THE PETROLOGY AND STRUCTURAL RELATIONSHIP OF THE STEENS MOUNTAIN VOLCANIC SERIES OF SOUTHEASTERN OREGON

by

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THE PETROLOGY AND STRUCTURAL RELATIONSHIP OF THE STEENS MOUNTAIN VOLCANIC SERIES OF 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 portion of the Great Basin. (Plate I) Rising gently from the northwest in an even slope some twenty-five miles long, formed by the slightly dissected surface of a great tilted fault block, the mountain ends abruptly on the east in a valley glaciated fault scarp, which drops precipitously to Alvord Desert, fifty-five hundred feet below. The summit, with an elevation of approximately ten thousand feet, lies in the south central portion of Harney County, a little less than fifty miles north of the Nevada line at a point approximately midway between the California and the Idaho boundaries. (Figure 1)

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. The author of this original name is apparently

Plate I. The area shown in the sketch map in Figure 1 is here superimposed on a section of "Physiographic Diagram of the United States" by A. K. Lobeck, Chicago, 1921. The scale is approximately one hundred miles to an inch.

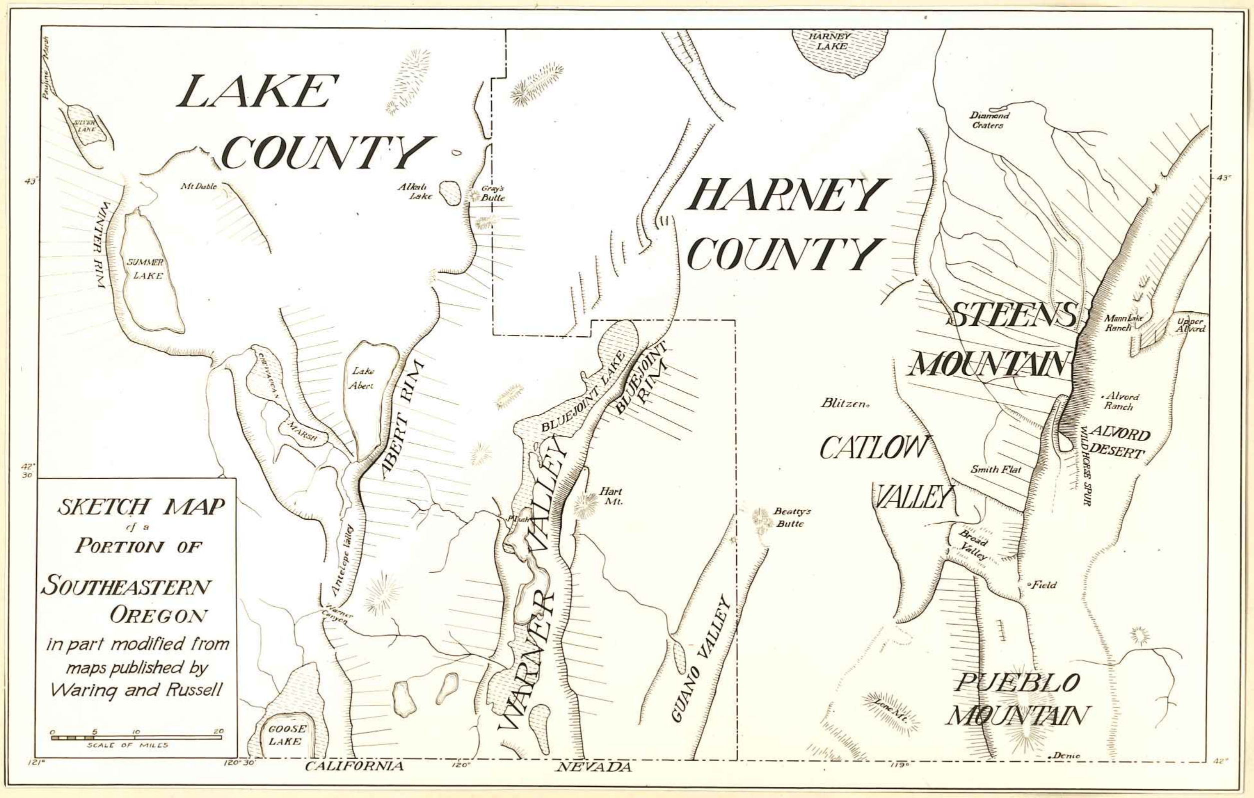

Figure 1.

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

unknown. Subsequently it was corrupted to "Steins". Popular usage of the present generation has, however, firmly established the derived appelation "Steens Mountain" for at least the last twenty years.

Field Work

The writer's field work in the region has been distributed over five 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 by the major fault scarps.

Subsequently proof of the origin of the structure formed the essential objective. This culminated in 1929 in a joint publication with Mr. Aaron C. Waters of Yale University 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.

Culture

Steens Mountain and the adjacent district is very sparsely populated, owing to the fact that its principal

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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 (1929), pp. 204-39.

industry consists in the grazing of sheep on the scanty vegetation of the higher mountains. This industry is largely in the hands of the Spanish Basques. There are also, however, in the region several well established cattle ranches, which are irrigated by the larger streams. The towns named on many of the maps usually consist of a single store, which contains the post office. In addition, there are numerous deserted homesteads that were mostly established about twenty-five years ago.

Accessibility

A network of roads in the country enables one to motor within walking distance of almost any topographic feature. Some of the main roads have been improved. (Plate II) Many of them, however, consist merely of trails worn in the sage brush. Locally these have been rendered very rough by occasional cloud-bursts. Owing to the trend of the faults, the chief difficulty in the area lies in going east and west.

To the north, a branch line of the Union Pacific ends at Burns about twenty 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 to 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 several thousand inhabitants. They are all on well con-

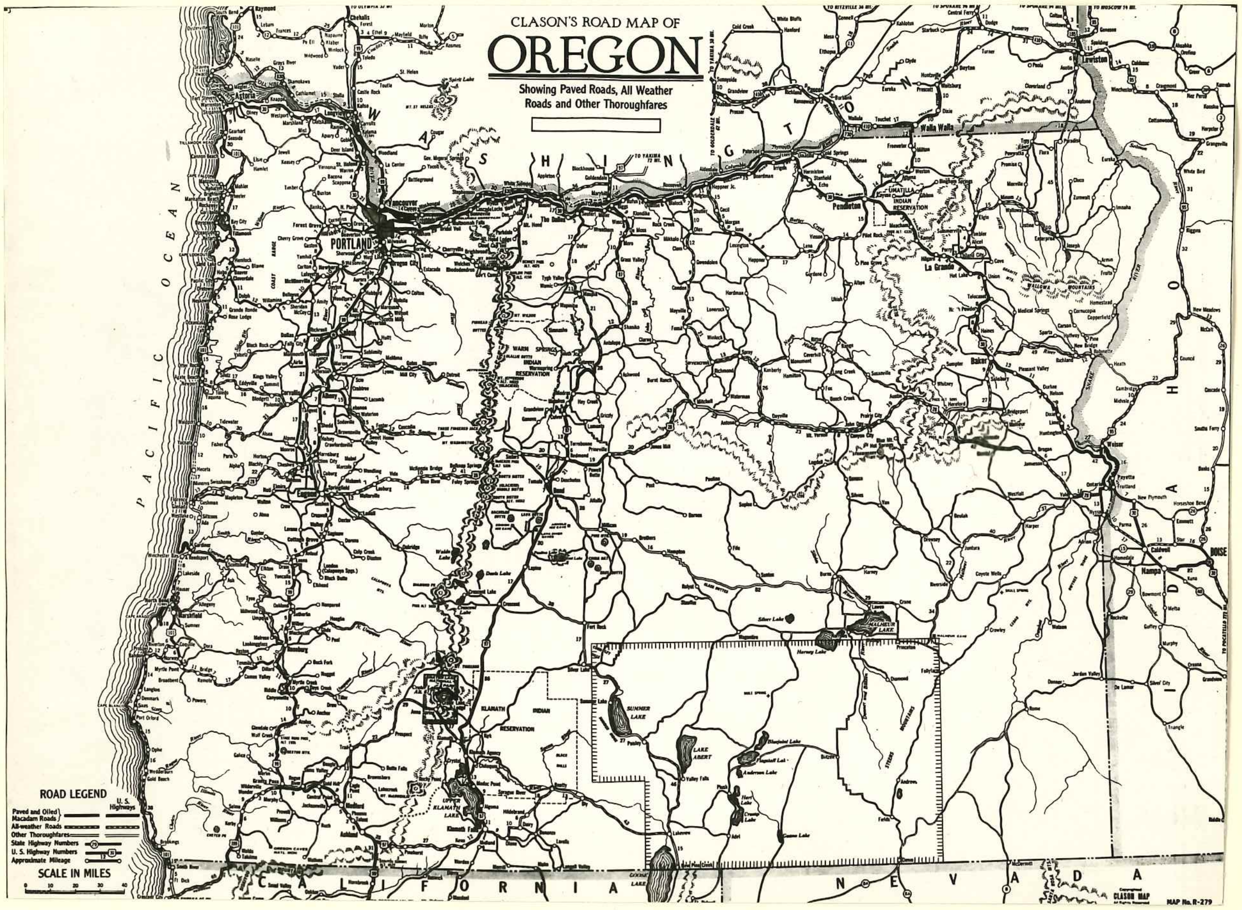

Plate II. The area shown in the sketch map in Figure 1 is here superimposed on a road map of the state of Oregon. The roads from Blitzen both westward to Warner Valley and southward through Guano Valley were inserted by the writer. The innumerable minor trails are omitted.

structed 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 blocks liberated by this faulting has resulted in the formation of seven major depressions which are bounded usually by precipitous fault scarps varying in height from a few hundred feet to several thousand. 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 three hundred feet above the silt, which in itself is probably many hundred feet in depth. The surface of these deposits, varying but slightly in the different basins, is over four thousand feet in elevation.

Since the melting of the Pleistocene glaciers on some of the higher mountains, the lakes have gradually diminished until now their former presence is indicated chiefly by playa flats, which usually have only slight marginal vegetation. (Figure 2) In recent years most of the active 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 precipitation.

These depressions, or grabens, are bounded longitudinally by the steep scarps of the gently tilted fault blocks that lie between 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 usually characteristic 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 (Figure 3) and the western side of Hart Mountain, which forms the eastern wall of Warner Valley. Owing to their elevation these mountains have many small active streams. The principal erosion, however, probably was confined to the Pleistocene, when the high portion of Steens Mountain suffered marked valley glaciation. Fortunately these two localities form the centers of the principal volcanic activity of the region, for the magnificent exposures in the network of valleys that cut the scarps permit an interpretation of

Figure 2. View northward from Alvord Desert, showing the slight encroachment of vegetation at the margin of a typical playa.

Figure 3. The high scarp of Steens Mountain viewed from north of Alvord Desert. A typical sagebrush growth is in the foreground.

many of their volcanic phenomena. The higher members of the series, however, have survived erosion only on the lower scarps, which lack the variation of the other two localities. As a consequence their complete interpretation involves merely the study of sections at a few carefully chosen localities.

This report is confined chiefly to the Steens Mountain volcanics, but includes evidence on the stratigraphic relationship of this series to that exposed in the adjacent region. The investigation practically ceases at the margin of the desert country which may be roughly demarked by continuing to the southwest the line formed by the western wall of the Summer Lake-Chewaucan Marsh depression to the western scarp of Warner Valley. West of this line, the exposures are less satisfactory, owing to the sudden 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.(2) 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

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(2) James Blake, "On the Pueblo Range of Mountains," Calif Acad. Sci. Proc., Vol. V (1873), pp. 210-214.

of the Steens Mountain volcanic series and the underlying crystalline rocks on which it rests. Blake gave a brief description of the metamorphics and the volcanics 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 (3) 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 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 part of

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

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

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 south 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)

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 south-

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(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 (1928), p. 427.

ern extension of the Steens Mountain volcanics exposed on Pueblo Mountain, the age and 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 directly overlying the Pueblo Mountain series. 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

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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 (1910-11), pp. 21-53, 199-304.

(8) Personal communication.

(9) Op. cit., p. 45.

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 apparent 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, in the opinion of the writer, the tuffs appear distinctly to curve upwards to the east conformably overlying the flows. These indications, however, are based only on indefinite criteria dependent on 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 four hundred feet, referred to as the Canyon Rhyolite. To the south on top of the irregular surface formed by this acidic lava, lies a tuffaceous series of sediments about one thousand five hundred feet in thickness. These are overlaid by a thin cap of basalt called the Mesa Basalt in re-

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(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 (1924), pp. 1-44.

ference to its physiographic form. This basalt was thought by Merriam to correlate possibly 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. In either case they were unsuitable for the collecting of possible fossils.

The fauna of the lower beds was considered by Merriam to belong to the Upper Miocene, while the upper part was considered to possibly correlate with the very similar beds in Thousand Creek. Subsequent work by Stock, (12) however, indicates the beds 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 ten 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,

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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 (1928), pp. 387-496.

which forms the western scarp of the southern continuation of the Warner Valley lying about seventy miles west of the southern spur of Pueblo Mountain. Russell was primarily interested in the structure and physiography of the region. For the purpose of mapping, the volcanic series was divided into stratigraphic units, but, owing to the absence of suitable exposures, this stratigraphy was, of necessity, of a reconnaissance nature. Most of the series is probably of a relatively local distribution, but a broader correlation was suggested for two of the upper members.

Near the top of the volcanic series here exposed, basaltic flows form a sheet thirty to six hundred feet in thickness. This lava, which was named the Warner Basalt, was indicated by fossil evidence to be Lower Pliocene age. Russell considered that this series thickened to the north to form the great exposures in the northern part of Warner Valley and at Abert Rim. He also correlated this basalt 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)

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(14) Op. cit., pp. 416-17.

Capping the Warner Basalt in northeastern California is some rhyolite of variable thickness, forming 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 to be confined chiefly to a prolonged rhyolitic period subsequent to the basalt. (15) In order that the sequence in Virgin Valley and the Thousand Creek basin might coincide with the type locality Russell considered that Merriam failed to appreciate the full significance of faulting and, in consequence, in part, 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 excavated by the writer, and fragments of the glassy rhyolite were found to be directly traceable into 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.

The Canyon Rhyolite, although its base is not exposed, shows a thickness of at least three hundred feet within a horizontal distance of a few hundred yards from the flat persistent cap of Mesa Basalt. If the rhyolite was sub-

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(15) R. J. Russell, op. cit., pp. 427-29.

sequent 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. There has, however, as Russell says, been acidic volcanic activity in the vicinity subsequent to the extrusion of the Mesa Basalt, for scattered small pebbles of obsidian may be found resting on it. These may have been deposited in now eroded tuffs.

The stratigraphic 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 hypothesis for the origin of the former. A similar theory (17) had been previously propounded to explain the structure of apparently analogous features in central Africa.

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(16) Warren D. Smith, "Contribution to the Geology of Southeastern Oregon," (Steens and Pueblo Mountains), Jour. Geol., Vol. XXXV (1927), pp. 421-41.

(17) E. J. Wayland, "Some Account of the Geology of the Lake Abert Rift Valley," Geog. Jour., Vol. LVIII (1921), p. 353.

This hypothesis demands that the tilted fault blocks in the region owe their elevation to steep upthrusts either with or without horizontal movement. This displacement was thought to be due to shearing at approximately forty-five degrees to the direction of compression. The grabens such as that forming Alvord Desert are considered to be due to mutually opposing thrust faults raising the blocks above the intervening flat floor that was thought to represent the undeformed prefaulting surface.

