows to the Mesa Basalt of this region will be discussed later.

Northward a large section of the series is exposed continuously on the eastern scarp of Northern Steens for a distance of about 30 miles. In this region many of the flows are somewhat more aphanitic and more acidic than usual. Vesicular flow breccias are more commonly encountered. Northwest of Alberson, in the lower portion of the scarp, there is interbedded with the basalt a 300 foot flow of dark aphanitic rock which closely resembles the glassy facies of the Upper Andesite. In thin section, sodic andesine may be observed in unzoned phenocrysts which range up to 3 mm. in length. The glassy ground as a rule is clouded with indeterminable microlites, but some specimens show numerous clean-cut feldspathic laths in a pale brownish glass. A chemical analysis of the fresh rock showed the composition to be that of a fairly acidic latite (table X). Near the base of the scarp the discordant relation of the latite and its breccias indicate that this lava was derived from local sources during the outpouring of the basaltic floods.

To the north, in Harney Basin, the fault scarps decrease in height so that only the members capping the basalt are usually exposed. In a general reconnaissance of the region farther to the north, the writer has failed to observe any similar basalt. The series does not resemble any member of the extensive section now being studied by Ralph L. Lupher[13] in the Ochoco Mountains to the north of Burns between Canyon City and Crow Flat. In this vicinity, the southern slope of the structure indicates that the uppermost members of the volcanic series underwent minor deformation during at least the most recent uplift of this part of the range, but the Steens Mountain Basalt and the lower members are considered by the writer to have been confined to a broad basin that lay to the south.

To the east of Alvord Desert the elevation of the fault blocks gradually decreases and at the same time the mantling sequence of tuffs and lavas increases (fig. 63), because of the less rigorous erosion at a lower elevation. The series has no analogy to the basaltic flows exposed in the Owyhee Gorge about 70 miles to the northeast. To the southeast of Steens Mountain, the western scarp of the McDermitt Valley depression rises close to 1500 feet in height. A few basaltic flows resembling the Steens Mountain type occur both at the base and near the top of the series. Acidic lavas about 1000 feet in thickness lie in the intervening

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[13] This statement is based on a personal examination of Dr. Lupher's specimens.

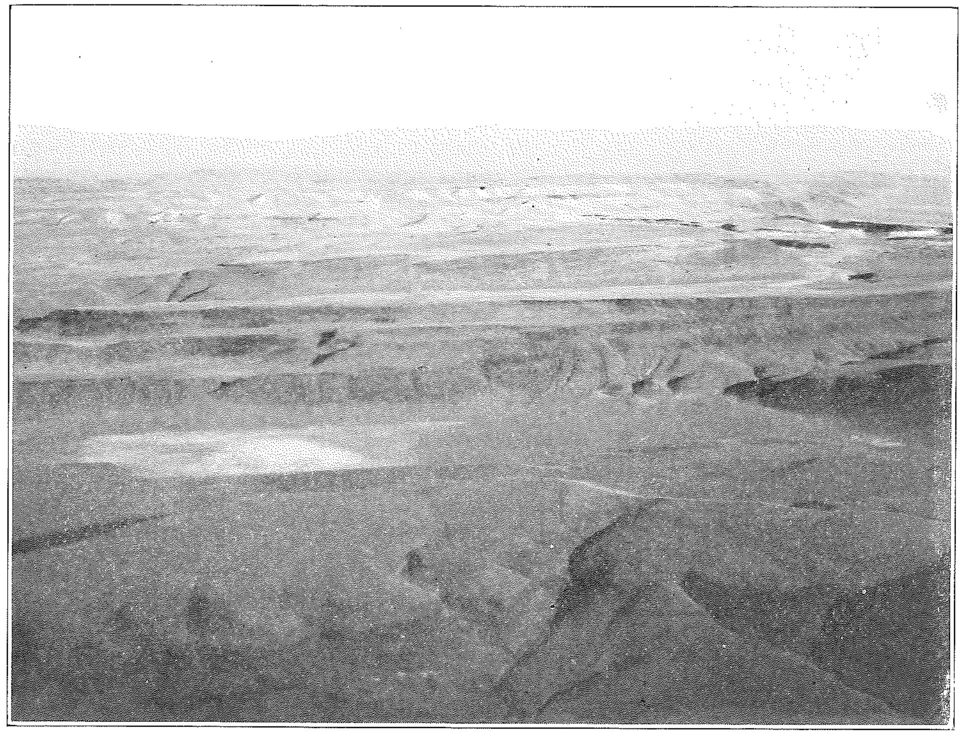

Fig. 63. Aeroplane view to the east from north of Upper Alvord basin. The light colored exposures in the middle distance are formed by the tuffaceous deposits overlying the basaltic series. In the foreground the step faults are remarkably well defined.

space. The upper basalt beneath a thin cap of glassy acidic lava consists of three flows varying in thickness from 5 to 10 feet. These flows, which are rich in phenocrysts of labradorite, are identical to characteristic types of the Steens Mountain series. This relationship suggests that the extrusion of the acidic lavas was contemporaneous with the outpouring of the great basaltic floods.

In Southern Steens, the uppermost flows on the eastern scarp can be traced across the slightly dissected horst, known as Smith Flat, to the western scarp where again the series shows a depth of over 1000 feet. Southward this curving scarp exposes the basaltic flows continuously until it ends abruptly in a transverse fault. South of this point both the geology and the topography are complicated by irregular minor faults and by the occurrence of a large homogeneous mass of dense altered porphyry forming Lone Mountain. This rock, which contains small feldspathic phenocrysts, is somewhat similar to the upper biotite-dacite of the Pike Creek Volcanic Series, and likewise erodes locally into pinnacles that suggest vertical flowage and therefore the position of a vent. The relationship of the porphyry to the southern continuation of the Steens Mountain Basalt was not determined. Southeast of Lone Mountain the exposures consist of stratified tuffs overlain by a thin layer of basalt, which presumably is a continuation of the

Mesa Basalt described by Merriam.[14] No conclusive evidence on the relationship of this basalt to the northern series was here obtained. The possibility of correlation will be considered later.

To the west near the Nevada border the surface rock is formed largely of basalt; but the exposures are not of sufficient magnitude to permit its correlation with that of Steens Mountain. Even in Guano Valley the scarps are low and the exposures unsatisfactory (fig. 64). Slightly to the north, however, in Warner Valley and still farther to the west at Abert Rim, there is exposed a series of thin basaltic flows, which show a total thickness of about 1500 feet. Although differing in detail, the series at these localities is similar to that of Steens Mountain in its general petrological characteristics as well as in its structural relationship. It may, therefore, be correlated with practical certainty. Similar flows, although not the most characteristic types, also form the small scarps bounding Pauline Marsh, but the vicinity was not studied in sufficient detail to permit a definite correlation. Farther to the west the exposure of older rocks appears to mark the margin of the volcanic basin. More flows of olivine basalt, however, are exposed in the scarp east of Klamath Lake. Although these are also somewhat

Fig. 64. Aeroplane view of the eastern scarp of Guano Valley from the north. The volcanic cone of Beatty's Butte is in the foreground.

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[14] J. C. Merriam, "Tertiary Mammal Beds of Virgin Valley and Thousand Creek in Northwestern Nevada," *Univ. Calif. Publ., Bull. Dept. Geol. Sci.,* vol. VI, pp. 36-38, 1910.

similar, they show predominantly a glomeroporphyritic texture that is quite distinctive. They may therefore be part of a separate series.

Fig. 65. Aeroplane view of Bluejoint Rim, which rises about 1800 feet as the eastern scarp of Warner Valley. R. E. Fuller and A. C. Waters, *op. cit.*, fig. 2, p. 212. Subsequently reproduced in the third edition of L. V. Pirrson's and Charles Schuchert's *Text-Book of Geology*, part I, fig. 269, p. 386.