Without considering the many inaccuracies on which this theory is based, the writer will review briefly the eight main arguments advanced by Fuller and Waters (18) to indicate the tensional origin of 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 the physiographic expression.

Normal Faulting

No thrust fault has been discovered in southern Oregon while 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

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(18) Op. cit., pp. 223-38.

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. In most instances the step faulting in this region is apparent only physiographically. 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 faults that show a normal displacement in the opposite direction.

Genetic Importance of Step Faults

Since the presence of step faults in the opinion of the authors formed one of the most important proofs of tension, the writer will quote from the original publication the principal paragraphs dealing with the subject.

8 pt

"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 Abertine Rift (19) is reproduced by

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(19) Op. cit., p. 353.

8pk

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 Figure 4. In the sketch of the scarp due to thrusting, the overhanging portion of the emerged block is assumed to have fallen as two narrow step blocks so that a result is achieved very similar to the escarpment produced by normal faulting. These step blocks are, then, according to Wayland's hypothesis, nothing more than landslides. No explanation is offered as to the failure of these blocks to show the characteristic reverse 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

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(20) Op. cit., p. 434, Figure 8.

(21) Bailey Willis, "Geologic Structures," p. 81, Figure 57.

(22) I. C. Russell, "Geology of the Cascade Mountains in Northern Washington," U. S. Geol. Survey, Ann. Rept. 20 (1900), Part II, p. 194; "Topographic Features Due to Landslides," Pop. Sci. Monthly, Vol. LIII (1898), pp. 480-90. Bailey Willis, op. cit., p. 44. C. K. Leith, "Structural Geology," (New York, 1923), pp. 202, 203-4.

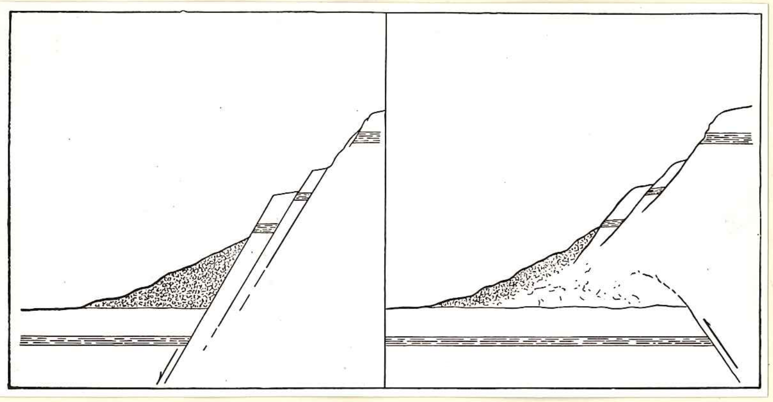

Figure 4. "Wayland's diagram showing the similarity of thrust and normal fault scarps. The step faults on the thrust scarps are regarded as superficial landslides."

R. E. Fuller and A. C. Waters, op. cit. Fig. 13, p. 226.

(23) Op. cit., p. 357.

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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

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(24) F. Dixey, "The Nyasaland Section of the Great Rift Valley," Geog. Jour., Vol. LXVIII (1926), pp. 120, 124-25 J. W. Gregory, "The African Rift Valleys," ibid., Vol. LVI (1920), p. 23. Douglas W. Johnson, "Block Mountains in New Mexico," Jour. Geol., Vol. XXXI (1903), pp. 136-37. Waldemar Lindgren, "The Tertiary Gravels of the Sierra Nevada," U. S. Geol. Survey, Prof. Paper 73 (1911), p. 42. G. D. Louderback, "The Basin Range Structure of the Humbolt Region," Geol. Soc. America, Bull.Vol. XV (1904), pp. 324, 334, 341-42. "Morphologic Features, of the Basin Range Displacements in the Great Basin." Univ. Calif. Publ.,Bull. Dept. Geol. Sci., Vol. XVI, No. 1 (1926), pp. 1-31. John Parkinson, "The Great African Troughs in the Neighborhood of the Soda Lakes," Geog. Jour., Vol. XLIV (1914), pp. 33-49. John A. Reid, "The Geomorphogeny of the Sierra Nevada Northeast of Lake Tahoe," Univ. Calif. Publ., Bull. Dept. Geol. Sci., Vol. VI (1911), pp. 115, 117, 135-36. H. L. Sikes, "The Structure of the Eastern Flank of the Rift

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 steplike relationship to those higher upon the escarpment. The diagrammatic sections in Figure 5 convey the writer's impressions of the necessary result. Upon a relatively small emergence of the thrust block, the first step, (1), would form, further thrusting would overturn this block, and its lower part would be overridden by the advancing mass. The second step block, (2), therefore, would not have a steplike 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 (Figure 6), 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.

Valley near Nairobi," Geog. Jour., Vol. LXVIII (1926), pp. 386, 389-90, 401.

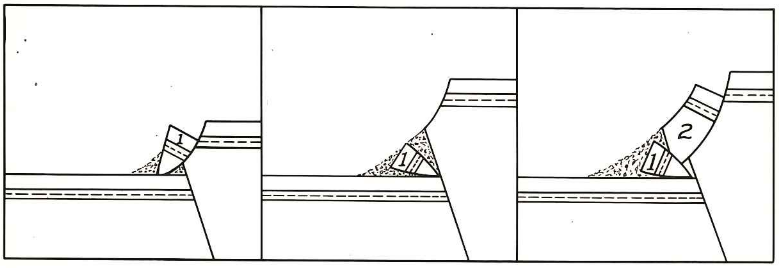

Figure 5. "Supposed stages in the evolution of a thrust fault scarp, provided step blocks actually do form. On slight emergence the tip of the thrust block would slip off, forming the step block 1. Further movement would overturn and override this block. If a second step block 2, is formed it will no longer have a steplike relationship to the first block." Compare Figure 6.

R. E. Fuller and A. C. Waters, op. cit., Figure 14, p. 227.

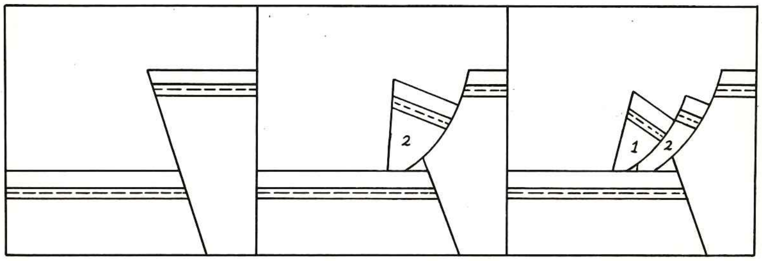

Figure 6. "Stages in the evolution of a thrust fault scarp according to Wayland's diagram (Figure 4). The entire block must first be shoved up to a position overhanging the valley, then step block (2) must slide down and later break and the outer portion of it slip down to form step block (1). Such a mechanism appears to be very improbable." Compare with Figure (5). (Talus omitted from diagram.)

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

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(25) Rollin T. Chamberlin & T. A. Link, "The Theory of Laterally Spreading Batholiths," Jour. Geol., Vol. XXXV (1927), p. 347.

(26) A. R. Andrew and T. E. G. Bailey, "The Geology of Nyasaland," Quar. Jour. Geol. Soc., Vol. LXVI (1910), p. 235. G. L. Collie, "Plateau of British East Africa," Geol. Soc. America, Bull., Vol. XXIII (1912), p. 313. 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 (1918), p. 229. 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 (1915), p. 279.

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 centripitally 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 one thousand 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."

The 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.

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 two hundred 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 five hundred miles. In southern Oregon there are seven well defined north-south fault depressions of about equal magnitude. It would require a rather unusual distribution of stress, if we assume compression, in order to produce such uniform structures as these. Compressional stress generally tends to localize the failure in narrow zones, but in this district the failure is practically uniform over the entire area."

Effects of Compressional Deformation in the Columbia River Plateau

"Comparison with adjoining districts shows that there is no reason why the basalts of southern Oregon should not fold if subjected to compression. To the north the compression of the Columbia River basalt appears invariably to have resulted in folds (27) rather than faults . . .

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(27) George Otis Smith, "Anticlinal Ridges in Central Washington," Jour. Geol., Vol. XI (1903), pp. 167-77. "Geology and Physiography of Central Washington," U.S. Geol. Survey, Prof. Paper 19 (1903), pp. 1-40. 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 (1913) pp. 22-25. Frank C. Calkins, "Geology and Water Resources of a Portion of East Central Washington," U.S. Geol. Survey, Water-Supply Paper 118 (1905) pp. 40-41. J. Harlen Bretz, "The Spokane Flood beyond the Channeled Scablands," Jour. Geol., Vol. XXXIII (1925) pp. 236, 242, 243, 249. 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 (1928) p. 270.

These anticlines are a very different kind of structural feature from that commonly observed in southern Oregon. Rising as long narrow ridges of from one thousand to three thousand 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 twenty-five to fifty miles in width and would probably average around four thousand feet in height."

The Absence of Marked Lateral Movement

In later pages an additional argument of importance was advanced in considering 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 planes at forty-five degrees to the direction of compression.

" . . . If, these mountains are considered to have risen on shears oriented forty-five degrees 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."

THE STRUCTURE OF STEENS MOUNTAIN

Although the absence of the upper members of the local stratigraphic sequence indicates that Steens Mountain has undergone considerable sheet erosion, the topography in a large measure is a direct expression of the structure. Although it is diversified by minor faults, the great structural mass as a whole dips westward with a slope of a few degrees. The most striking feature is, therefore, the eastern scarp, which is roughly continuous for over fifty miles. The southern part of this scarp lies approximately north-south, but to the north it swings eastward about thirty degrees. Structurally the mountain may be divided into three general parts, consisting of an extremely simple high central block, bounded on both the north and the south 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 twenty-five miles in length, trending predominantly North thirty degrees East. (Figure 18) At its southern end it rises close to three thousand feet, but to the north it decreases to less than one thousand. 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 fifteen miles. The northern half, however, is far more complex. This region was well described by I. C. Russell (28) 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

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(28) I. C. Russell, "A Geological Reconnaissance in Southern Oregon," U. S. Geol. Survey, Ann. Rept. 4 (1882-83) p.439.

accompanied by the sedimentation of the depressed areas. Farther to the west this portion of the mountain merges into a region of irregularly tilted small fault blocks.

High Steens

The central portion, known as High Steens, structurally is the simplest of the three units, although due to erosion its topography is more complex. Its eastern scarp towers above the desert about fifty-five hundred feet, (Figure 7) reaching an elevation at least two thousand feet greater than that of Northern or Southern Steens.

High Steens consists of a homoclinal block (Figure 8) about fifteen miles across, dipping westward at about three degrees for a distance of over twenty miles, until it reaches the richly alluviated valley of the Donner und Blitzen River. Although the block is truncated on the north by definite fault scarps dropping down to Northern Steens, the transition is accompanied by a slight monoclinal warp to the north. The scarp bounding High Steens (Figure 9) 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.

Southern Steens and Its Relationship to Pueblo Mountain

Southern Steens is a true horst, bounded on the western side by another well defined fault (Figure 10)

Figure 7. Aeroplane view of High Steens from the northeast. Mann Lake Ranch is in the foreground. The scarp of Southern Steens and part of Pueblo Mountain may be seen on the extreme left.

Figure 8. Aeroplane view of High Steens from the northwest showing the gently tilted surface of the block. The scarp in the foreground is formed by one of the east-west faults that bounds the lower block of Northern Steens. Kieger Canyon is visible on the extreme left.

Figure 9. 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.

Figure 10. Aeroplane view showing the curving western scarp of Steens rising over a thousand feet above Catlow Valley. The scarp on the right divides Southern Steens. The higher block is Smith Flat.

which continues southward to the northern end of Pueblo Mountain (Figure 11) At the northern end, this scarp has an orientation about North 30 West, but traced southward it swings towards the west in a fairly even curve, which increases more sharply near the southern extremity until it reaches approximately North 70 East. Where the scarp first appears above the alluvium at the north end 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 a thousand feet.

Southern Steens is divided by a fault trending roughly North 60 West into a northern and southern part. The northern division, which is about ten miles across, is a very level and homogeneous block known as Smith Flat. At its eastern scarp this block dips westward at two or three degrees, but within a few miles to the west, the slope gradually decreases. Towards the western fault there is a suggestion of a reverse dip of about one degree 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. (Figure 9)

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

Figure 11. 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., Figure 6, p. 218.

Figure 12. Aeroplane view from the north of the tilted blocks forming the southermost limit of Southern Steens. Broad Valley lies in the middle distance to the north of the extensive reentrant. Still farther south on the extreme left the older metamorphics form the domelike 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.

are accompanied by the tilting of the small units 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 block capped with trachyte which dips South 60 West at about twelve degrees. This inclination closely corresponds to that of the tilted lavas forming the Pueblo Mountain series, which gradually increases in dip as it continues southward to approximately twenty degrees.

Viewed from the north, the stratigraphic sequence and structure appear continuous. (Figure 12) 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 one hundred miles in length. This depression is due to the presence of a number of minor tilted blocks with a predominant strike of approximately North 65 West, and a dip to the southwest of about ten to fifteen degrees.

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

The re-entrant which this ridge bounds is filled at least at its northern end with soft sediments whose conglomeratic facies contain the predominant types of lava characteristic of Steens and Pueblo Mountains. With north-south faulting or a continuation of it, the block on which these sediments rest has been tilted to the west at an angle of about five degrees, raising the eastern end four hundred 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.

THE EASTERN SCARP OF STEENS MOUNTAIN

Structure

The displacement of the eastern scarp of Southern Steens appears to have occurred in two main faults that converge towards the north. The eastern one of these trends roughly north-south. Although never a marked topographic feature it is very persistent and continues southward defining Pueblo Mountain on the east. The final displacement on this fault is so recent that as W. M. Davis recorded, (29) it cuts an alluvial fan, (Figure 13) which

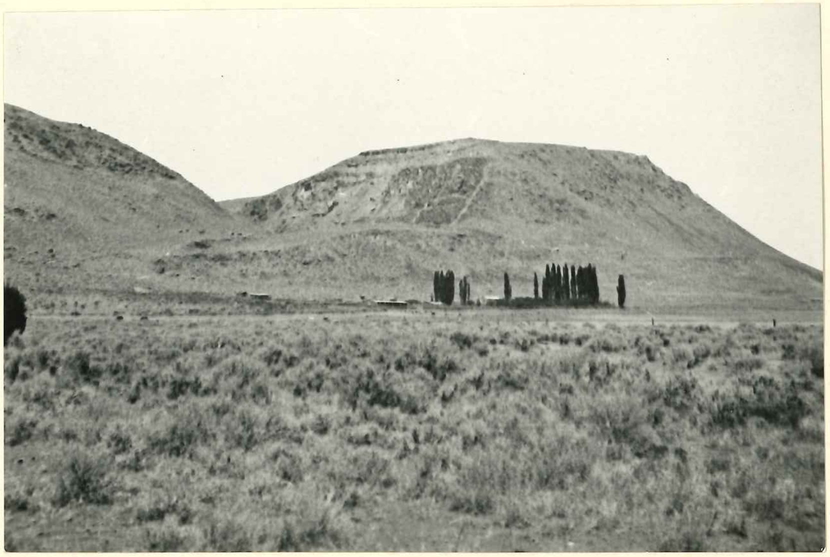

Figure 13. Faulted alluvial fan on the scarp of Southern Steens back of the Hollis Ranch, previously described by W. M. Davis as proof of the recency of movement.

is but slightly eroded.