The distribution of the sequence exposed in Warner Valley demands more detailed consideration in view of the previous correlation of this great series with the Warner Basalt when the latter was described by R. J. Russell in his paper on the Warner Range of California.[15] This range forms the eastern wall of Surprise Valley, which is a southern continuation of Warner Valley. In this region Russell found a varied sequence of andesitic flows and tuffs to be locally capped by a series of basaltic flows which show a maximum thickness of 600 feet. This basalt is in part overlain by rhyolite.

About 40 miles north of the Nevada border, an elevated portion of the eastern scarp of Warner Valley is known as Bluejoint Rim. Here, about 1500 feet of basalt is exposed above the talus (fig. 65). These flows exhibit almost all of the peculiarities that characterize the Steens Mountain series. To the south, this eastern block diminishes gradually in elevation until at a transverse fault it is sharply uplifted to form the relatively narrow horst known as Hart Mountain (fig. 66), which is bounded by a fairly low scarp on the east, and, on the west, by one that rises over 3000 feet as the eastern boundary of Warner Valley.

Hart Mountain is composed of a complex series of lavas and volcanic intrusions. The lowest exposed member of the local stratigraphic sequence consists of a few badly decomposed basaltic flows of a phenocrystic lava that is also strongly suggestive of a Steens Mountain type. This lava is overlain by rather viscous flows of acidic basalt extruded from local vents. Above this there is a varied sequence of tuffs and andesitic flows. This series is cut by a number of andesitic sheets that dip at low angles towards the center of the mountain. These intrusions, which resemble petrographically the uppermost flows, vary in thickness from a few feet to about 200. The summit of the andesite rises a few hundred feet above the subsequent basaltic flows that abut against it.

Fig. 66. Aeroplane view of the southern end of the eastern scarp of Hart Mountain. The flat top of the narrow horst is visible on the right. In the middle distance, directly to the left, the western scarp of Warner Valley may be seen.

Gradually increasing in depth towards the north these flows show a thickness of at least 700 feet at the northern end of the western scarp of Hart Mountain. Here the base is not well defined, but the lower exposures indicate that the series overlies some rather acidic basaltic flows, which are accompanied by much scoraceous lava. Judging from the evidence of viscosity, this lower basalt is of local distribution, but the overlying series from its physical characteristics appears

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[15] R. J. Russell, "Basin Range Structure and Stratigraphy of the Warner Range, Northeastern California," *Univ. Calif. Publ., Bull. Dept. Geol. Sci.*, vol. XVII, pp. 416-425, 1928.

to be the direct continuation of that which is exposed at Bluejoint Rim. At the northern end of Hart Mountain (fig. 67), these flows are locally overlain by a thickness of approximately 125 feet of stratified, light colored tuffs that are capped by a basaltic flow about 20 feet in thickness. This flow, which survives in a local butte, is also similar to a less distinctive Steens Mountain type.

Fig. 67. Aeroplane view of the western scarp of Hart Mountain at the northern end of the horst. At the top, the butte is capped by basaltic flows considered to be the northern continuation of the Warner Basalt. The slope beneath it marks the position of the tuffaceous sediments. The precipitous exposures below the shoulder are formed by the basaltic flows of the Steens Mountain series. On the right these flows show a maximum thickness of about 700 feet.

To the south, the andesite forming the central portion of Hart Mountain is also overlain by basaltic flows that in the southern portion of the mountain are about 1300 feet in thickness (fig. 68). These flows appear identical to the Bluejoint series except for the fact that phenocrysts of labradorite are less common. This lava is locally overlain by a flow of andesite filled with inclusions that appear to have a cognate origin. Lower on the scarp, exposures of this same andesite suggest a crosscutting relationship.

Fig. 68. Basaltic flows about 1300 feet in thickness capping the southern end of Hart Mountain. These flows are considered to correlate with the Steens Mountain series. Warner Lake is visible at the base of the scarp, which here is over 3000 feet in height.

The horst forming Hart Mountain is bounded on the south by a fault. Farther to the south, the scarp defining the eastern wall of Warner Valley continues with a height of about 1200 feet. This lower scarp is capped by two thin basaltic flows. Their base is hidden by coarse talus that continues downward for about 200 feet. Below this, there is exposed a dense dark grey rock filled with inclusions. This rock appears identical to that capping the southern end of Hart Mountain. Here, however, its jointing suggests that it may be an intrusive phase. Beneath this exposure, there outcrops a single thin basaltic flow that rests slightly disconformably on stratified tuffs about 400 feet in thickness. Below these beds, thin basaltic flows, extending to the talus, show a total thickness of over 200 feet. This lava is very similar to that which is exposed in the section at the southern end of Hart Mountain. Although the two localities are only about a mile apart, the lack of exposures renders it impossible to explain the absence of the tuffs beneath the andesite capping the series to the north.

On the western side of Warner Valley the relationship is simpler. In a central portion of the valley, the western scarp is lacking, although basaltic flows are exposed at the Coyote Hills, where they have been uparched by the intrusion of acidic lava.[16] To the south of Plush the scarp reappears above the alluvium,

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[16] R. J. Russell, *op. cit.*, p. 427.

and exposes a thickness of over 200 feet of basalt disconformably overlying stratified tuffs that locally show a thickness of about 100 feet. These beds appear similar to those both at the north of Hart Mountain and in the scarp to the south of the mountain.

Traced southward, the western scarp gradually increases in elevation. West of the northern end of Warner Lake it reaches a maximum of about 2300 feet (fig. 69). The block, here, is capped by about 400 feet of basalt, which is the stratigraphic continuation of the exposures to the north. The base of this uppermost basalt is covered by soil and talus which continues downward for about 300 feet. This slope ends in a persistent shoulder formed by the surface of an underlying series of basaltic flows. In this soil-clad zone, which can be traced for the length of the scarp, were found fragments of consolidated light colored tuffs. To the north in two localities tuffs outcrop at this same horizon. In consequence, this shoulder is considered to be formed by the continuation of the tuffaceous beds occurring to the north beneath the basaltic cap.

Fig. 69. The 2300 foot scarp west of Warner Lake. About 300 feet of basalt, which presumably represents the Warner Basalt, overlies tuffaceous sediments. These beds, which are thought to be part of the Upper Cedarville, form a persistent tree-clad horizon of about equal magnitude. The prominent exposures at the base are formed by a series of basaltic flows about 1300 feet in thickness. These flows are correlated with those of Steens Mountain.

Below these tuffs, however, are precipitous exposures of thin basaltic flows that appear to be identical to those forming the great cap at the southern

end of Hart Mountain on the opposite side of the graben. These flows form a continuous outcrop over 1000 feet in height. Although they also are not so porphyritic, they presumably form the southern continuation of those of Bluejoint and Abert Rims, and are, therefore, thought to be part of the Steens Mountain series.

The overlying tuffs both from their lithologic similarity and from their uniform stratigraphic relationship are considered to correlate with those to the south of Hart Mountain as well as with those in the butte at the north end of the mountain, while the basaltic flows capping these beds are thought in each of these localities to belong to the same later series. This interpretation indicates that both the upper tuffs and the basalt, which caps them, decrease in thickness to the north.

Russell considered the capping basalt on the western side of Warner Valley to be the direct continuation of the Warner Basalt, but he did not realize the presence of the underlying series. In fact, referring to this scarp, Russell states[17] "While the capping of Warner Basalt is relatively thin in that area, its debris so thoroughly covers the Upper Cedarville beds that only careful search will reveal their presence. It is likely that this condition caused Waring to indicate a great thickness of basalt in the cliff west of Warner Lake while in actuality the flow is relatively thin."

From this interpretation the capping tuffs are considered to be part of the Upper Cedarville, while the overlying flows are correlated with the Warner Basalt. The underlying series in consequence must be earlier than the Upper Cedarville, although the intervening time probably is insignificant. Southward the capping basalt appears to merge into the exposures in the Warner Range, but the relationship of the lower series to that of the Warner Range was not determined.

The difficulty in correlating isolated horizons of basalt is well shown on the eastern scarp of Surprise Valley about 15 miles to the east of Cedarville (fig. 70). Here basaltic flows about 60 feet in thickness overlie light colored tuffs which are more than twice as thick. These in turn rest conformably on thin basaltic flows about 125 feet in thickness. Beneath these is another bed of acidic tuffs forming an horizon of about the same depth. These lower tuffs rest on more basaltic flows whose base is not exposed. The uppermost basalt has no analogy to the northern lavas and is presumably later. The other two horizons, from their physical characteristics, might be correlated with the Warner Basalt and the northern series respectively, but the evidence is not conclusive. The exposure, however, at least shows the futility of classing all the basalt in the region as a single stratigraphic unit.

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[17] *Op. cit.*, pp. 439-440.

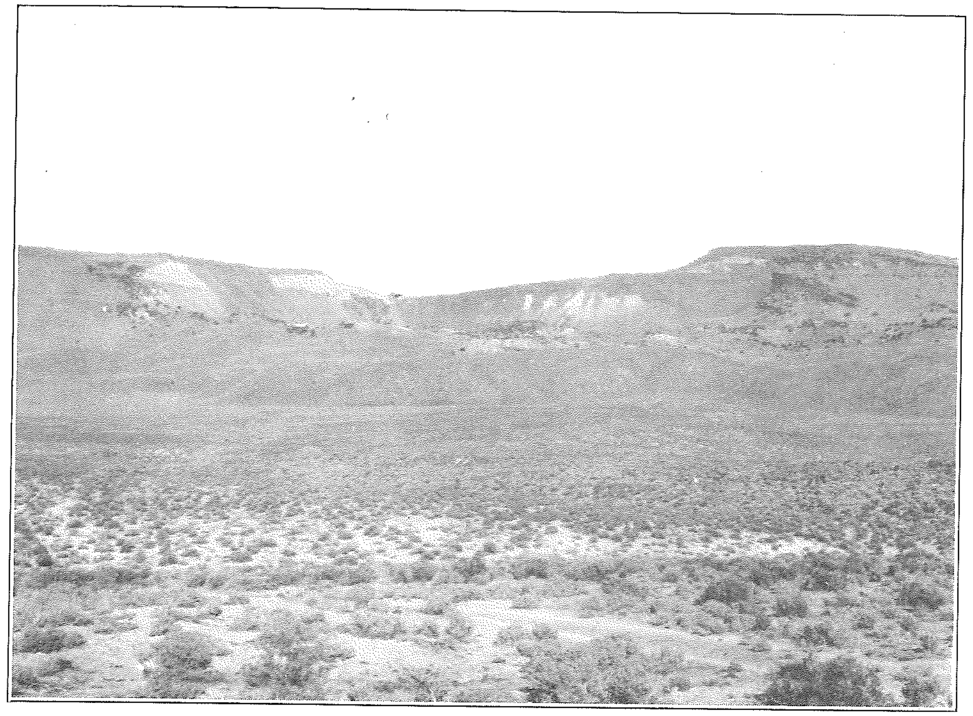

Fig. 70. The eastern scarp of Surprise Valley to the east of Cedarville. On the left the butte at the top is formed by about 150 feet of tuffaceous sediments, which are capped by a few thin basaltic flows. Beneath these beds in the center of the picture about 125 feet of basalt overlies a slightly greater thickness of stratified tuffs, which rest on still lower basaltic flows of unknown thickness.

AGE RELATIONSHIP

From fossil leaves, the Upper Cedarville Beds beneath the Warner Basalt were considered by Chaney[18] to correlate with the Mascall Formation overlying the Columbia River Basalt in the John Day Valley. They were, therefore, thought to be of Middle Miocene age. Vertebrate remains, however, found in the same beds indicated a later age. From paleobotanical evidence the Upper Cedarville beds should correlate with those of Alvord Creek at the base of Steens Mountain, but stratigraphically the entire Steens Mountain volcanic series apparently lies between them. Although the extrusion of these varied volcanic rocks probably was relatively rapid, the evidence indicates that the Mascall flora was quite persistent and possibly that it continued into the Pliocene.

To the east Russell definitely correlates[19] the Warner Basalt with the Mesa Basalt and tentatively not only with the flow exposed to the north at Railroad Ridge, but also "at least in part" with the Pueblo Mountain series. The Mesa Basalt caps the Virgin Valley Beds which contain in their lower horizons vertebrates of the Middle Miocene.[20] These lower beds should therefore be older than the Steens Mountain volcanic series. The upper strata, however, appear to be nonfossiliferous, so that the precise age of the Mesa Basalt cannot be determined. The Railroad Ridge Basalt caps the Thousand Creek Beds, which Stock[21] considers from a study of their vertebrate fauna to be fairly late in the Pliocene. These beds, however, in the opinion of the writer overlie the Pueblo Mountain series approximately conformably. This series, as previously mentioned, appears from almost continuous exposures to be the direct stratigraphic continuation of the Steens Mountain lavas.

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[18] R. J. Russell, *op. cit.*, p. 412.

[19] *Op. cit.*, pp. 416-417.

Since the basalt forming these three units at the southern end of Pueblo Mountain is not sufficiently distinctive to permit a petrographic correlation, the problem at present cannot be definitely settled, but it appears certain that the Pueblo Mountain series and the Railroad Ridge Basalt are widely separated stratigraphically. Locally, however, no definite evidence was obtained to prove whether the Mesa Basalt correlated either with the Railroad Ridge lava, which it resembles physiographically, or with the uppermost lava of the Pueblo Mountain series. The basalt exposed near the southern end of Pueblo Mountain, as well as being overlain by acidic lava and tuffaceous beds, has been intruded by a number of small sills of obsidian. Although, possibly due to this later activity, the series is quite badly altered, the effect may be too local to be used as a distinctive criterion. The facts suggest, however, that these flows have an earlier origin than the Mesa Basalt. The latter, therefore, may correlate with the Warner Basalt as Russell proposed.

In general the evidence indicates that the Steens Mountain Basalt is definitely younger than the Columbia River flows and occurred either late in the Miocene or early in the Pliocene. In the Warner Valley region the overlying tuffaceous beds, which are presumably a continuation of the Upper Cedarville, suggest that the Mascall flora continued into the Pliocene, as the vertebrate evidence indicates. The Warner Basalt, overlying these beds slightly disconformably, appears to thicken southward rather than northward as Russell suggested. On the other hand the apparent absence of the Steens Mountain series both in Virgin Valley and on Warner Range indicates that it ceases abruptly to the south, but the actual relationship to its barrier was not determined. In Virgin Valley, however, the advance of these lavas may have been halted by the great thickness of the Canyon Rhyolite, which lies on the northern side.

PETROGRAPHY

Although most of the basalt of southeastern Oregon is normal in its mineral content, it exhibits a number of textural and structural characteristics, which easily distinguish it from the more typical varieties encountered to the north on the Columbia River Plateau. Some of the most distinctive regional characteristics, however, are repeated at such widely separated horizons that they are not

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[20] Chester Stock, personal communication.

[21] *Ibid.*

of any great stratigraphic value. Petrographic correlation is also complicated by the fact that such striking features as the concentration of phenocrysts may vary rapidly in a single flow.

The extreme fluidity of the lava has already been indicated by the remarkable thinness of the flows, their level surfaces, and the merging of successive sheets. This testimony is also supported by petrographic evidence, for most of the textural peculiarities demand great mobility, which was presumably caused by an unusually high volatile content.

Although the series is composed predominantly of fairly basic olivine basalt, the perfectly fresh rock is of a far lighter shade of gray than one would expect. Most of the flows, in spite of their thinness, are relatively coarsely holocrystalline. As a rule, the texture is almost uniform throughout each sheet. In many flows, the most noticeable megascopic constituents consist of coarse plates of clear glassy labradorite and small grains of olivine, which, as a rule, has been rendered iridescent by a thin film of alteration. In most flows, however, the texture of the groundmass forms the most unusual feature.