The western fault, lying roughly North 20 East, is indicated by the more marked escarpment which bounds Smith Flat. Below it an irregular shoulder forms the surface of the poorly defined step fault block. With the convergence of these scarps the steep single exposure continues approximately due northward and forms the eastern 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. (Figure 14) 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 Wildhorse 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 ten miles. The position of the valley directly in line with the southern scarp must be due to a structural weakness caused by a minor continuation of the fault. Its presence parallel to the eastern scarp renders the southern crest of High Steens extremely serrate.

Owing to erosion and to minor deformation the eastern scarp of the spur is not very well defined, but it trends

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(29) W. M. Davis, "Mountain Ranges of the Great Basin," Mus. Comp. Zool., Bull. (Harvard University), Vol. XLII (1903-5) p. 1.

Figure 14. Aeroplane view from the south of the summit of High Steens. 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.

approximately North 20 West. 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 (Figure 15) 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. Roughly paralleling the southern continuation of the main fault, this one cuts higher on the scarp to the north of Pike Creek. Its throw, however, gradually decreases and it disappears within about half a mile.

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. (Figures 18 & 81) In this 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 to-

Figure 15. In Toughey Creek a view of the main scarp shows one of the numerous step faults, which occur in this locality.

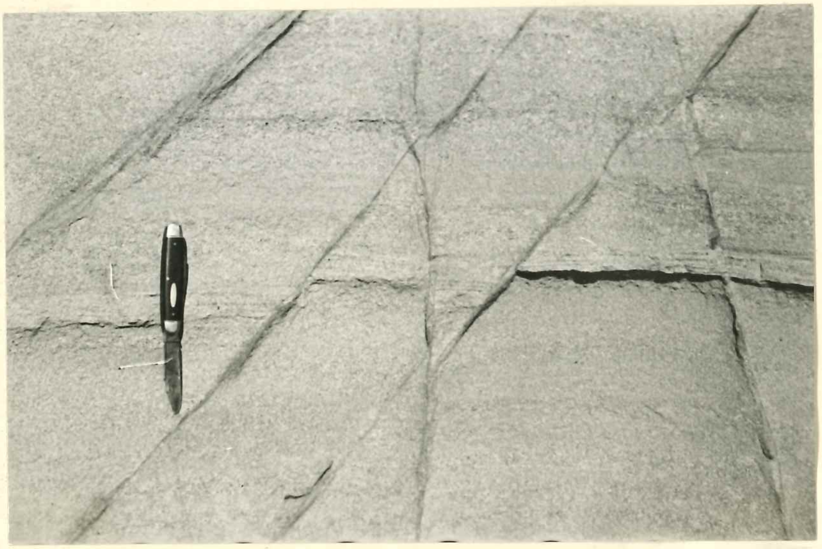

Figure 16. View of the minature faults exposed in the bedded tuffaceous sediments on the northern side of the lower cirque in Mosquito Creek. The inclined normal faults dip westward towards the main mass of the mountain. Some of the vertical fractures show a slight displacement, which permits the depression of minature wedges.

pography. 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 a thousand feet.

This locality was the only one where the actual surface of the faults forming the scarps was observed. (30) These fault planes dip eastward at an inclination varying from about fifty to sixty-five degrees. They appear to average about sixty degrees. In a few instances inclined slickensided grooves indicate a slight tendency to slip. In adjacent planes, however, this lateral adjustment showed no regularity. Most of the polished surfaces testify to its absence.

To the north of this point for over ten miles, the scarp continues approximately on the 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 a thousand feet above the desert. (Figure 7) Usually the exposures are not sufficient to permit the interpretation of their relationship to the main scarp.

In the Cottonwood Creek, however, a vertical fault is exposed at the western margin of the bench that indicates that the eastern side has been elevated. The extent of

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(30) R. E. Fuller and A. C. Waters, op. cit., Figure 11, p 223.

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. It seems possible that they may be due to later isostatic adjustment, although no evidence of the time of faulting was obtained.

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. The largest in the valley of Alvord Creek, owing to the intersection of a dike, shows the western block to be downthrown about two hundred feet. (Figure 17) To the north, in the valley of Mosquito Creek, two of the smaller faults converge downward indicating 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 tuffs adjacent to a basaltic vent on the northern margin of the lower cirque shows miniature normal faults dipping westward. (Figure 16) The intersection of vertical faults with these normal ones have, in this instance also permitted the depression of minute wedge shaped blocks. Although displacement is only a matter of inches, it furnishes additional testimony to the tensional forces.

Although individual exposures on High Steens are very

Figure 17. Looking south across the head of the cirque of Alvord Creek. The ravine in the center of the picture follows a normal fault dipping westward. The offset of the dike cutting the basaltic series indicates the normal displacement.

R. E. Fuller and A. C. Waters, op. cit., Fig. 12 p. 224.

precipitous, the scarp as a whole shows a slope close to twenty degrees. On the other hand, the vertical jointing of the basaltic series at Bluejoint Rim, in the northern portion of Warner Valley, has preserved locally a slope of almost seventy degrees, 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.

Elsewhere in the Great Basin the scarps show a relatively uniform slope, usually of about thirty degrees, although the actual faults, as on Steens Mountain, have averaged close to sixty degrees. (31) 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 very varied volcanic rocks, which are exposed.

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(31) W. M. Davis, "The Basin Range Problem," Nat. Acad. Sci. Proc., (1925) p. 389. J. Gilluly, "Basin Range Faulting along the Oquirre Range, Utah," Geol. Soc. America, Bull., Vol. XXXIX (1928), pp. 1113. A. C. Lawson, "Recent Fault Scarps at Genoa Nevada," Seismological Soc. America, Bull., Vol. II (1912), pp. 193-200. I. J. Pack, "New Discoveries relating to the Wasatch Fault," American Jour. Sci., Vol. XI (1929) pp. 398-410.

Although the scarps in the southern portion 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, (Figure 18) while others show sharp changes that produce a marked zigzag course. These changes in direction locally 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 (Figure 19) where the scarp curves sharply eastward to about North 30 East. 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 North 25 West.

To the north of this curve the eastern scarp of Northern Steens continues for nearly thirty miles, gradually diminishing in elevation from approximately three thousand feet to a few hundred. The most marked irregularity occurs about fifteen miles to the north of High Steens at Stone House Creek. Here the scarp is offset over a quarter of a mile to the

Figure 18. Aeroplane view of the circular fault basin known as Upper Alvord. The playa is about two miles in diameter. The eastern scarp of Northern Steens is in the distance. Near the center this shows the offset with the formation of the step fault (Figure 20). To the east the minor blocks parallel to the main fault are clearly defined.

Figure 19. 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.

east. The eastern scarp emerges from the valley alluvium as a tilted block plunging southward at about seven degrees. (Figure 20) Traced northward it flattens within the distance of a mile to form a well defined step fault block (Figure 18) several hundred yards in width with a surface about three hundred feet below the local crest of the mountain. This thin subsidiary block continues for several miles until at an east-west scarp the upper block is depressed to an equal elevation. 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 North 20 East, while that of the eastern scarp is about North 30 East.

This step fault block dips westward at about three degrees, 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 one hundred 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. (Figure 21)

To the north the eastern scarp of Northern Steens

Figure 20. 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 a thousand feet.

Figure 21. 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.

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

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

East of High Steens an expanse of about ten miles lies between the two scarps of the graben in which Alvord Desert lies. Opposite to the southern end of Northern Steens a number of isolated fault blocks rise above the playa flats. (Figure 2) The dip of these blocks is very varied. To the east of them, lies the circular fault basin referred to as Upper Alvord. To the north, however, the structure is dominately parallel to that of Northern Steens, and two blocks dipping to the northwest define ellongate alluviated valleys. (Figure 18) These blocks are also cut by transverse faults.

Erosion

Structural Control

At the southern end of High Steens the previously mentioned Wildhorse Canyon renders the crest very rugged. 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 cirque at the head of these two valleys, which are on the same north-south line, are within approximately six miles of each other. This drainage must be controlled by a minor structural displacement parallel to the scarp although the actual fault plane was not observed by the writer.

Glaciation

I. C. Russell (32) and Waring (33) considered that the broad U-shaped valley of Kieger Canyon (Figure 22) was due to stream action subsequently modified by glacial erosion.

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(32) I. C. Russell, "Hanging Valleys," Geol. Soc. America, Bull., Vol. XVI (1905), pp. 83-87.

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

Figure 22. 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.

Smith (34) later observed the well-marked evidence of glaciation in Wildhorse Canyon. In addition, however, the presence of broad shallow cirques, <u>roches moutonnee</u>, 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.

All the larger valleys on the eastern scarp of High Steens also show marked indications of glacial erosion in their upper parts. Usually the main stream at about two miles from the foot of the scarp ends in a broad cirque some twenty-five hundred feet above the desert. (Figure 99) Here as a rule two or three small tributaries descend precipitously from well-defined glacial valleys as a rule about fifteen hundred feet above. These shallower valleys, extending a mile or more farther to the west, end in small 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 (35) 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

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(34) Op. cit., p. 424

(35) I. C. Russell, "Hanging Valleys," Geol. Soc. America, Bull., Vol. XVI (1905), p. 84.

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 the volcanics, 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 (Figure 7) on the scarp suggest a periodic uplift, permitting a great erosional break. Although they are locally demarked by faults, these shoulders all appear to be the direct physiographic expression of a change in rock type.

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.

Names of the Creeks

Many of the names (See sketch map Figure 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 large 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.

THE VOLCANIC SERIES

General Features

The most extensive stratigraphic sequence in south central Oregon is exposed on the great eastern scarp of High Steens. Here occur continuous exposures over five thousand feet in thickness, (Figure 24) while across Alvord Desert, on the lower opposing wall of the graben, (Figure 101) higher members of the series survive, making a total section of at least six thousand feet. The volcanic activity responsible

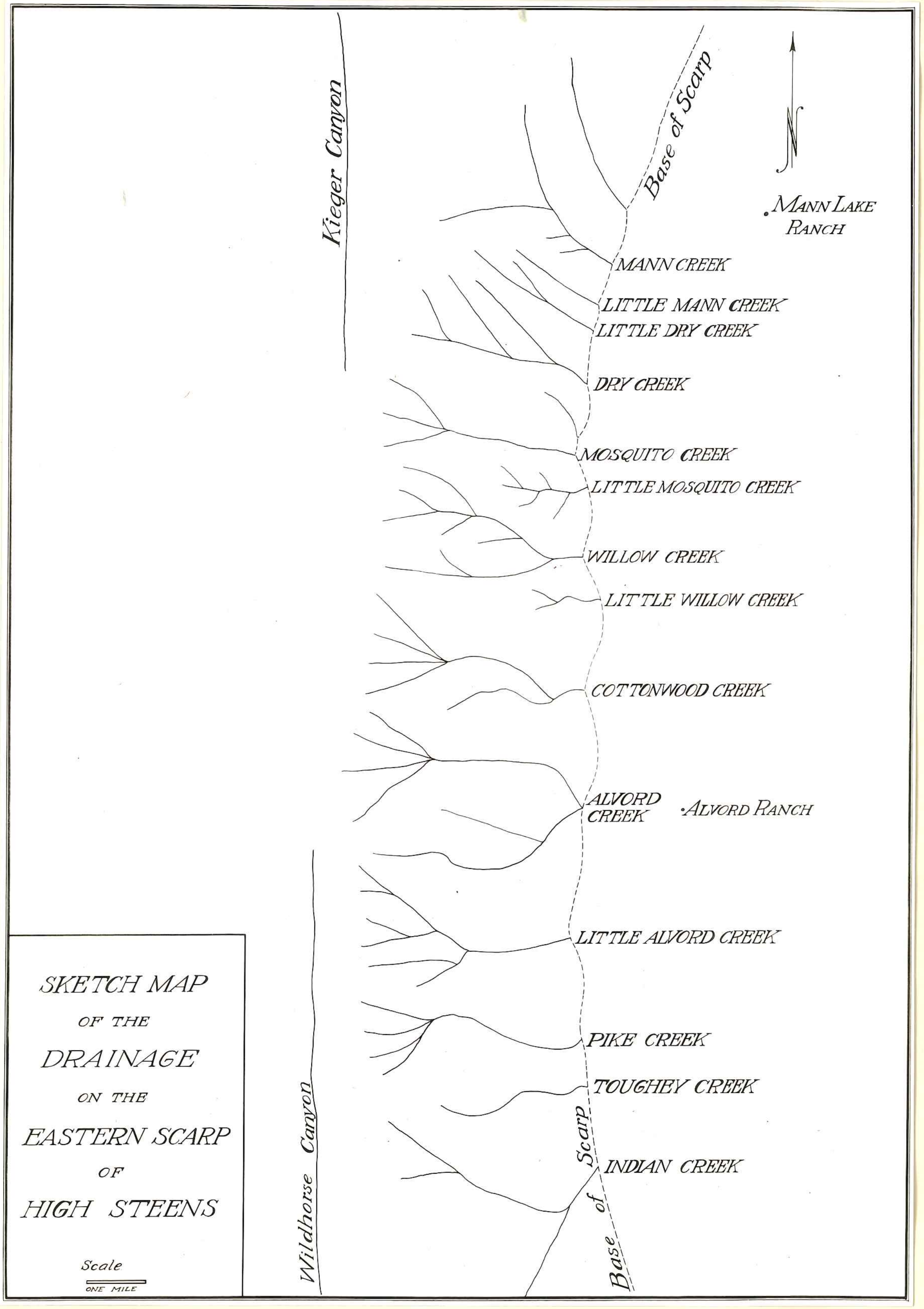
Kieger Canyon
Base of Scarp
N
Mann Lake Ranch
MANN CREEK
LITTLE MANN CREEK
LITTLE DRY CREEK
DRY CREEK
MOSQUITO CREEK
LITTLE MOSQUITO CREEK
WILLOW CREEK
LITTLE WILLOW CREEK
COTTONWOOD CREEK
ALVORD CREEK
Alvord Ranch
LITTLE ALVORD CREEK
PIKE CREEK
TOUGHEY CREEK
INDIAN CREEK
Base of Scarp
Wildhorse Canyon
SKETCH MAP OF THE DRAINAGE ON THE EASTERN SCARP OF HIGH STEENS
Scale
ONE MILE

Figure 23.

Figure 24. Aeroplane view of High Steens west of Alvord Ranch, which is in the foreground on the left. The valley on the right is formed by Alvord Creek. 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.

for this lava was chiefly parallel to the potential line of weakness later followed by the great fault. Most members of this sequence are, therefore, formed by the thick accumulation of the near vent phase.

Some of the lava at the time of extrusion was highly viscous. Its distribution consequently is extremely local. On the other hand, fluid flows may be widely distributed and if of a characteristic variety, may be of great stratigraphic value. The sediments of the region, unfortunately, show such a marked lithologic similarity that their correlation must be based largely on a rather meager fossil content.

In piecing together the regional geology of the area, it is necessary to correlate the series exposed in isolated scarps, which are usually twenty to thirty miles apart. Only the ubiquitous presence of a thick series of basaltic lavas, which were extruded in great fluidity, make this correlation possible. Otherwise the rapid changes in the stratigraphic sequence even in the same scarp clearly indicate the impossibility of basing regional correlation on the distribution of viscous lava or on minor stratigraphic variations in the volcanic sequence.