Under the hand lens, it is clearly apparent that open cavities exist locally between the crystalline constituents. The most striking characteristic of these minute irregular cavities is the presence of delicate laths of light gray labradorite, which project into them and, in some specimens, form a network of conflicting plates. These usually range from .5 to 1.5 mm. in length. Less commonly olivine and augite come in contact with these spaces. The angular shape of the cavities resembles the interstitial areas occupied by the glassy mesostasis in some basalts.

The only established term that suggests this texture is "miarolitic," but this has been previously applied to plutonic rocks and as a rule in reference to the presence of drusy cavities lined with a crystalline coating. In this basalt, however, the cavities are not of the drusy type, and the orientation of the enclosing crystals has no reference to the space they bound. Since this texture apparently has not been previously described, the writer proposes the name "diktytaxitic" (Greek, diktuon, net, + taxis, arrangement)[22] in reference to the net-like arrangement of the feldspar laths.

"Diktytaxitic" texture is most clearly defined in coarsely crystalline rocks, where the cavities are usually relatively uniform in their distribution. In this type, however, the examination is necessarily confined to a hand lens (fig. 71), for most of the specimens are too friable to preserve their features in thin section, except when the cavities have been subsequently filled with zeolites such as chabazite or thompsonite, which have been derived from the endomorphic alteration of the feldspar. In the more aphanitic varieties, which are usually darker in color, the open spaces are more scattered in their distribution. The consolidation of this type is usually sufficient to permit the grinding of satisfactory thin sections (fig. 72).

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[22] The writer gratefully acknowledges the advice of Dr. Charles E. Weaver and Professor G. E. Goodspeed in the selection of this name.

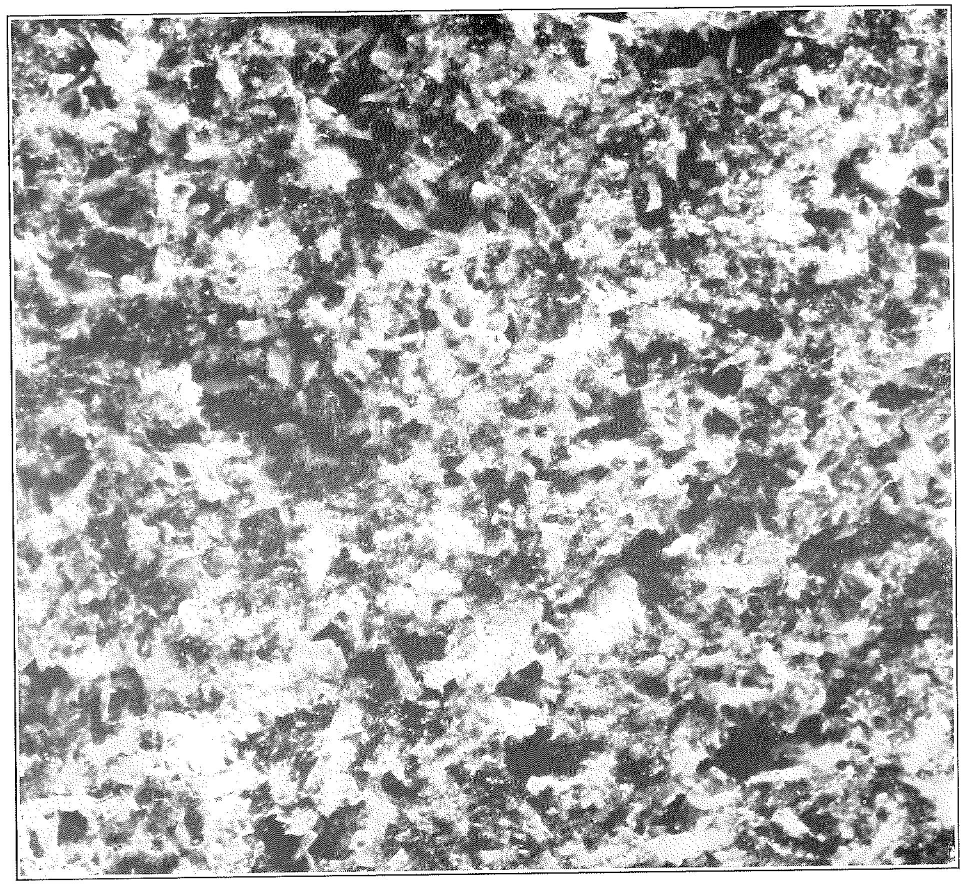

Fig. 71. Photograph (magnified 7×) of a hand specimen of a basaltic flow, which was observed near the base of the series in the valley of Mann Creek. The flow, which has a maximum thickness of about 70 feet, exhibits the coarsest crystallization observed. It shows typical "diktytaxitic" texture with labradorite laths forming an open net work of plates. The olivine occurs as clear light colored grains, while the ophitic augite is dark. The deeper cavities appear black.

The distribution of the labradorite and the size of the laths appears as a rule to be relatively uniform throughout the groundmass of an individual specimen. In part, however, the plagioclase is intergrown with ophitic augite. This mineral occurs generally in isolated patches composed of one or more crystals, and is usually enclosed by a zone containing intersertal grains of olivine and magnetite. In fact in some specimens the intersertal grains have been completely converted to iron oxide, which renders the ophimottling very apparent in thin section. These mafics are seldom enclosed in the augite.

Ophimottling is probably the most persistent feature in the texture of these basalts. It is also encountered in this region in many rocks that show no tendency of being "diktytaxitic." Some of the more aphanitic flows, however, show small intersertal grains of augite as the principal mafic, while olivine may be either absent or a very minor constituent. A few rocks show the feldspar laths imbedded locally in an almost opaque ground, which suggests decomposed glass. As a rule this substance shows parallel streaks principally defined by magnetite. This type is formed from the alteration of a mafic mineral that exhibits a single well defined cleavage, and an extinction that suggests augite.

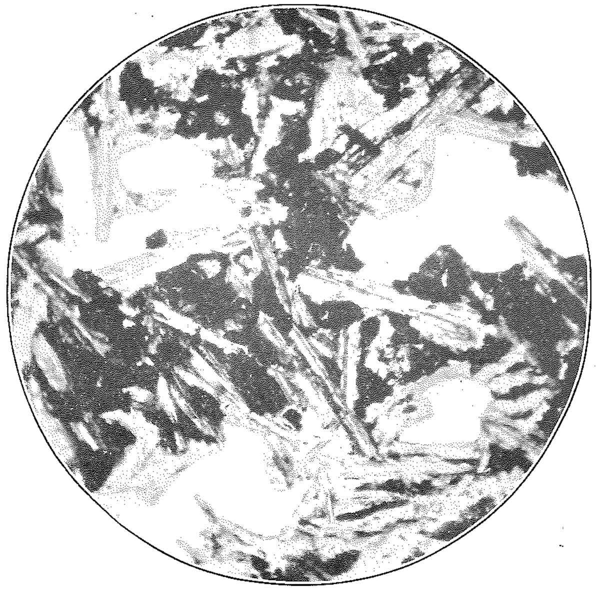

Fig. 72. Microphotograph of a thin section of a basaltic flow exposed at the northern end of Hart Mountain at the top of the lower series. "Diktytaxitic" texture is rendered more apparent by the use of the mica plate and crossed nicols. The cavities are white. The visible mafic consists principally of partially altered grains of olivine. (36×).

As a rule, however, the augite is free from alteration, while the olivine is found in various stages of decomposition. In some instances the latter appears to have been discolored to a reddish brown without being completely decomposed. The staining usually is marginal, although in a few specimens the centers of the crystals are discolored while the margins are perfectly fresh. More often the olivine is found to be altered to a dark orange-brown non-pleochroic platy mineral which exhibits parallel extinction with the same orientation as the olivine. This product is classed as iddingsite.