The Sequence of Events

The lowest member of the series is formed by stratified tuffs of the Middle Miocene which are at least eight or nine hundred feet in thickness and possibly close to twice that figure. These beds are called the Alvord Creek Beds from the location of their major exposures. Unfortunately, owing to the difficulty in correlating isolated exposures the complete structure was not conclusively interpreted. It suffices here to say that these beds at least locally bear a nonconformable relationship to the later lavas. The principal structural irregularity is due to the intrusion of acidic lava, probably in the form of a laccolith. At the top of the exposure of the overlying sediments, transverse to the apparent axis of the uparched structure, an elongate acidic vent is exposed, cutting parallel to the scarp. The absence of deformation indicates its intrusion to be subsequent to that of the laccolith. Extrusive material from this vent, however, is not exposed and cannot have been very great.

Before the initiation of obvious erosion, the dip slope of this anticlinal structure formed on the south the retaining wall for a massive flow of rhyolite about four hundred feet thick. In Little Alvord Creek the vent for this flow is exposed, cutting the inclined beds of the laccolith. Unfortunately poor exposures render it difficult to trace this rhyolite flow to the south so as to permit an accurate correlation with a very 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 two hundred feet of tuffs overlaid by an equal thickness of platy rhyolite, which locally exhibits vent characteristics. On this flow was deposited more tuffaceous material to a depth of almost three hundred 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 rhyolite to the north in Little Alvord Creek. The two flows, however, appear to be distinct. This lava was followed by another bed of stratified tuffs about forty feet in thickness.

Above this is a thick dacitic flow, the vent of which appears to be disclosed in Little Alvord Creek at about a mile from the scarp. This flow is capped by a greater mass of dacite which shows distinct vent characteristics in Toughey Creek, where its exposures have a thickness of over five hundred feet in spite of the erosion of its surface features. Northward this 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.

In addition, still farther to the north, other masses of acidic lava outcrop low on the scarp in Cottonwood and Willow Creeks. The former unfortunately 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 followed by the eruption of andesite.

This andesite welled from a series of vents paralleling the scarp into a huge viscous flow with a maximum thickness of at least nine hundred feet and of approximately fifteen hundred feet from the interpretation of the writer. This gigantic flow in the process of solidification developed, in the opinion of the writer, its own satellitic cones and minor flows. The southern end of the main andesitic vent cuts the acidic series on the northern side of Little Alvord Creek. Farther to the south above the thick accumulation of earlier acidic lavas the andesite decreases rapidly in thickness. To the north, however, its exposures are continuous for about ten miles until truncated by a transverse fault at the northern margin of High Steens.

Before any marked erosion had taken place these volcanics were covered to a depth of at least three thousand 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 the extrusion. The identical series can be traced southward to Pueblo Mountain and westward to Warner Valley and Abert Rim.

R. J. Russell (36) refers to the capping basalt in the

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(36) R. J. Russell, op. cit., pp. 416, 427, 439.

Warner Mountain region of California as the Warner Basalt and correlates it both with the capping basalt exposed to the north near Plush, and also with the great thickness of lava in both Bluejoint and Abert Rims. He did not realize, however, that in the Warner Lake region the capping basalt, which is several hundred feet in thickness, rests disconformably on stratified tuffs capping the far greater series formed by a 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 sequence. In general it consists of miscellaneous alternation of acidic, intermediate or 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 the irregularities due merely to the viscosity of the lava. This varied series has a maximum thickness of about five hundred feet.

ALVORD CREEK BEDS

General Characteristics

Light colored tuffaceous sediments outcrop locally at a number of places (Figure 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. Although it is impossible to correlate these sediments they are tentatively considered to belong to the same formation. Invariably the excellent preservation of the bedding in these incompetent rocks testifies to the absence of compressional forces. (Figure 27)

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 phases are relatively common. The green coloration, however, is definitely exotic and possibly also to a less extent the brown. In consequence in the field the color does not form a satisfactory criterion for correlation. In two localities a content of fossil leaves indicate 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 local horizons 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 varies rapidly in distribution. It is possible that a correlation might be attained by detailed petrographic methods.

North of Alvord Creek

The greatest exposure (Figure 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 seven degrees. The lowest beds are of brownish tuffs that are exposed continuously for a horizontal distance of about five hundred feet.

The central part of these beds are relatively coarse and contain pumiceous fragments of dark glass, which are usually not over one and a half centimeters in diameter. Stratification is locally apparent, but as a rule it is rather indistinct. An impregnation with calcite and zeolitic material is common. The lower part of the exposure shows a number of displacements. Although the lithologic homogeneity renders it difficult to be sure of the extent of move-

Figure 25. The main exposures of the Alvord Creek beds north of Alvord Creek. A flow of basic andesite about a hundred feet in thickness is interbedded in the upper part of the series. The fossil beds are a little over a hundred feet below its base.

ment, the distance in any instance did not appear to be more than a few feet. This lower brownish phase grades upwards into buff colored stratified tuffs about fifty feet in thickness. These in turn are overlaid by about two hundred feet of whitish tuffaceous sediments, which contain horizons of shale rich in fossil leaves. These upper two hundred and fifty feet are locally highly opalized, or altered to a greenish tinge.

Capping these beds is a flow of rather basic andesite close to one hundred feet in thickness. This lava is overlaid by less than a hundred 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 underlaid by well stratified white tuffs about one hundred feet in thickness. (Figure 49) As in the section to the south these sediments cap a lower andesitic flow, which here shows a fault contact with a mass of acidic agglomerate several hundred feet thick. This fault, which is roughly vertical and parallel to the scarp, has an upthrow to the east. This displacement hides the basal contact 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 and apparently their interbedded andesitic flow dip southward at about seven degrees. In this case, the relationship of the andesite was unfortunately not accurately determined, but it appeared to lack this deformation.

South Fork of Alvord Creek

About a half a mile further to the south, however, on the northern side of the south fork of Alvord Creek (Figure 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 seventy-five 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 four hundred and fifty feet without exposing either the top or the base of the section. Again the lowermost exposures are of a brownish color, (Figure 27) but here the beds are only about fifty feet in thickness. Higher in the section the beds are very light colored. In this zone, about thirty 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 two hundred feet below the massive andesite, which is stratigraphically above the two previously mentioned andesitic flows to the north

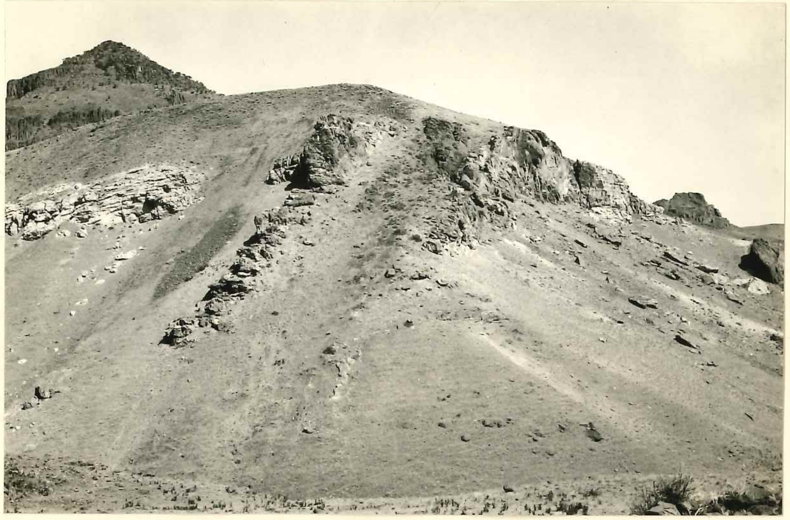

Figure 26. Looking northward at the Alvord Creek beds north of the south fork of Alvord Creek. The cliff on the right is formed of tuffaceous sediments indurated by a seventy-five foot basaltic dike, which is visible in the center of the view. The fossil locality is about fifty feet below the base of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

of Alvord Creek.

North of Little Alvord Creek

It is also impossible to determine the stratigraphic relationship of the tuffs already described to those beds exposed on the main scarp southward to Little Alvord Creek. Although the exposures are scattered over a distance of nearly a mile, they appear to be definitely in the form of an arch, at the center of which is an intrusive mass of rhyolite, outcropping at the base of the scarp for about a quarter of a mile.

The structure presumably is a laccolith, although the base is not exposed. Judging from the inclination of the overlying beds, the exposure is formed by the eastern margin of the intrusion. The beds on the northern limb have a strike of North 30 West and dip at about eleven degrees to the northeast, while farther to the south at the margin of the Little Alvord Creek Valley the beds have a strike of North 80 East and dip south at about fifteen degrees. Farther westward in the valley the strike swings more to the east.

The possible height of this dome is hidden by acidic vents that cut the arch parallel to the scarp at about a thousand feet above the desert. To the south, the exposures are only scattered so that the thickness of the beds forming the southern limb can not be accurately determined, but presuming a uniform inclination there is a thickness of well over one thousand feet. The dip slope of this limb, as has been previously mentioned, forms in Little Alvord Creek, the retaining wall for a thick flow of rhyolite. 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 make it impossible to determine if this surface was formed by a continuation of the tuffaceous series as it flattens out away from the margin of the laccolith.

In the valley of Pike Creek, however, nearly two miles to the south, there are exposed beneath the stratigraphic continuation of this flow over four hundred feet of stratified tuffs and agglomerates with a lower two hundred-foot flow of rhyolite interbedded in them. The base of these beds is not exposed. They may well correlate with the upper members of the Alvord Creek formation, but unfortunately the relationship again is only hypothetical.

Alteration of the Tuffs

Opalization.

One of the most striking features of the Alvord Creek Beds is the local opalization encountered in the upper part of the two main exposures immediately to the north and south of Alvord Creek. This opalization is chiefly confined to thin bedded shales which, in both localities form horizons rich in fossil leaves. The silification is so extreme that the beds are converted into massive glassy opal of a very dark grey. (Figure 28) With slight weathering the fine bedding becomes apparent as parallel light grey streaks which slightly suggest flow structure in a glassy lava. With greater weathering the rock loses its glassy lustre together with its conchoidal fracture, and disintegrates finally into a highly laminated paper shale.

This silification is so concentrated at certain horizons, usually only three to six inches thick, that at first it appeared possible that it was formed by the deposition of colloidal silica. The occurrence, in the tuffs, however, of rounded and pipe-like opalized concretions, (Figure 29) which preserved the stratification perfectly in spite of their clean cut outline, proved the silification to be secondary in origin.

The opalization was also observed as a massive porcelanous type. This is extremely white on the exposed surfaces, but is a brownish grey on fracturing. This type occurs in the main exposure north of Alvord Creek at about one hundred feet below the interbedded flow of andesite. Its relationship is extremely irregular (Figure 30) although it roughly follows the bedding. The most massive exposure thickens from about four feet to nearly ten in the course of forty feet. In its central part, it encloses a lense of tuff that is apparently unaltered. On the north this lense is sharply truncated by the opal. The minor distortion of the

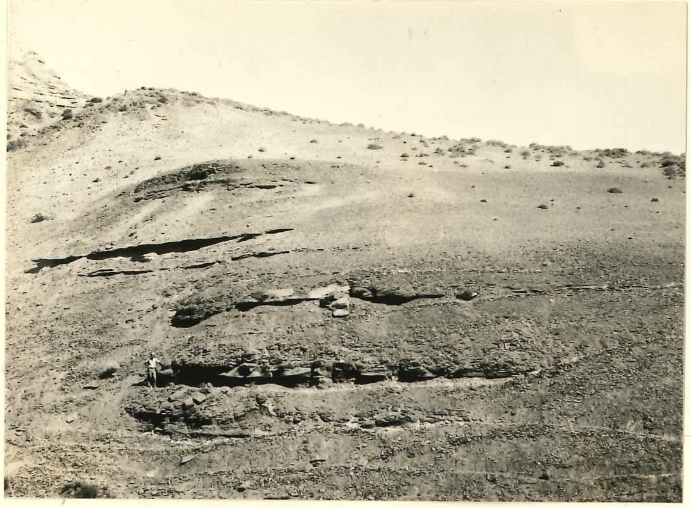

Figure 27. The brownish shales forming the lowermost exposures north of the south fork of Alvord Creek. The perfect preservation of the stratification testifies to the absence of compressional forces.

Figure 28. Opalized Shale in the beds north of Alvord Creek. The dark glassy variety forms the ledge beneath the hammer head. The paper shales are both above and below.

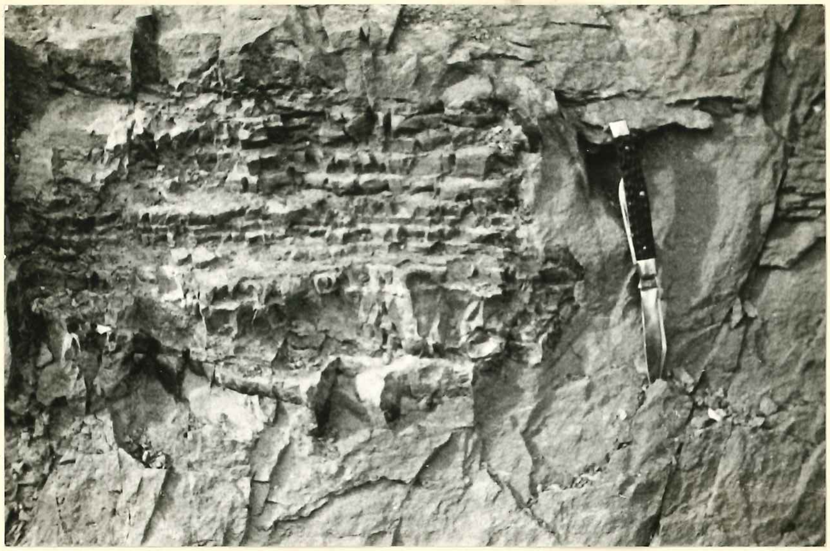

Figure 29. The bedding of the tuffaceous sediments is clearly defined in an opalized concretion in the beds north of Alvord Creek. The irregularly rounded outline of the concretion is partially visible.

Figure 30. Irregular lenticular masses of opal interbedded in the tuffaceous sediments north of Alvord Creek. The opal exhibits a white porcellaneous surface.

bedding in the opal in this exposure suggests that it actually underwent movement while saturated with soft gelatinous silica. This phenomenon is also suggested by another exposure about seventy-five feet below. Here an opalized bed a few inches thick actually shows an overturned fold, although the adjacent strata both above and below appear undisturbed.

On the north side of Cottonwood Creek at the top of the stratified tuffs between the two lowermost andesitic flows, there occurs some black opalized material that has been prospected extensively for coal. This opal lacks the glassy lustre that is found in the fossil-bearing shale. The major exposure is on a landslide block about fifty feet below the contact.

Green Coloration.

Another form of alteration characteristic of all white tuffs near the contact of acidic intrusions is their pale green coloration. This coloration, like the silica, is also chiefly confined to certain horizons and, in general, occurs as thin streaks following the bedding. That it is not due to primary deposition is proved by the fact that the pigmentation may be observed locally to cut sharply across the bedding. The most intense shade of green observed in the region is adjacent to the acidic intrusions on the scarp to the north of Little Alvord Creek. Here the color is massive, rather than parallel to the stratification. No effect from this alteration is apparent in thin section.

Localization of Alteration.

In general, outside the actual zone of contact, the alteration is confined to horizons that show marked primary stratification. In Pike Creek the thin horizons of coarse agglomeratic material with their angular to subangular fragments of acidic lava are highly silicified and very distinctly green, probably due to the easy access of magmatic gases from the adjacent vents owing to the former porosity of the beds. In the case of the shales, their fine horizontal bedding would have formed a more impervious horizon to concentrate the action of ascending or descending solutions. The localization of silicification in the rounded concretions or in the pipe-like masses is unexplained.

Basaltic Induration.

The third characteristic form of alteration of the tuffs is caused by the optalic metamorphism of basaltic dikes. This induration is so intense that the sediments adjacent to large dikes are baked to a dark grey dense rock with a conchoidal fracture. This rock is so resistant that it forms prominent outcrops while the igneous rock may be completely decomposed. (Figure 31) Away from the contact, the tuffs gradually become less aphanitic and then usually develop a reddish shade that grades into the normal white or buff colored tuff. At a maximum the entire transition takes place in about twenty feet. This relationship clearly indicates that the red coloration, which is quite commonly de-

Figure 31. The indurated margin of one of the smaller basaltic dikes cutting the beds north of the south fork of Alvord Creek. The dike has been removed by erosion. The indurated rock has suffered minor normal faulting.

veloped at the basal contact of basaltic flows with tuffs or other clastics, demands a less intense temperature than the dark grey.

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 one hundred feet below the interbedded flow of dark 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 possibly has been 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 fifty feet below a wall formed by the induration of the great basaltic dike, which cuts about north ten degrees east. 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, (37) which is exposed

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(37) J. C. Merriam, "A Contribution to the Geology of The John Day Valley," Univ. Calif. Publ. Dept. Geol., Vol. II No. 9, (1901). R. W. Chaney, "The Mascall Flora; its Distribution and Climatic Relation," Carnegie Inst. Washington, Publ. No. 349, (1925).

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in the John Day Valley above the Columbia River Basalt. In submitting the following list of the fossils (Table 1) he stated, (38) "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 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."

East of the southern end of Alvord Desert, tuffaceous beds are exposed underlying the inclined basaltic series. From fossil leaves these beds, which are known as the Trout Creek Formation (39) were considered to be of the Eocene (40)

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(38) R. W. Chaney, Personal communication.

(39) W. D. Smith, op. cit., p. 206.

(40) Gerald A. Waring, "Geology and Water Resources of the Harney Basin Region," U.S. Geol. Survey, Water-Supply Paper 231 (1909), p. 20.

Table 1

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

Preliminary Comparison by Dr. Chaney of the Flora from the Alvord Creek beds with that from the Mascall Formation.

Vertebrate remains, however, recently collected by Stock "indicated quite clearly that the beds were not earlier than the Middle Miocene." (41) They may, therefore, correlate with those exposed at the base of Steens Mountain.

VOLCANIC INTRUSIONS IN THE ALVORD CREEK FORMATION

The Great Basaltic Sill

On the scarp, north of Little Alvord Creek, the upper margin of the rhyolitic intrusive, wherever observed, was in contact with tuffs. At the northern end of the exposure these tuffs still preserve their bedding roughly parallel to the inclined contact of this laccolith. These beds, however, were found to be less than fifty feet in thickness. They are overlaid by a concordant mass of basalt, which appears to form a sill over two hundred feet thick. Viewed from the desert, the brownish exposures of this rock cause the domed structure above the acidic intrusive to be apparent. (Figure 32)

From a megascopic examination, however, this rock above the laccolith is locally almost indistinguishable from a basic tuff, owing to its extreme alteration, which is especially marked adjacent to the vertical lines of silicification. The slight survival of its primary horizontal platy jointing even gives a suggestion of stratification.

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(41) Chester Stock, Personal communication.

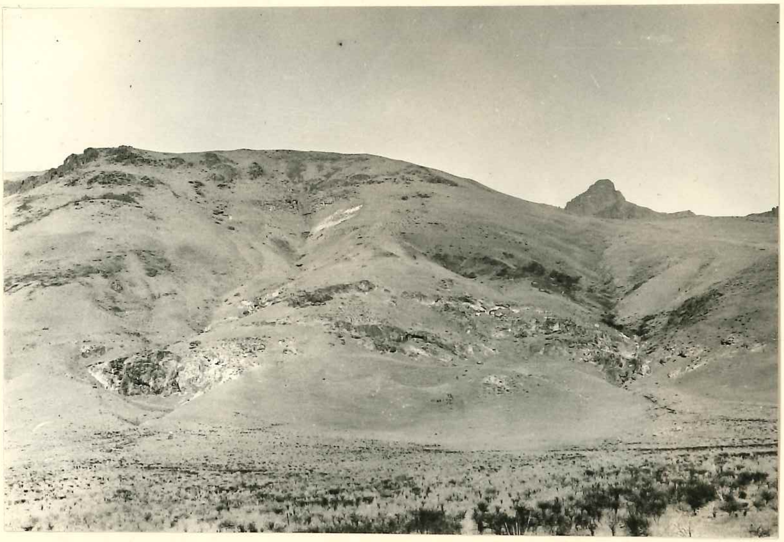

Figure 32. The lower thousand feet of the main scarp at about a mile north of Little Alvord Creek. The light colored exposures in the lower half of the view are formed by the rhyolite laccolith and by the tuffaceous beds with which it is in contact. The darker outcrops above them are formed by the uparched basaltic sill. The northern end of the rhyolite vent is visible at the top.

In fact, to the north, where the alteration is less extreme and the upper portion of the lava relatively fresh, it requires very careful observation to determine the contact with the underlying tuffs. The presence of small siliceous amygdules, together with the survival of a few less altered remnants formed the only criteria.

The upper contact of this igneous mass appeared to be best exposed in the extremely altered zone above the intrusion. Here the determination of its position and relationship also required minute examination, for the stratified beds for the next twenty-five feet above are of approximately the same light brownish color. The basalt at the contact shows no surface features suggestive of a flow, but, at the same time, the overlying tuffs show no marked induration. It is possible that the latter might be destroyed by later alteration caused by the acidic intrusion. The contact lava, in spite of its poor preservation, exhibits many minute vesicles that are filled with a dark powdery substance suggestive of decomposed chlorophaeite. This segregation of magmatic residuals from the observations of the writer, is characteristic of the contact phase of basaltic intrusives high in volatiles. The induration from such masses is not extreme, although it is usually accompanied by the impregnation of the wall rock with calcite and iron rich solutions. The actual surface of the lava was found to fluctuate slightly without disturbing the stratification of the beds about three feet above.

Petrographically the rock appears to be a basalt. In thin section a specimen from near the lower contact shows a seriate development of labradorite laths, ranging from less than .1 mm to 2 mm. in length. These show a slight tendency to an irregular alignment. The rock also contains a few grains of augite, which are usually about .5 mm. in diameter. The ground is formed by a brownish semi-opaque substance, which locally shows a faint suggestion of spherulitic structure, due possibly to an incipient development of variolites in a glass. This material is especially concentrated in thin veinlets, which are roughly parallel. Throughout the ground and at intervals along these veinlets there are amoebaform patches of a yellowish birefringent substance, which as a rule exhibits radiating structure. This substance is at least closely allied to a basic colloidal magmatic residual known as chlorophaeite. (42) The formation of this mineraloid depends largely on the retention of volatiles, and is, therefore, commonly developed in basic intrusives. In this instance it is not due to the decomposition of the pyroxene, for the latter is unaltered.

Considering the thickness of the basaltic mass the

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(42) M. A. Peacock & R. E. Fuller, "Chlorophaeite, Sideromelane and Palagonite from the Columbia River Plateau," Am. Mineralogist, Vol. XIII (1928), pp. 361-369.

texture is remarkably homogeneous. Apparently it must have been intruded as a relatively cool and viscous magma already partially crystalline. A slight trachytic tendency shown in the rough alignment of all the feldspar laths, the absence of apophyses and the lack of marked contact metamorphism, all coincide with this interpretation.

RHYOLITIC LACCOLITH

The acidic intrusion which is apparently responsible for the local deformation of the Alvord Creek Beds, is exposed at about a mile north of Little Alvord Creek (Figure 32) At the base of the scarp, for several hundred yards, there are scattered outcrops of light grey rhyolite. This rock shows marked cavernous weathering, due to the erosion of locally kaolinized areas. The resistant portion occurs predominantly as a thin zone, less than a half an inch in thickness, adjacent to the major joint cracks. This phase is not caused by silicification. It may be explained, however, by the fact that the magmatic gasses, on the solidification of the rock, had the opportunity to escape along the major joints and thereby to decrease locally the deuteric alteration in the lava immediately adjacent to these cracks.

This resistant rock shows phenocrysts of quartz and highly altered feldspar in a felsitic ground that is usually kaolinized to a whitish grey. The quartz, which composes about twenty percent of the rock, attains a maximum diameter of about four millimeters, although the grains average less than half that size. 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.

To the north is exposed the actual intrusive contact of this rhyolite with fine tuffs, which are highly brecciated and altered to a dense greenish rock. At about two hundred feet above the basal exposures, the local surface of the intrusion may be observed in contact with the white tuffs. This contact curves upwards into the hill, as if forming a small segment of a dome. The actual contact is very sharp, but the adjacent lava contains 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 fifty feet higher on the slope the rhyolite is again exposed, possibly in some measure due to a small fault, but more probably it is caused chiefly by the gradient 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, were observed a few irregular veins of massive white quartz which were two or three inches across.

Just below this uppermost exposure of the intrusive a well slickensided surface in the tuffs marks a vertical fault trending roughly North 70 East. 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 North 60 East. Owing to differential erosion these zones of silicification, on cutting the badly decomposed basalt, outcrop as resistant dikelike masses, one to two feet thick.

ACIDIC VENTS

Above the sill at the center of the laccolith, stratified tuffs exhibit a thickness of about two hundred and fifty 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 a hundred 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 fifty 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. (Figure 32) 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 fifty 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, usually ranging from one to ten centimeters in diameter. As a whole, the surface usually attains an irregular reniform structure. Some of the rounded nodes exhibit a craterlike 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 whitish substance, which, where less altered, is found to be formed by the decomposition of perlitic glass.

The localization of the spherulites is thought to be due to the concentration of volatiles along lines of flowage in the glassy lava. This concentration may be due to the liberation of volatiles into the minute tensional cracks, which are developed by the friction between successive layers of a viscous lava. (43) The expulsion of volatiles on the crystallization of the spherulites may account for the rather characteristic alteration of the surrounding glass. The writer has found spherulitic partitions to be extremely characteristic of acidic vents, and to occur principally as a marginal phase. Usually these bands mark the contact between the felsite and the glassy phase. In this instance, however, there is massive perlite on both sides.

To the south of this marginal phase there are continuous exposures of a lava that is very similar 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 three hundred feet high. (Figure 33) 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

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(43) R. E. Fuller, "The Mode of Origin of the Color of Certain Varicolored Obsidians," Jour. Geol., Vol. XXXV (1927) pp. 571-73.

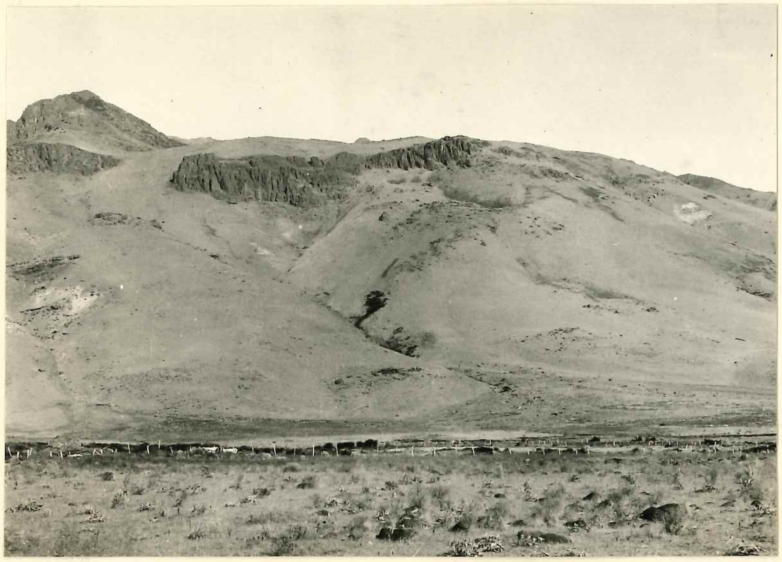

Figure 33. The lower thousand feet of the main scarp about a half mile north of Little Alvord Creek. The rhyolite vent forms the large horizontal exposure in the center of the picture. To the left of it is the upper flow of biotite-dacite. The principal outcrops directly beneath the northern part of the vent are attributed to landslides.

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.

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 with strong vent characteristics 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. There is, however, no petrographic evidence of a genetic relationship between the two bodies.

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 quite similar petrographically, although they are both very variable in their phases. Chemical analyses, however, show at least the satellitic intrusion to the north to be quite 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 they each contain oligoclase and orthoclase. In both, 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 two to three millimeters in diameter, contain aggregates of smaller grains. Biotite, although it usually constitutes less than one percent, is common to both of them, but the flakes in the rhyolite are seldom visible megascopically. They are generally less than a millimeter 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 content of feldspathic phenocrysts varies from about ten to twenty percent of the rock.

Table II - Part 1

	I	II
Silica	73.00	68.66
Alumina	14.23	14.44
Ferrous Oxide	1.28	1.28
Ferric Oxide	.28	.80
Magnesia	.24	.18
Lime	1.25	1.96
Soda	2.96	3.86
Potash	4.86	3.28
Water above 105 C.	1.00	4.80
Water at 105 C.	.60	.40
Carbon Dioxide	none	none
Titanium Dioxide	.18	.25
Phosphorous Pentoxide	trace	trace
Sulphur	none	none
Manganese Dioxide	none	trace
	99.88	99.91

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

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

Table II - Part 2

	I	II
Quartz	33.24	28.68
Orthoclase	28.91	19.46
Albite	25.15	32.49
Anorthite	6.12	9.73
Corundum	1.73	.92
Hypersthene	2.32	1.72
Magnetite	.46	1.16
Ilmenite	.46	.46
Water	1.60	5.20
	99.99	99.82

Norms calculated from the analyses in Part 1

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 lies a great series of acidic flows and stratified tuffs, in all over fifteen hundred feet in thickness. (Figure 34) Aside from the gentle westward dip of the fault block this series is flat lying. The flows forming their upper thousand 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 two hundred 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, noncomformable 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 exposed best in Pike Creek, that name is given to the series. (Figure 35) To follow the chronology

Figure 34. 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.

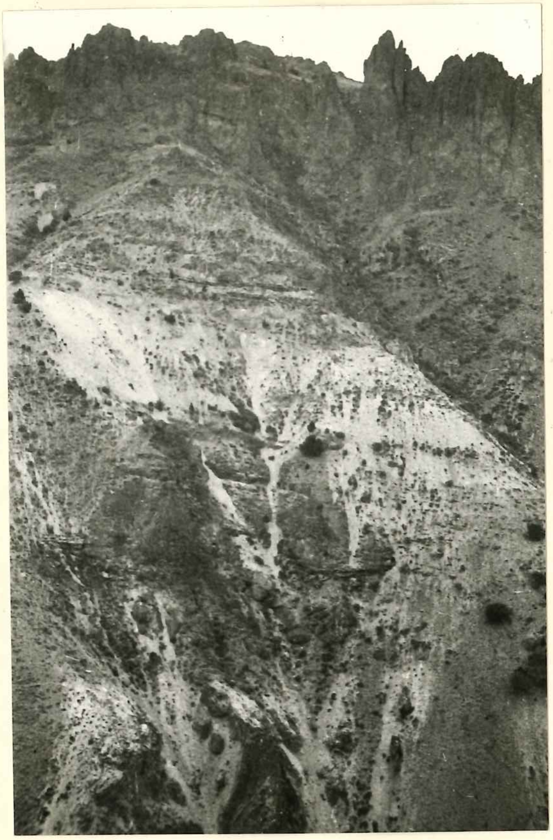

Figure 35. The volcanic series disclosed in an exposure about fifteen hundred feet in height on the southern side of Pike Creek valley. At the base the lower platy rhyolite may be seen. Above it the dark exposures are formed by the middle tuffs. These are overlaid by the upper platy rhyolite, which is 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.

of events as well as the origin of its different members it is necessary, however, to digress geographically both to the north into Little Alvord Creek and southward into Toughey Creek.