In some specimens, the alteration is confined to these clean-cut pseudomorphs of olivine. In others, the decomposition of this mineral has contributed to the formation of both green and orange colored deuteric residuals, which locally exhibit fibrous structure possibly due to the crystallization of chlorite. These substances, which are at least similar to chlorophaeite, locally fill the "diktytaxitic" cavities and even intrude the cracks in the feldspar. The rock thus impregnated is of a very dark color and forms a marked contrast with the unaltered facies. In a number of flows a "sheaf-and-core structure"[23] is defined by a localization of this type of alteration in the center of the major joint blocks. A discussion of the origin of this remarkable feature will be treated in detail in a later paper.

The phenocrysts of olivine are usually less than 2 mm. in diameter, but in some flows their mass was sufficient to permit gravitational accumulation in the very fluid lava. The phenocrysts of plagioclase are far more variable in size. They occur principally as plates, which locally attain a diameter of over 4 cm. In many flows they are relatively uniform in their concentration and show no tendency to alignment. In this type a radial grouping of the coarse crystals is quite characteristic (fig. 73). In some flows, however, they are very variable in their concentration and occur either as swirls or in roughly horizontal zones. Some of these variations are attributed to the merging of successive sheets of slightly different composition, while others are considered to be due to gravitational action. These petrogenetic features as well as the consideration of the origin of the horizontal segregations, which are quite common in the Steens Mountain Basalt, are also left to a subsequent publication.

Fig. 73. A basaltic flow near the base of the series to the south of Alvord Creek, showing the typical radiating clusters of rather small plates of basic labradorite. A ¾ inch disk furnishes the scale.

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[23] "Tertiary and Post-Tertiary Geology of Mull," *Memoirs of Geol. Surv. Scotland*, pp. 261-264, 1924.

The plagioclase, which in most flows forms about 60 per cent of the mineral content, shows little or no tendency towards zonal growth. The composition appears to range between an intermediate and a calcic labradorite with a preponderance of the latter. Most of the crystals of the groundmass, as well as the phenocrysts, show a distinct crystal outline. In a number of specimens, however, feldspar also occurs locally as interstitial grains. These poorly defined grains invariably show an indistinct wavy extinction and an index of refraction which is but slightly less than the crystals which they enclose.

Many of the ill-defined sheets near the base of the series are amygdaloidal, with thompsonite and chabazite filling amoebaform vesicles. As their composition suggests, these zeolites are derived from the decomposition of the plagioclase. This alteration is considered to be endomorphic and to have been caused by the retention of the volatiles beneath the overlying sheets which had advanced prior to solidification. Locally, however, calcite and both chalcedonic and crystalline quartz are found either as amygdules or as a partial filling of irregular cavities between the flows. Scolecite was observed in association with the calcite. This deposition, at least in part, has probably been caused by later hydrothermal activity. In addition hyalite is quite commonly encountered as a coating on the major joint cracks.

Chemical analyses of this basalt (table VIII) indicate that it is fairly constant in composition, although at least some of the upper flows are slightly more acidic. Flows of a similar type, however, occur sporadically throughout the series. The specimens analyzed fall predominantly in the subrang of Hessose, which demands a moderately high content of lime. Although typical basalts, they show a far higher content of alumina and titanium oxide than usual. Since these constituents should not be expected to add to the fluidity of the flows, their physical characteristics are all the more remarkable. In the calculation of the norms, the high content of ilmenite and magnetite, and in some cases hematite, depletes the ferrous iron and thereby results in the development of residual quartz, in what are in reality fairly basic basalts.

The alumina is explained by the unusually high feldspar content, which causes the rock to approach an effusive equivalent of anorthosite. It is not determined, however, in what mineral the titanium occurs. The augite as a rule is colorless or slightly brownish in thin section and does not suggest a titaniferous variety. A partial analysis of some of the olivine, which is not included, shows only a trace of titanium dioxide. It is therefore considered to be present as ilmenite, as the norm suggests, although the characteristic alteration to leucoxene was not observed.

TABLE VIII

PART 1

	I	II	III	IV
Silica	47.20	47.60	48.46	51.30
Alumina	18.08	18.27	18.09	16.06
Ferrous Oxide	3.29	8.93	8.59	9.17
Ferric Oxide	7.77	1.91	2.20	1.95
Magnesia	4.15	6.54	4.26	3.58
Lime	9.96	8.70	9.75	7.44
Soda	2.82	3.11	2.99	3.15
Potash	.93	1.03	.92	1.63
Water above 105° C	1.30	.80	.50	.74
Water at 105° C	1.55	.33	.40	.40
Titanium Dioxide	2.60	2.20	3.05	3.25
Carbon Dioxide	none	none	none	none
Phosphorus Pentoxide	.29	.27	.46	1.20
Sulphur	trace	trace	.06	.05
Manganese Dioxide	trace	.39	.22	trace
	99.94	100.08	99.95	99.92

I. Basaltic flow near the base of the cirque in Mosquito Creek at about 2,500 feet below the summit. Analyst W. H. Herdsman.

II. Basaltic flow on the southern side of the cirque of the south fork of Alvord Creek at about 1,000 feet below the summit. Analyst W. H. Herdsman.

III. Basaltic flow about 200 feet below the summit of the highest scarp bounding Upper Alvord Basin on the north. Analyst W. H. Herdsman.

IV. Basaltic flow capping the scarp north of Upper Alvord. Analyst W. H. Herdsman.

PART 2

	I	II	III	IV
Quartz	3.48	.....	.24	5.16
Orthoclase	5.56	6.12	5.56	9.45
Albite	23.58	26.20	25.15	26.72
Anorthite	33.92	32.80	32.80	25.02
Diopside	10.58	6.80	9.83	3.93
Enstatite	5.70	.....	.....	.....
Hypersthene	.....	4.45	15.10	16.84
Olivine	.....	14.82	.....	.....
Magnetite	3.02	2.78	3.25	2.78
Hematite	5.76	.....	.....	.....
Ilmenite	5.02	4.26	5.78	6.08
Apatite	.67	.67	1.34	2.69
Sulphur	.....	.....	.06	.05
Water	2.85	1.03	.90	1.14
	100.14	99.93	100.01	99.86

Norms calculated from the analyses in Part I:
I. Hessose, C. I. P. W. Symbol, II".'5."4.4.
II. Hessose, C. I. P. W. Symbol, II(III).5"."4.4.
III. Hessose, C. I. P. W. Symbol, II".5."4.4.
IV. Hessose, C. I. P. W. Symbol, II"."5.(3)4."4.

Basaltic Intrusions

Basaltic dikes are frequently encountered on the eastern scarp of High Steens. A number of these may be observed to traverse the underlying tuffs and lavas, but some of the most prominent ones are exposed cutting the basaltic series in the lower cirques. Both the size and the orientation of these dikes vary greatly. Most of them, however, are vertical and the larger ones are confined to an approximate north and south axis (fig. 6).

Many of these dikes show large phenocrysts of labradorite and presumably form the feeders for the overlying basaltic series, which they closely resemble. Commonly, however, they lack the open texture, and resemble the altered phases of the flows, for the retention of volatiles has resulted in the impregnation of the rock with deuteric residuals. In some instances the alteration is very irregular and in other cases confined to well-defined vertical bands. In some dikes, chlorophaeite occurs as minute globules, which are usually concentrated in the vertical bands. The marked contrast in the resistance of the two facies may give the appearance of a multiple dike. The localization of the alteration appears to be due to the irregular distribution of the volatiles at the time of consolidation. The alignment may be explained by marginal chilling, but the evidence is not conclusive.

A number of the larger dikes are formed by successive intrusions and hence are true multiple dikes. The largest of these multiple dikes is well exposed near the base of several of the lower cirques and on the intervening divides. It may be traced for many miles as a wall which is usually about 50 feet in width and locally rises close to 100 feet in height (fig. 74). Although the exposures are not continuous, Waring[24] considered the prolongation of this large dike to form a prominent exposure near the southern end of the eastern scarp bounding Smith Flat.

In spite of the numerous basaltic dikes exposed on the eastern scarp of High Steens, an actual locus of extrusion was observed only at the base of the Mosquito Creek cirque on its northern side (fig. 75). Unfortunately, the locality, especially to the east, is covered either with talus or with morainal material, which renders it impossible to determine if the vent were formed by a true fissure eruption. The exposure shows a coarse basaltic breccia enclosed in a reddish vesicular lava, some of which is of a brilliant shade. At its western margin, this lava crosscuts the previously mentioned bed of grey stratified tuffs, which is interbedded near the base of the series. Upwards, to the west, the basalt merges into thin flows, some of which are less than a foot in thickness (fig. 76). Jointing and differential weathering causes these flat sheets to be very apparent, but on examination the actual contacts are locally difficult to determine. These sheets are considered to have been formed by successive gushes of lava that was so fluid that it was able to attain a relatively level surface and to become approximately stationary before the next sheet submerged the partially solidified surface.

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[24] G. A. Waring, "Geology and Water Resources of the Harney Basin Region, Oregon," *U.S. Geol. Survey, Water-Supply Paper* 231, p. 22, 1908.

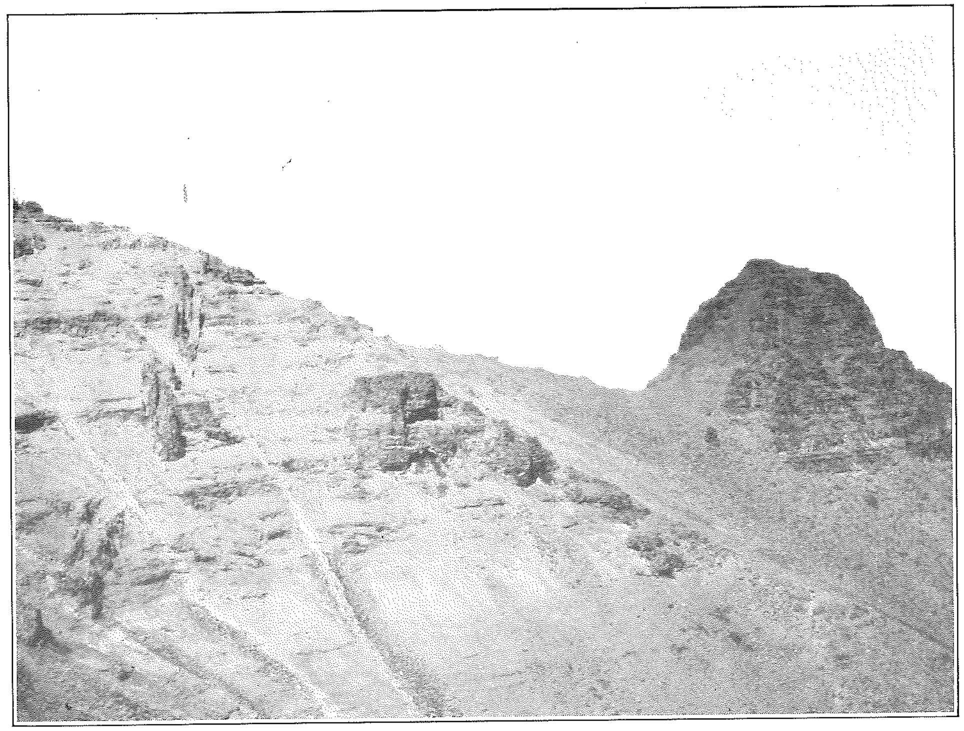

Fig. 74. On the left may be seen the broad multiple basaltic dike cutting the basaltic series in the cirque of the south fork of Alvord Creek. The saddle marks the position of the 200 foot normal fault, which dips westward at about 80°. The prominence on the right rises about 500 feet above the saddle. The flows exposed to the west have been bevelled by sliding talus.

Although most of the basaltic dikes are approximately vertical, two small ones, in the fault zone between Toughey Creek and Pike Creek, follow an inclined course parallel to the planes of the step faults and dip eastward at about 60°. The exposures are not sufficiently distinct to prove if either of the dikes were displaced. It is probable that these dikes were either contemporaneous with or subsequent to the initial movement on the faults, and therefore far later than the main basaltic series. One of these dikes, on coming in contact with a tuffaceous bed, follows it for about 100 feet and then cuts upwards with the same inclined orientation as its lower part. These dikes are probably contemporaneous in origin with the small sills of similar composition, which intrude the lower tuffs in Pike Creek.

The large basic sill exposed in the valley of Indian Creek, beneath the southern continuation of the upper flow of platy rhyolite, is also considered to be of late origin. Its precise relationship has not been determined, but it is remarkably fresh and shows no resemblance to any of the lavas observed on the mountain. Megascopically its central facies suggests a coarsely holocrystalline rock. Petrographically it consists of about equal quantities of sodic labradorite and pale brownish augite in a rather opaque grayish or brownish ground, which forms

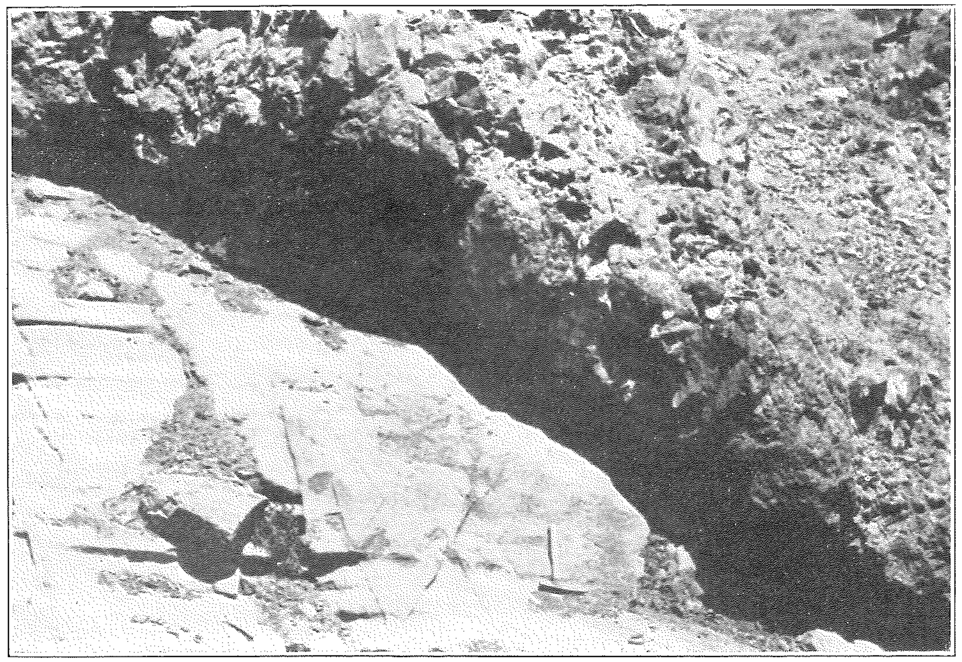

Fig. 75. The flaring margin of the basaltic vent crosscutting the stratified tuffs interbedded with the lower basaltic flows on the northern side of the Mosquito Creek cirque.