In 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 a hundred 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 two hundred 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 fifteen feet. The smallest of these, at its western extremity, diminished 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 two hundred feet in thickness. Overlying the tuffs, the laminations are largely horizontal and the mass is definitely a flow, but farther to the west it developes 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.

To the south a continuation of this rhyolite forms the basal exposure in the valley of Toughey Creek. Although this exposure shows the lava underlying well bedded tuffs, it does not otherwise contribute to an interpretation of its origin. Northward this horizon is not exposed. Therefore, the extent neither of the flow nor of its probable vent can be determined.

The most striking feature of this lava is the extreme

Table III - Part 1

	I	II	III	IV
Silica ----------------	73.60	75.62	74.50	68.10
Alumina ---------------	12.96	11.52	12.45	13.16
Ferrous Oxide ---------	1.19	1.19	.83	1.03
Ferric Oxide ----------	.82	.82	.85	.43
Magnesia --------------	.20	.26	.28	.34
Lime ------------------	.64	.62	1.62	1.06
Soda ------------------	1.71	1.80	3.88	4.74
Potash ----------------	7.27	6.50	4.27	2.78
Water above 105 C. ----	.80	.90	.66	7.60
Water at 105 C. -------	.40	.33	.30	.60
Carbon Dioxide --------	none	trace	none	none
Titanium Dioxide ------	.30	.34	trace	.18
Phosphorous Pentoxide -	trace	trace	.07	trace
Sulphur ---------------	none	trace	.04	none
Manganese Dioxide -----	none	none	trace	none
	99.89	99.90	99.95	100.02

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

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

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

IV. Dacitic intrusion of vitrophyre on the north side of the valley of Toughey Creek. Analysts W. H. & F. Herdsman.

Table III - Part 2

	I	II	III	IV
Quartz	33.60	38.16	31.98	26.70
Orthoclase	43.37	38.36	25.58	16.68
Albite	14.15	15.20	33.01	39.82
Anorthite	3.34	3.06	3.61	5.28
Corundum	1.02	.41	----	.41
Diopside	----	----	3.00	----
Wollastonite	----	----	.35	----
Hypersthene	1.56	1.66	----	1.86
Ilmenite	.61	.61	----	.46
Magnetite	1.16	1.16	1.16	.70
Apatite	----	----	.34	----
Water	1.20	1.23	.96	8.20
Sulphur	----	----	.04	----
	100.01	99.85	100.03	100.11

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, I.3(4).1.2.

III. Toscanose, C. I. P. W. Symbol, I."4.2.3.

IV. Kallerudose, C. I. P. W. Symbol, I."4.1(2).(3)4.

regularity of the parallel laminations. Although some of the banding is remarkably straight, much of it is slightly wavy (Figure 36) or even contorted. In the later 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.

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 .3mm. in width, contains individual quartz grains over a millimeter 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

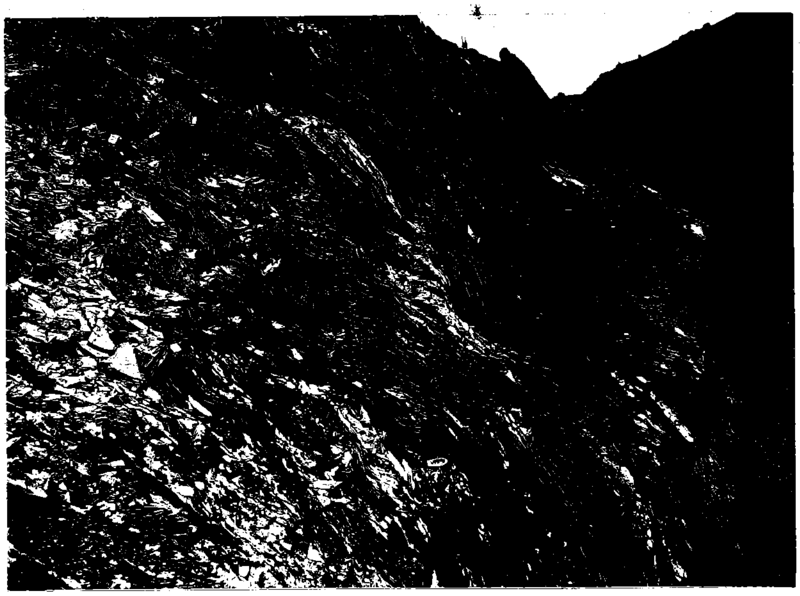

Figure 36. Typical exposure of the lower flow of platy rhyolite in the Pike Creek series.

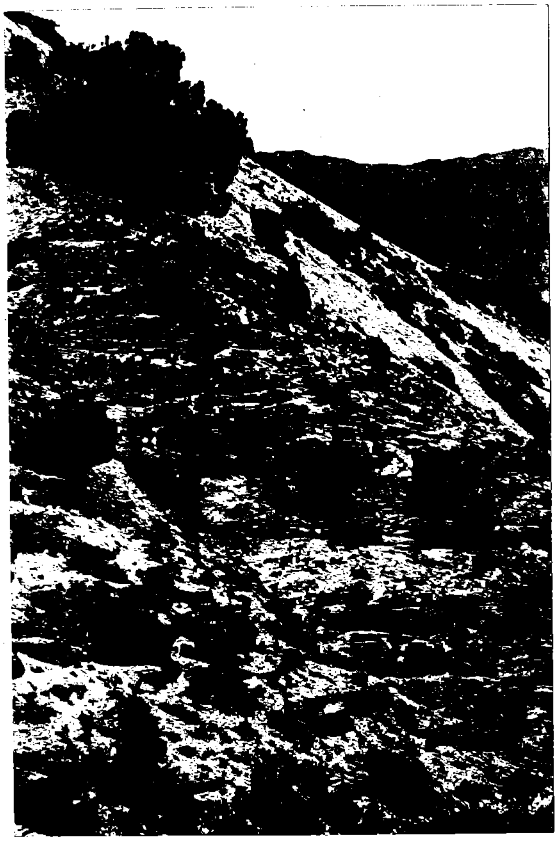

Figure 37. The middle tuffaceous beds in the main exposure of the Pike Creek series.

stratified beds lack the silicification exhibited by the perlite and its associated tuffaceous material. This silicification of perlite, both here and higher in the series, is chiefly noticeable from differential erosion. In extreme cases a whitish honeycombed structure is formed, due to 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 kaolinized and subsequently eroded.

Middle Tuffs

Capping this lower rhyolite are well bedded tuffaceous sediments close to three hundred feet in thickness. (Figure 37) These beds, which dip predominantly to the northwest at about fifteen degrees, are exposed on the south side of Pike Creek at about a half a mile from its mouth and also to the south in Toughey Creek.

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 due to 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 advance along well defined stratification and would be 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.

Upper Laminated Rhyolite

These 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 acidic plagioclase.

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

Traced less than two hundred 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 a hundred yards. In this lava, a hundred 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 five hundred feet in thickness, even disregarding the step faults, which cause a repetition of the flow at the face of the scarp. (44) 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 (Figure 38) 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

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(44) Although there are innumerable minor faults on this scarp, the major displacement previously mentioned by 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., Figure 10, p. 222.

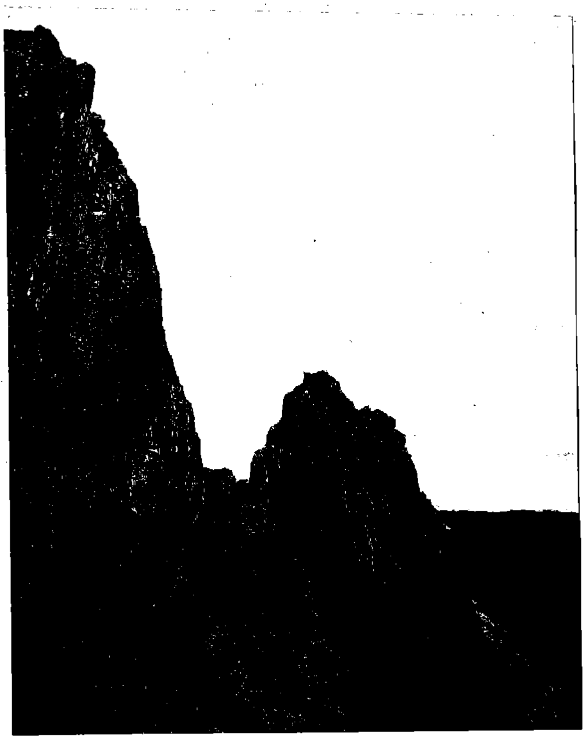

Figure 38. Vertical jointing in the upper platy rhyolite on the northern wall of Toughey Creek. The cliff on the left is about a hundred feet in height.

outcrop beneath the rhyolite. To the west, however, the rhyolitic exposure crosscuts this strata. Defining this basal contact, a dark mass of bitrophyre about thirty to forty feet in thickness outcrops for almost a hundred yards. At its eastern end the glassy rock appears to be approximately conformable with the underlying tuffs, and dips westward at about fifteen degrees. Traced to the west, this dark vitreous mass shows a progressive change in inclination (Figure 39) and crosscuts the stratified beds.

In a fairly regular arc, it gradually increases in dip to about twenty-five degrees to the southwest and finally at about fifty feet above the stream attains a slope of almost sixty degrees, (Figure 40) while in the same exposure immediately to the south, the lines of flowage become almost vertical. This lower extremity of the glassy rock, however, is not formed as an even marginal selvage on the rhyolite, for bedded tuffs are exposed in the stream bed in contact with it on the south.

In spite of this fact, the vitrophyre was considered in the field to form an irregular marginal phase of the platy lava, which is directly above it. The chemical analyses, subsequently obtained, appear definitely to disprove this relationship. It is, therefore, thought to be a later intrusion which has in part followed the margin of the rhyolitic vent. This locus of extrusion for the platy lava is indicated by the vertical laminations, which it ex-

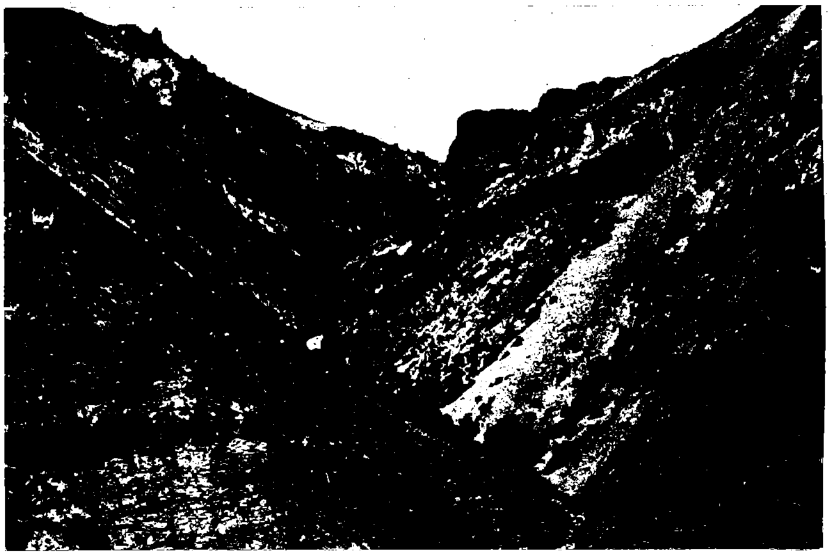

Figure 39. View of Toughey Creek showing the middle tuffaceous beds in the foreground. On the right wall of the valley the dark sheet of vitrophyre parallels the curving contact of the upper platy rhyolite, which forms the precipitous exposures both above and to the west. The cliff on the right in the distance is formed by the upper flow of biotite-dacite.

Figure 40. The steeply inclined lines of flowage in the Toughey Creek vitrophyre near the base of its exposure.

Figure 41. Inclined alignment in the spherulites at the base of the upper platy rhyolite on the northern wall of Toughey Creek. An eighteen inch hammer is visible in the center of the picture.

hibits in the creek bed about another hundred feet to the west. Again the gradient of the stream prevents the determination of the width of the vent, but its occurrence to the north in Pike Creek on approximately the same line suggests that both exposures intersect an elongate volcanic neck, which follows approximately a north and south axis.

Both the vitrophyre and the overlying rhyolite, near its lower contact, develop spherulites, (Figure 41) which are roughly concentrated in zones parallel to the flowage. At the margin of the vent, directly above the steeply inclined phase of the vitrophyre, there are some spherulites in an altered perlite that attain a diameter of about three feet. These show a slightly reniform surface of a pale greenish shade, while the inner part is of a reddish brown. The center of these masses consists of a single spherulite. The outer zone, however, in thin section shows an irregular succession of conflicting segments of spherulites that roughly radiate from the center of the mass. Between these segments there is usually a microscopic band of quartz.

Both the vitrophyre and the large spherulites are unaltered and were therefore selected for chemical analysis in place of the highly kaolinized platy lava. In the analyses, (Table III) the glassy selvage that parallels the border was found to be a true dacite, while the spherulite was an acidic rhyolite, high in potash, and almost identical in composition to the lower laminated flow. Spherulites are usually considered to have formed slowly in a static glass and they should therefore represent the true magma, aside from the fact that with crystallization the volatiles would be largely expelled.

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 either in 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 laminations. It lacks the irregular segregations of cryptocrystalline quartz that characterizes 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 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 four hundred feet high formed by this flow of rhyolite. (Figure 42) 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 also 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 a hundred 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 partially to define the rounded northern end of the rhyolitic vent.

To the east of this margin lies the inclined well stratified tuffs, which dip to the southwest at over fifteen degrees. The inclination of these beds towards the vent

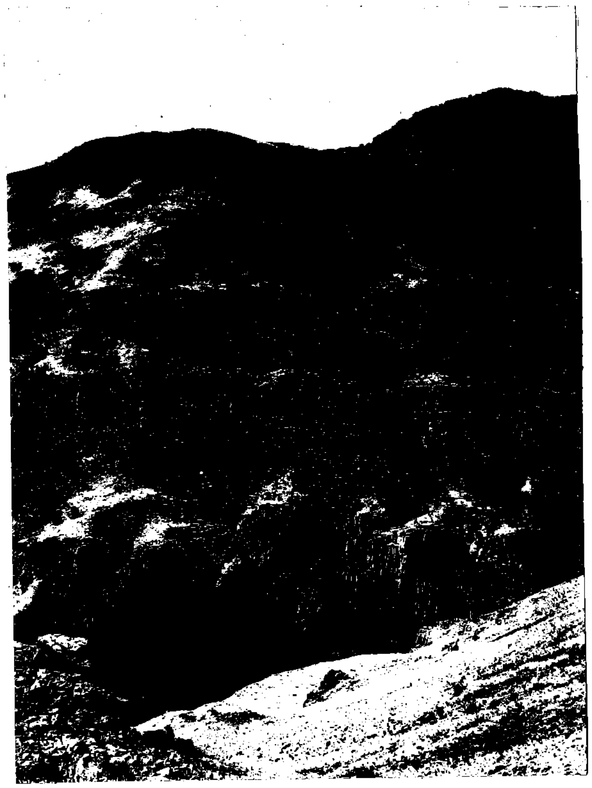

Figure 42. A view of the southern wall of the valley of Little Alvord Creek showing the four hundred foot flow of rhyolite overlaid by the two flows of biotite-dacite.

suggests a genetic relationship, but the extreme classification of the clastics demands an aqueous stratification. The slope is, of course, easily explained by the deformation induced by laccolith.

To the west, the perlite develops steeply inclined bands of spherulites. (Figure 43) Locally, some of these radiating masses attain a diameter of eighteen inches. As usual, these partitions mark the transition to the felsitic phase, which shows pronounced vertical flowage. This felsitic phase also shows bands of lava covered with small nodes formed by conflicting spherulites. (Figure 44)

Above the center of the vent, a breccia formed of perlitic fragments in a light colored tuff, rises about two hundred 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 fifteen feet or more. (Figure 45) As a rule these injections which are considered to be near surface features of the rhyolitic vent, cannot be traced for more than thirty or forty feet. They appear to end rather bluntly.

About a hundred 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

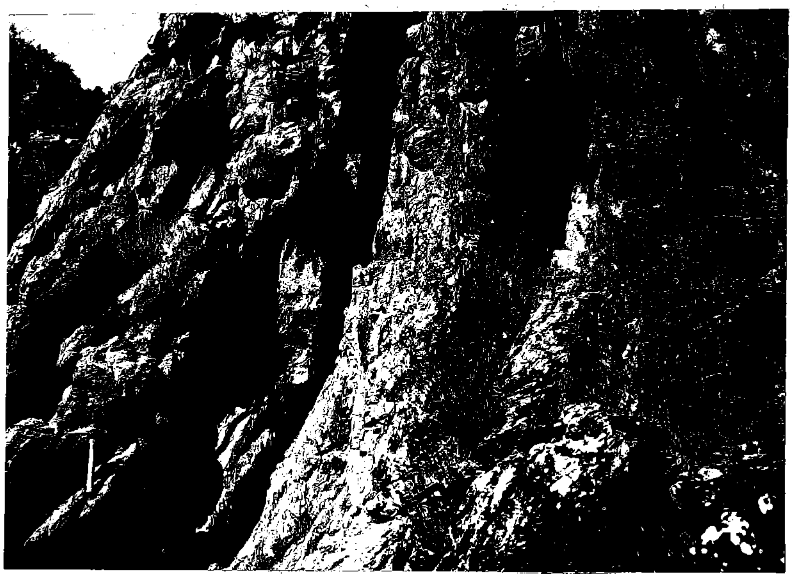

Figure 43. Coarse spherulites forming inclined partitions in the perlite at the margin of the rhyolite vent on the northern wall of Little Alvord Creek.

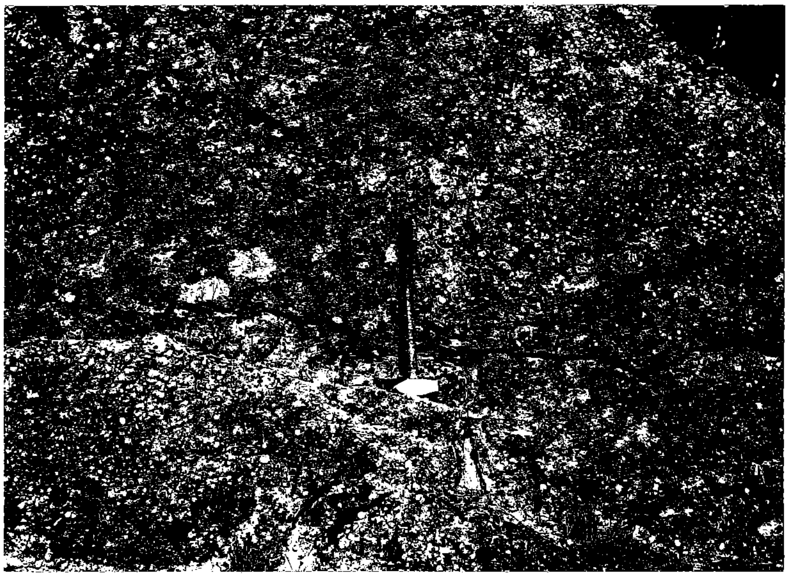

Figure 44. In the rhyolite vent on the northern wall of Little Alvord Creek, a vertical partition formed by conflicting spherulites, which are visible as small rounded excrescences.

Figure 45. Perlitic injections curving to a horizontal position in the tuffaceous breccias above the rhyolite vent on the northern side of Little Alvord Creek. An eighteen inch hammer is beneath the center of the lower injection. The basal exposure of the andesitic vent is visible at the top.

shades. This vitreous lava presumably formed the surface of the flow. As in the case of varicolored obsidians previously described by the writer (45) 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 at least 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 destroyed.

UPPER PIKE CREEK 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 (Figure 35) Here well stratified tuffs about forty 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 which are about one and a half and 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

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(45) R. E. Fuller, "The Mode of Origin of the Color of Certain Varicolored Obsidians," Jour. Geol., Vol. XXXV (1927), p. 570.

lower in the series. The alteration may be due both to the overlying lava and to the proximity of an adjacent vent to 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 possible 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 thirty percent 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 four to six millimeters 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.

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
Phosphorous 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. & F. Herdsman.

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

Table IV - 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 I

I. Toscanose, C. I. P. W. Symbol, I."4.2.3.

II. Toscanose, C. I. P. W. Symbol, I.4.2".3".

These smaller individuals average less than a millimeter in length. Some of the feldspar is an acidic 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 two millimeters 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.

Both flows appear to have been erupted from the same vents 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 two hundred 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 it forms exposures close to six hundred feet in height. (Figure 34)

In the main Pike Creek section, (Figure 35) the lower biotite-dacite shows, above the upper tuffs, a basal perlitic phase about fifty 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 even very marked in the coarse perlitic spines at the upper surface. The lower flow of dacite is here close to three hundred feet in thickness, although it decreases greatly within a hundred 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. The genetic relationship of the two flows is, however, more convincing in Little Alvord Creek valley over a mile from the scarp. There, they appear to merge into the same mass, which shows extremely persistent vertical flow structure throughout an exposure over a hundred yards in width. This locality possibly may be the direct continuation of the one to the south. At least, since the flows are exposed continuously, the activity in the two centers must have been contemporaneous.

Between Pike and Indian Creek, 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 kaolinized and exhibits a minutely hackly jointing, which causes it to erode in this interfluvial region like a coarsely granular rock. The shape of the exposures, however, is largely controlled by its highly inclined flow structure which gives rise to steep pinnacles and cliffs. (Figure 46) Between the irregular prominences is a gently rolling terrain supporting a scattered growth of junipers. (Figure 47) On the west the precipitous exposures formed by the overlying basaltic flows rise abruptly about two thousand 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 five hundred 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, the lines of flowage are inclined southward as if emerging from a vent lying to the south. Here as elsewhere to the north, perlite defines the base. 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 an indeterminable distance to the south.

The complete removal of the overlying basalt suggests that this mass of dacite might be a laccolith whose dynamic and gaseous metamorphism has rendered the overlying rock susceptible to erosion. Although the physiography is not conclusively interpreted, this idea was found to be untenable. The actual upper contact was not observed, but locally with-

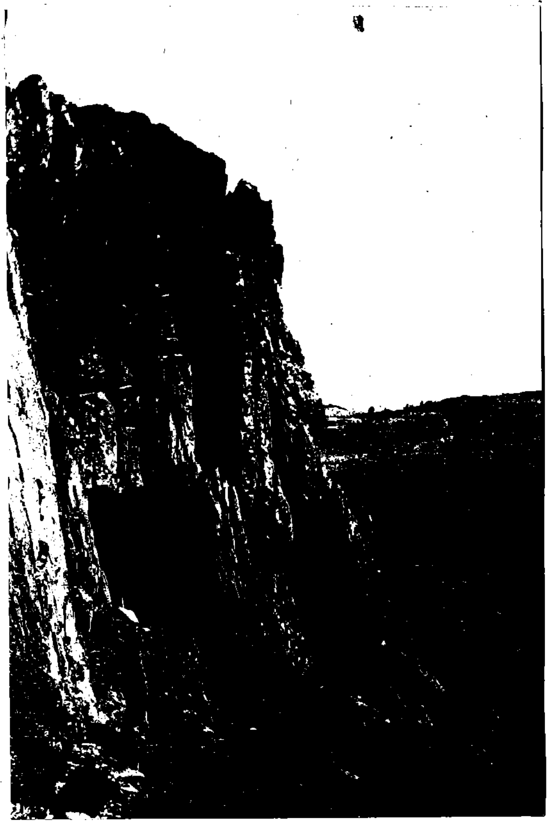

Figure 46. Vertical jointing in the vent for the upper biotite-dacite north of Toughey Creek. The exposure on the left is seventy-five feet in height.

Figure 47. The broad divide between Toughey Creek and Pike Creek exposing the upper biotite-dacite. The basalt forms the precipitous exposures in the background.

in a few hundred feet of the acidic lava, basaltic flows were found to show no indication of alteration in spite of a porous texture that would have rendered them very susceptible. To the north, on the divide between Pike Creek and Little Alvord Creek the stratigraphic relationship is well exposed and gives no indication of the deformation of the overlying formations. Added evidence is furnished by the fact that this biotite-dacite is cut by both basaltic dikes and andesitic intrusives, both of which rocks have stratigraphic equivalents higher in the section.

Rhyolitic Volcanics of Cottonwood Creek and Willow Creek

Rhyolitic volcanics, 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 three hundred feet. (Figure 48)

This rock is high in angular fragments, but it is so kaolinized that the writer has been unable to determine whether it be 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

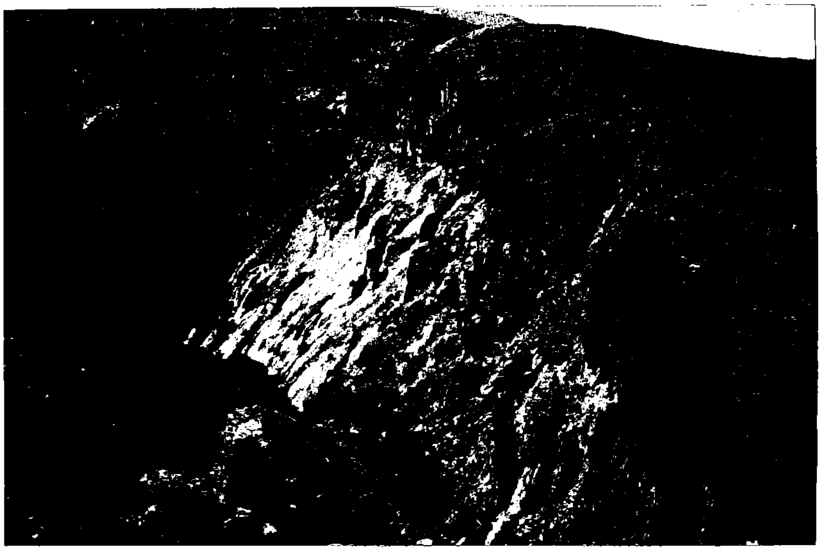

Figure 48. Rhyolitic tuffs and agglomerates at the base of the scarp in Cottonwood Creek. In the center of the view the valley is about three hundred feet deep.

Figure 49. The valley of Cottonwood Creek. At the base of the view the uppermost Alvord Creek beds may be seen between the two flows of basic andesite. Above them in the middle distance the massive phase of the main andesitic flow stands out prominently in a cliff about five hundred feet in height.

hand in thin section it appears to show slight traces of flowage and no indications of relic 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 four thousand 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 two miles to the north. There, rhyolite is definitely overlaid by the later andesite and yet near the contact it appears to have 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 kaolinized. These exposures, which continue for about a quarter of a mile, show a thickness of approximately five hundred 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 there appears to be a poorly defined vertical fault which has permitted the uplift of the eastern wall. The displacement cannot be much more than a hundred feet for the upper surface of the rhyolite sloping westward at about twenty degrees is exposed beneath the overlying andesite. This fault presumably is the northern continuation of the one previously mentioned in Cottonwood Creek. The displacement which is the reverse of that occurring in the customary step faults is attributed to later isostatic adjustment.

This rhyolite in Willow Creek shows a few scattered feldspathic phenocrysts, up to four millimeters 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
Phosphorous 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. & F. Herdsman.

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

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

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

Table V - 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	25.16	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.

Andesitic Lavas

Lower Andesitic Flows

To the north of Alvord Creek, as previously mentioned, a flow of basic andesite, about one hundred 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. (Figure 49) The exposure can be followed a short distance southward and then found again with similar relationship about another mile to the south on the northern side of Alvord Creek. (Figure 50) Here it is exposed for several hundred yards. In the valley of Cottonwood Creek the flow is over two hundred 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 sixty percent 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

Figure 50. 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 massive phase of the great andesitic flow rises about nine hundred feet.

Figure 51. The tuffaceous material interstitial to the flow breccia of the upper flow of basic andesite to the north of Alvord Creek.

Table VI - Part 1

	I	II
Silica	55.30	56.90
Alumina	17.80	17.55
Ferrous Oxide	5.28	6.05
Ferric Oxide	1.98	.27
Magnesia	3.38	3.82
Lime	7.40	7.05
Soda	3.92	3.36
Potash	1.78	1.75
Water above 105 C.	.70	1.56
Water at 105 C.	1.10	.30
Carbon Dioxide	none	none
Titanium Dioxide	.92	.98
Phosphorous Pentoxide	.36	.18
Sulphur	none	none
Manganese Dioxide	.13	.20
	100.05	99.97

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

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

Table VI - Part 2

	I	II
Quartz ----------------	4.68	7.86
Orthoclase ----------------	10.56	10.01
Albite ----------------	33.01	28.30
Anorthite ----------------	25.85	27.80
Diopside ----------------	6.58	5.07
Hypersthene ----------------	12.04	16.22
Magnetite ----------------	3.02	.46
Ilmenite ----------------	1.67	1.98
Apatite ----------------	1.01	.34
Water ----------------	1.80	1.86
	100.22	99.90

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.

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 flowage of the laths which it enclosed. In another specimen of the same flow there are 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 partially decomposed glass. Small grains of magnetite are distributed throughout the rock.

The upper one of these two flows shows at the surface a vesicular flow breccia. Between the coarse fragments is a pale buff colored tuffaceous material that appears to be derived from the comminution of the breccia. Locally the relationship indicates that the vesicular masses were actually in the process of disintegration and of alteration to the tuffaceous material at the time of consolidation. (Figure 51) More commonly, however, the origin of the fragmental material is hidden by a flow alignment that curves roughly around the larger blocks.

Overlying this breccia is a bed of well stratified tuffaceous material which varies from a thickness of about twenty feet in Cottonwood Creek to less than half that figure in the exposures on the northern side of Alvord Creek valley. Aside from its stratification the material composing this bed is identical to that forming the interstitial particles in the breccia. Although the bedding, in general, is parallel and quite level, it shows some irregularities, which are visible in photograph. (Figure 52) The origin of these features was not interpreted.