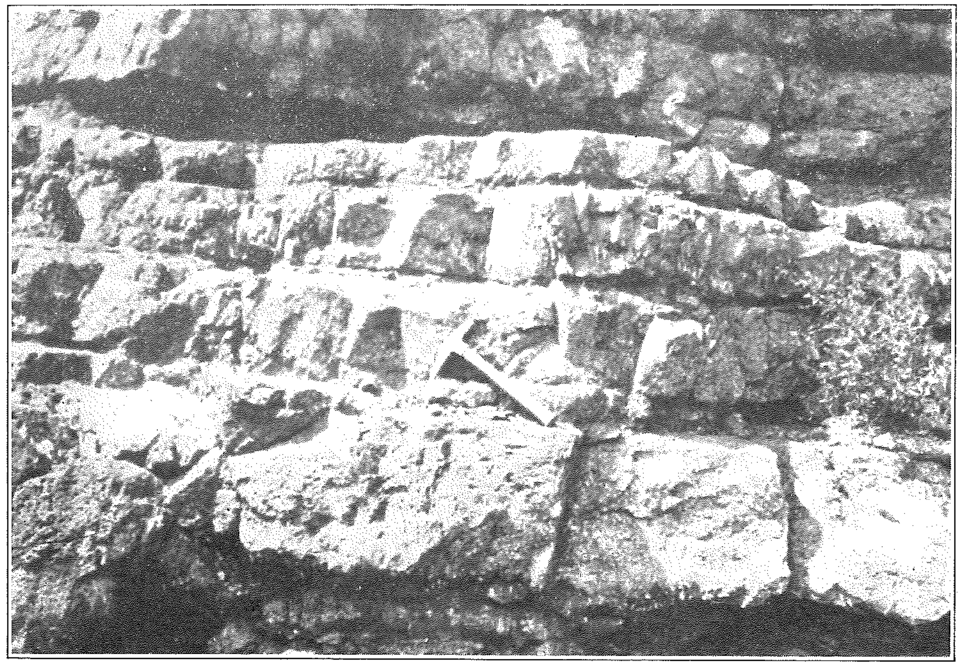

Fig. 76. Thin basaltic sheets extruded from the vent in the Mosquito Creek cirque.

about 30 per cent of this facies. This ground contains a high content of magnetite, chiefly in thin skeleton plates, which attain locally a diameter of nearly 4 mm. A few laths of plagioclase are also over 3 mm. in length, although they average approximately 1 mm., and are but slightly coarser than the augite with which they are associated. Most of the plagioclase and some of the pyroxene show euhedral faces. The minerals exhibit no predominant alignment and no tendency to ophitic intergrowths. The principal accessory appears to be an indeterminable zeolite, which has been partially altered.

THE LATER SERIES

On top of Northern Steens some fragments of acidic lava suggest that a capping flow of that type may have been removed by erosion. On High Steens the basaltic flows form the surface of the block. South of Smith Flat, however, the rugged crest of Southern Steens is capped by reddish brown lava which is disconformable to the basaltic series. This flow, which is at least 150 feet in thickness, appears to be a typical trachyte. In thin section small phenocrysts of orthoclase are found in a ground formed of indistinct roughly aligned feldspathic microlites, which were not determinable.

In the southern part of Pueblo Mountain a flow of grey rhyolite caps the basaltic series. This flow, which is about 300 feet in thickness, shows partially resorbed phenocrysts of quartz about .2 mm. in diameter in a cryptocrystalline groundmass. It was once suggested by Merriam[25] that this flow might correlate with the Canyon Rhyolite to the south. Aside from the increased discrepancy between the ages of their overlying sediments, which has already been discussed, chemical analyses of the two lavas suggest a distinctive origin (table IX).

East of Alvord Desert the basaltic series exposed in Upper Alvord Basin gradually decreases in elevation with a gentle dip to the south. Before the uppermost flows of this Steens Mountain Basalt disappear beneath the alluvium, an overlying series of tuffs and lavas are exposed above them. This series, which shows a thickness of almost 600 feet, forms a butte about four miles in length (fig. 77). On the north it is completely truncated by an erosional escarpment. At the southern end of the butte, a far lower escarpment marks the removal of the upper half of the series. Farther to the south the lower members continue to form the fault scarp for several miles, until they end abruptly where the underlying basalt is again exposed by a transverse fault.

The lowermost exposures above the basalt are formed of a black, rather vitreous lava, which was proved by chemical analysis to be a latite, very similar to that interbedded with the basalt on Northern Steens (table X). In thin section it shows roughly aligned feldspathic microlites in a glassy ground. This latite forms an exposure about 200 feet in thickness and can be traced southward at least five miles. From its persistence it appears to form a stratigraphic unit, but its characteristics, wherever observed, suggest that it directly overlies a fissure-like vent which was later paralleled by a very straight north-south fault.

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[25] J. C. Merriam, "Tertiary Mammal Beds of Virgin Valley and Thousand Creek in Northwestern Nevada," *Univ. Calif. Publ., Bull. Dept. Geol. Sci.*, vol. VI, p. 32, 1910.

TABLE IX

Part 1

	I	II	III
Silica	58.45	73.80	78.60
Alumina	18.25	12.45	9.94
Ferrous Oxide	4.55	.93	.85
Ferric Oxide	1.80	1.53	.74
Magnesia	2.38	.28	.11
Lime	6.32	.96	.70
Soda	3.56	3.72	3.30
Potash	2.83	5.35	4.33
Water above 105° C	.90	.40	.40
Water at 105° C	.40	.30	.70
Titanium Dioxide	.40	.12	.24
Carbon Dioxide	none	none	none
Phosphorus Pentoxide	trace	trace	trace
Sulphur	.07	trace	trace
Manganese Dioxide	trace	trace	none
	99.91	99.84	99.91

I. Andesitic sheet of undetermined relationship interbedded with the Steens Mountain Basalt about 1,500 feet below the summit. Analyst W. H. Herdsman.

II. Rhyolite flow capping the series at the southern end of Pueblo Mountain. Analysts W. H. and F. Herdsman.

III. The Canyon Rhyolite in Virgin Valley underlying the Virgin Valley beds. Analysts W. H. and F. Herdsman.

Part 2

	I	II	III
Quartz	8.52	30.06	41.76
Orthoclase	16.68	31.14	25.58
Albite	29.87	31.44	26.72
Anorthite	25.30	1.67	.....
Acmite	.....	.....	.92
Diopside	5.07	2.26	2.13
Wollastonite	.....	.12	.46
Hypersthene	9.58	.....	.....
Magnetite	2.55	2.09	.46
Ilmenite	.76	.15	.61
Sulphur	.07	.....	.....
Water	1.30	.70	1.10
	99.70	99.63	99.74

Norms calculated from the analyses in Part I:

I. Shoshonose, C. I. P. W. Symbol, "II."5.3.3".
II. Liparose, C. I. P. W. Symbol, I."4.1".(2)3.
III. Alaskose, C. I. P. W. Symbol, I.3".1."3.

The latite is capped with vesicular breccias, which fluctuate gently at least 50 feet in elevation. In a manner rather similar to that of the upper andesite on Steens Mountain, the breccias are injected by aphanitic lava showing irregular platy jointing that is predominantly highly inclined. The breccias with their elongate vesicles are not confined to the near surface phase, but also occur in broad vertical zones, into which the dense lava both grades and injects.

Unfortunately the contact with the basalt is not exposed, but vertical flow structure, occurring within 15 feet of the surface of the uppermost member of

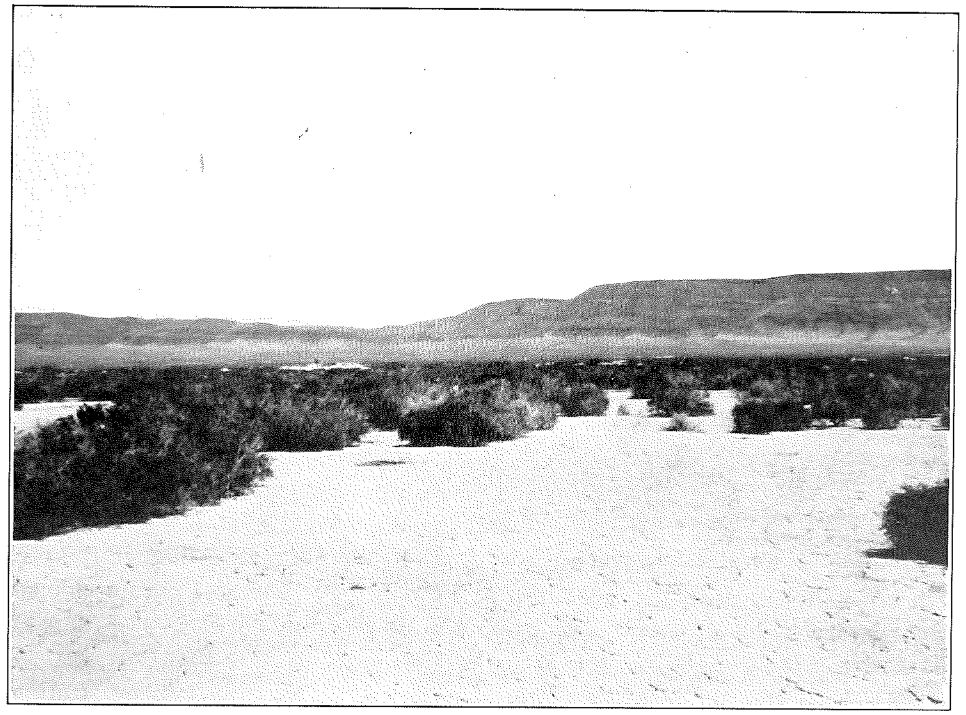

Fig. 77. The scarp east of Alvord Desert, showing in the center the northern end of the butte in which the later members of the series survive. To the left the structure may be seen to be gently dipping southward. The basaltic flows capping the butte are slightly non-conformable.

TABLE X

Part 1

	I	II	III
Silica	65.20	62.30	78.55
Alumina	15.80	15.22	9.82
Ferrous Oxide	4.35	2.73	.92
Ferric Oxide	.89	3.56	1.11
Magnesia	.13	.82	.14
Lime	3.40	3.32	.68
Soda	4.13	4.00	3.57
Potash	3.90	3.49	4.34
Water above 105° C	.50	2.30	.50
Water at 105° C	.15	1.40	.30
Titanium Dioxide	.12	.34	.18
Carbon Dioxide	none	none	none
Phosphorus Pentoxide	.19	.19	trace
Sulphur	none	trace	trace
Manganese Dioxide	.13	.23	none
	99.91	99.90	100.11

I. Latite flow interbedded in the basaltic series near the base of the scarp of Northern Steens, northwest of Alberson. Analysts W. H. and F. Herdsman.

II. Latite exposed at the base of the scarp east of Alvord Desert. Analysts W. H. and F. Herdsman.

III. Rhyolite flow about 300 feet below the top of the series exposed in the scarp east of Alvord Desert. Analysts W. H. and F. Herdsman.

PART 2

	I	II	III
Quartz	15.06	17.04	40.74
Orthoclase	22.80	20.57	25.58
Albite	35.11	34.06	26.20
Anorthite	13.07	13.07	.....
Acmite	.....	.....	3.23
Diopside	2.60	2.04	3.13
Hypersthene	8.70	3.35	.....
Magnetite	1.39	5.34	.....
Ilmenite	.15	.61	.46
Apatite	.34	.34	.....
Water	.65	3.70	.80
	99.87	100.12	100.14

Norms calculated from the analyses in Part I:
I. Adamellose, C. I. P. W. Symbol, (I)II.4".2".3.
II. Toscanose, C. I. P. W. Symbol, I(II).4".2".3.
III. Alaskose, C. I. P. W. Symbol, I.3".1."3.

the basaltic series and at the same level, suggests that the latite is crosscutting. In addition an adjacent "diktytaxitic" flow is highly altered. Although the relationship is not distinct, the latite is considered to have welled from an elongate vent, paralleled by the scarp, and to have formed a thick viscous flow capping the basalt.

At the northern end of the butte, this dark breccia is overlain by stratified tuffs which are about ten feet in thickness. These beds locally exhibit a high content of feldspar and a minor amount of biotite. These tuffs have been indurated and altered to a brilliant red both by a thin indistinct glassy sill, at about two feet below the top, and by an overlying 50 foot basaltic flow. The latter has been badly decomposed, probably due to deuteric alteration as well as to the subsequent intrusion of the sill.

Above this basalt is a flow of rhyolite which outcrops persistently to the south for approximately five or six miles. At the northern end of the butte, the flow is about 40 feet in thickness. At the southern end it is locally considerably thicker, but here the underlying basalt is absent and the rhyolite rests on light grey tuffs, which overlie the latite. Still farther to the south, the rhyolite appears to be in direct contact with the lower lava and varies greatly in thickness, depending on the irregularity of the surface over which it advanced. In spite of the fact that the rhyolite appears to have been relatively fluid, chemical analysis shows it to have been highly silicic (table X). Quartz phenocrysts 1 to 2 mm. in diameter form less than five per cent of the rock.

Above the rhyolite there are light colored stratified tuffs, which at the southern end of the butte, are close to 200 feet in thickness. To the north, these beds thin gradually to about half that figure. These sediments are overlain by a small series of basaltic flows. Viewed from the desert, these capping flows may be seen to become slightly nonconformable as the northern end of the butte is approached. Here, the sediments and the underlying series dip southward at about 2°, while the uppermost flows remain approximately horizontal.

Aside from this variation in inclination, the irregularity of the surface on which the basalt was extruded demands a slight erosional interval. Owing to this irregularity the series varies from about 75 to 200 feet in thickness. Individually the flows range from 10 to 25 feet in depth. Although these thin flows may be traced individually for several miles, they were relatively viscous in comparison to the Steens Mountain Basalt.

This viscosity is apparent in the field not only from the absence of the "diktytaxitic" texture, but from the elongation of the vesicles and from the presence of surface features that indicate movements in a partially solidified lava. In thin section some specimens show a marked alignment of feldspar and in addition exhibit an ophitic crystallization of a light colored pyroxene in localized patches, between which are small altered grains of a mineral suggesting olivine. Aside from this a few larger grains of olivine were observed.

The highest portion of the scarp of the lower shoulder of Southern Steens shows a repetition of the upper part of the series exposed to the north, on the opposite side of the desert, aside from the fact that each member is of greater magnetite. A thick flow of gray rhyolite is overlain by light colored tuffs which in turn are capped by nonporphyritic basalt. Farther to the north, a dark aphanitic lava shows distinct vent characteristics. A complex system of intersecting faults renders it almost impossible to determine the relation of these members to the main sequence. Similar rocks were not observed either on the high scarp to the west or on the still higher one bounding Smith Flat. It is possible, however, that this series may correlate with that east of Alvord Desert, and that it may represent a graben filling which has been faulted.

To the west of Steens Mountain various lavas and coarse tuffs of local distribution form the capping rock, but it is usually impossible to determine their exact stratigraphic relationship to the great basaltic series. In Warner Valley, north of Bluejoint Rim, the overlying series forms a low scarp, which rises about 400 feet in height. Unfortunately the exposures are for the most part unsatisfactory. To the south a fault of undetermined displacement masks the precise relationship to the Bluejoint series, for the basalt is not exposed at the base of the low scarp and no remnant of the northern series was observed on the up-thrown side.

In several sections this northern series was found to vary considerably. In general, however, it consists of light buff colored tuffs with which a few minor basaltic and acidic flows are interbedded. The lower basaltic flows are of a rather aphanitic dark colored type accompanied by scoraceous flow breccias. These basal flows have no analogy to those capping the Bluejoint Rim a few miles to the south. How far they are separated stratigraphically could not be determined. It is of interest to note, however, that two small "diktytaxitic" flows, rather similar to those of Bluejoint Rim, occur near the top of this small northern series above the tuffs.

Towards the northern end of the scarp, the series dips northward at about 1°. Here it has been roughly bevelled by erosion to an irregular horizontal surface and has been unconformably overlain by a coarsely jointed acidic flow, which shows cryptocrystalline quartz in a highly kaolinized felsitic ground. This lava is remarkably high in lithophysae and in irregular gas cavities. It probably owed its great fluidity to a very high volatile content. About 20 miles to the north in Buzzard Canyon a similar lava may possibly be part of the same flow. This, however, is overlain by two thin basaltic flows, which are capped by a well-consolidated breccia consisting largely of coarse pumiceous and glassy fragments. This uppermost horizon, which is widespread throughout Harney Basin, shows some local features that suggest flowage. It appears to be the only member of the volcanic sequence, here described, that is also represented in a section now being studied by Ralph L. Lupher in the region to the north between Canyon City and Crow Flat.

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