These beds appear to have formed on the surface of a flow which was still liquid. This relationship is proved by exposures north of Alvord Creek where the bedded tuffs have locally been cut and upturned by intrusions from the underlying andesite flow. (Figure 53) These injections are attributed to the hydrostatic pressure of the still molten lava forcing it to escape through the breccia, which capped the flow, and thereby to disrupt the tuffaceous beds resting on its surface.

The origin of the bedded tuffs is not conclusively determined. Their gradational relationship with the underlying breccia suggests that they may, at least in part, be due to the accumulation of the fine particles of the breccia at the surface as they were carried upwards by the liberated gasses. In this case the bedding might possibly be explained by flowage. If, as in a liquid, the movement took place in planes parallel to the contact, the fragments in such a plane would be comminuted and thus formed into a finer bed. No conclusive evidence of flowage, however, in the stratified beds was found. In consequence the tuffs are attributed chiefly to the aeolian accumulation of volcanic ash on the surface of a still molten flow. The ash, however, from its relationship and composition must have been contemporaneous in origin with the lava.

The Great Andesitic Flow

General Relationship

Directly overlying this flow there are exposures of massive columnar andesite varying in thickness from five hundred to nine hundred feet in Cottonwood Creek (Figure 61) and Alvord Creek (Figure 60) respectively. In both instances the massive phase is capped by coarse vesicular andesitic breccias containing numerous injections of dark aphanitic andesite, which usually curve into a roughly horizontal position. This phase of injected breccias varying from at least three hundred to a thousand feet in thickness can be traced northward to Mann Creek, where it is truncated by a transverse fault. It is exposed for a total distance of about ten miles. This breccia and its injections are considered to have been formed as the surface feature of a great viscous flow which, in the opinion of the writer, welled above its vent to a maximum thickness of approximately fifteen hundred feet.

Near the northern limit of the exposures, between Mosquito Creek and Little Mann Creek, there is evidence that this great mass of lava developed its own subsidiary volcanic activity. In this locality both cinder cones and flows occur above the injected breccias. These volcanics are con-

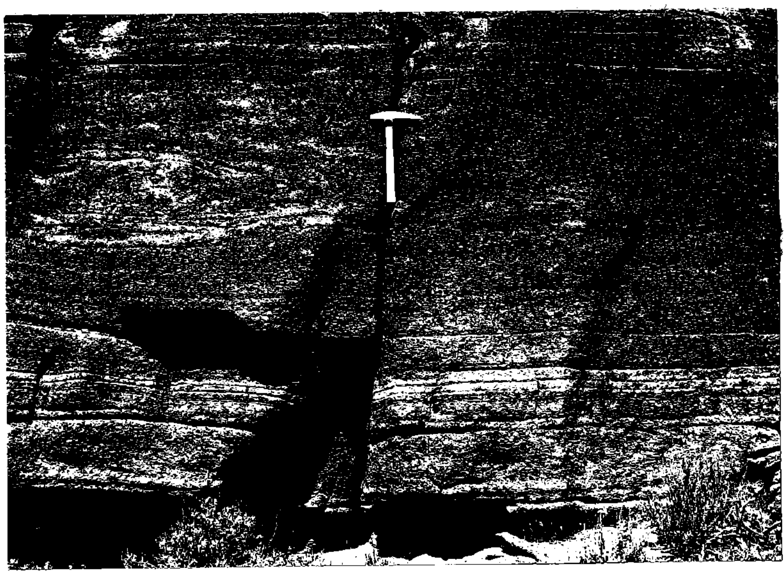

Figure 52. Bedded tuffs on the surface of the flow breccia capping the upper flow of basic andesite north of Alvord Creek. The hammer marks the horizons showing the unexplained irregularities.

Figure 53. The tuffaceous beds upturned by the local intrusion of the andesite from the flow on which they rested. A similar intrusion is exposed in the background on the left.

sidered to have been formed by the lava of the great viscous mass breaking through the poorly consolidated breccias that capped it. Farther to the south, similar satellitic flows may be present although no definite evidence was observed.

The vent characteristics of the andesite are best exposed at its southern end where it cuts the uparched Alvord Creek Beds and the northern margin of the Pike Creek volcanics. The rounded southern end of this large andesitic vent is exposed on the northern side of Little Alvord Creek, directly in line and in contact with the northern end of the previously described rhyolite vent. Evidence of the northern margin of possibly the same andesitic vent is noted in Alvord Creek. Northward erosion has not sufficient depth to expose a source, although features in the overlying lava testify to the presence either of an elongate vent parallel to the scarp or of a series of vents along a continuous line of weakness.

The low degree of crystallization testifies to the high viscosity of the andesite. Away from the vent it would therefore be expected to decrease rapidly in thickness. The topography permits it to be traced only to the west, and for merely a mile or so at the most. As a rule the upper limit of the andesite is hidden by the talus from the overlying basaltic flows. Where it is exposed, however, it shows thin sheets of basalt abutting against a surface that sloped at about fifteen degrees. (Figure 77) No evidence was observed to indicate an erosional interval prior to the extrusion of the basalt.

Vent Characteristics

Owing to the complexity of the geology in the valley of Little Alvord Creek a brief review of some of the facts already stated may be necessary to enable the reader to grasp the relationship of the andesite. On the northern side of the valley near the scarp, the Alvord Creek beds are exposed dipping southward. This deformation is due to the rhyolitic laccolith, which outcrops on the main scarp about a mile to the north. On the southern side of the valley a roughly horizontal rhyolitic flow nearly four hundred feet in thickness forms a precipitous cliff. Although the stream has eroded the contact, this flow must have abutted against the dip slope of the southern limb of the laccolith. At not more than a half mile from the scarp the rhyolite flow, which has been referred to as the Little Alvord Creek rhyolite, developes definite vent characteristics. Above this vent on the northern side of the valley, white tuffaceous material injected by perlite rises about two hundred feet higher than the surface of the flow. On the southern side of the valley, this flow is overlaid by the two biotite-dacite flows that cap the Pike Creek volcanic. The lower of these two flows also outcrops on the northern side of the valley. The surface of this flow is slightly higher than the tuffaceous material that marks the vent for the underlying rhyolite. A few hundred yards north of the valley

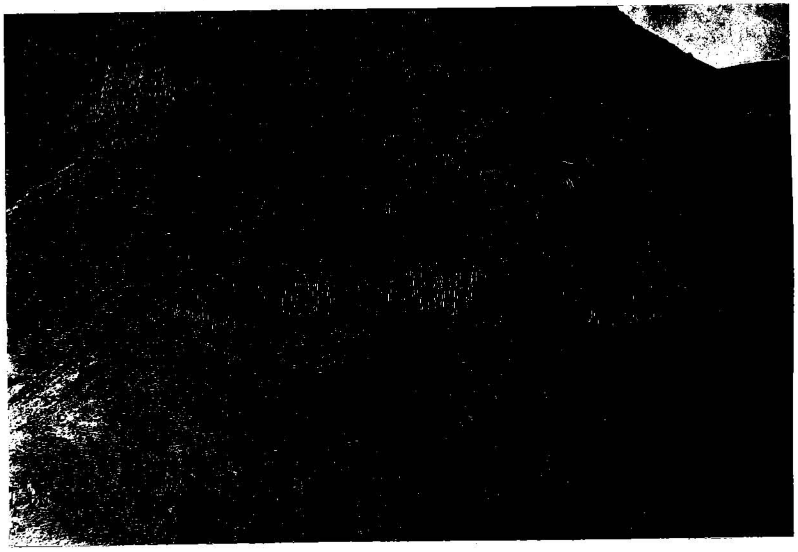

Figure 54. The rounded exposure in the center is formed by the southern margin of the great andesitic vent on the northern side of the valley of Little Alvord Creek. The upper part of the rhyolitic vent outcrops on the lower left at about eight hundred feet below the basaltic flows which form the cliff at the top.

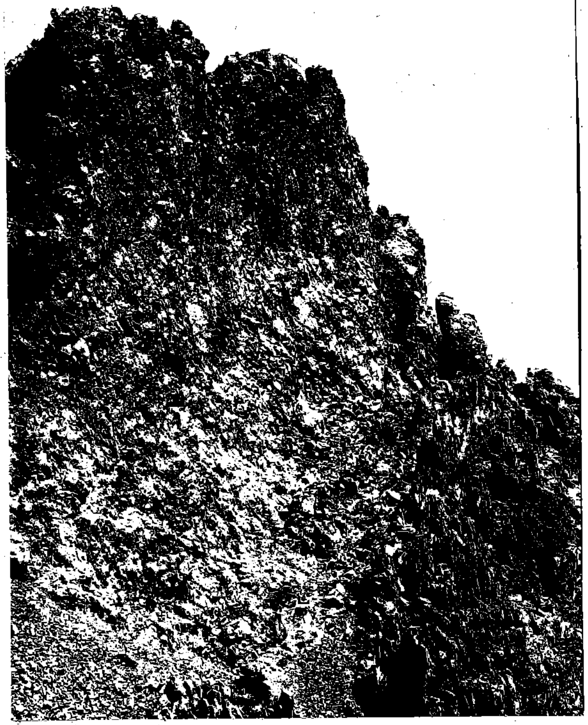

Figure 55. Reddish andesitic breccias in the center of the andesitic vent north of Alvord Creek. On the right is a platy injection with vertical jointing. A figure in the foreground on the left furnishes the scale.

least in part, by the abrupt margin of a viscous flow. In general, however, the exposure is considered to represent andesite welling from a vent into a flow which caps the dacite.

Farther to the west on the north side of the valley of Little Alvord Creek the andesite may be observed in scattered exposures beneath the basalt. These outcrops lack the vent characteristics. In spite of the fact that some of them are at the same level as the upper dacite on the opposite side of the valley, they are considered to be part of the andesite flow. Where the canyon of the stream intersects this same horizon of andesite at about two miles from the scarp, platy flow structure and red breccias again strongly suggest a locus of extrusion.

This locality is about a mile and a half due north of some small andesitic intrusions of the dark glassy type, that are exposed cutting the dacite in the western part of the valley of Pike Creek. It is possible that together they may mark the position of another series of vents on a north and south line of weakness. If so, however, they are contemporaneous in their activity with the main ones to the east.

To the north only the upper part of the andesite is exposed in the relatively shallow valley formed by the south fork of Alvord Creek. These exposures show considerable vertical platy jointing that suggests the continuation of the main vent, but erosion has not sufficient depth to disclose a crosscutting relationship. On the south side of Alvord Creek, (Figure 56) however, there is a magnificent exposure of columnar andesite, showing individual columns over three hundred feet in height. Although the upper exposures are not distinct the columns appear to extend upward for over twice that height. Downward on the eastern side of the exposure they curve eastward and become progressively reduced in size from about four feet to approximately six inches in diameter.

To the north at an elevation several hundred feet lower, curving columns are exposed at a water fall in Alvord Creek dipping northward to an unexposed cooling surface. (Figure 57) These two localities are considered to mark points adjacent to the rounded end of a broad fissure like vent which may extend continuously to Little Alvord Creek. The wall rock presumably is formed by the Alvord Creek beds which are exposed to the east.

Within about two hundred yards to the east of the main exposure a small elliptical intrusion of dark aphanitic andesite cuts the tuffs. The outline is roughly about one hundred by one hundred and fifty feet across. (Figure 58) Two similar far smaller intrusions are exposed within a few hundred yards to the south. These three volcanic necks lie almost precisely on a common north-south line which their major axes parallel. In like manner the vents, from which

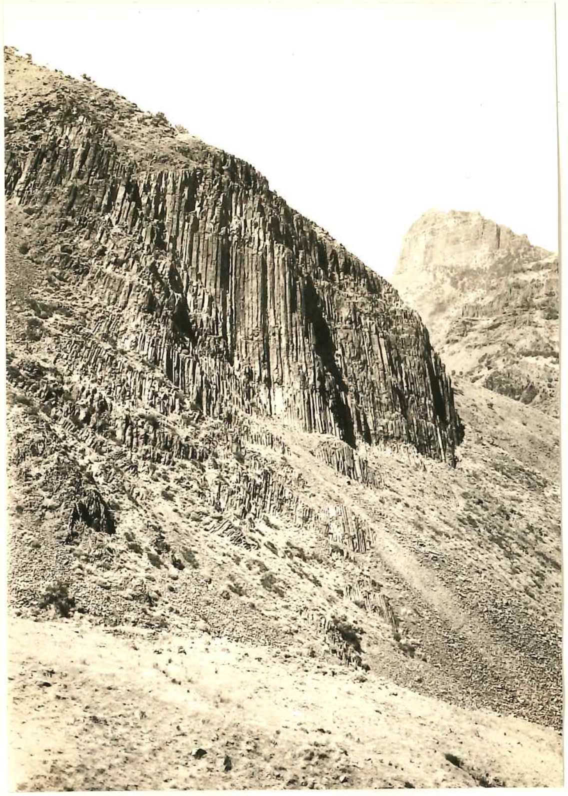

Figure 56. Columnar andesite forming the great neck on the southern wall of Alvord Creek valley. The columns are at least three hundred feet in height. At the basal margin they curve until normal to a roughly vertical contact.

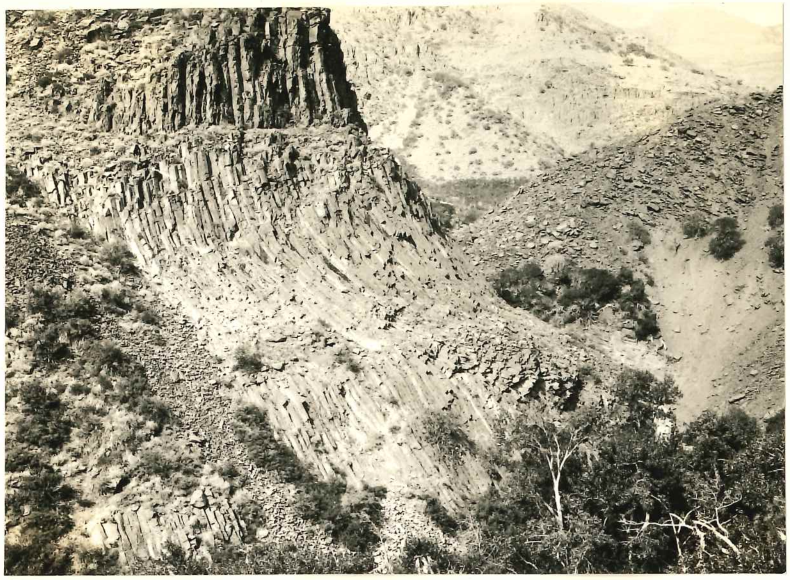

Figure 57. The curving columns at the northern margin of the andesitic vent in Alvord Creek.

Figure 58. View of the southern wall of Alvord Creek valley showing the great andesitic vent on the right, and the largest of the series of smaller intrusions on the left.

the great mass of lava was extruded, may have occurred at intervals along one main line of tensional weakness.

The base of the great flow is exposed on the northern side of Alvord Creek valley directly opposite the curving phase of the magnificent columns, which presumably marks the margin of one of the main necks. Farther northward it is also exposed both in the valleys of Cottonwood Creek and Willow Creek, but to the east of the zone in which the andesite exhibits vent characteristics, consisting of the typical vertical platy jointing accompanied by brecciation. At the mouth of Little Mann Creek there are exposed inclined andesitic tuffs, (Figure 59) which represent the lip of a crater, from which the lava was probably in part extruded. Elsewhere the base in not visible. The discordant relationship of the volcanic necks, from which the andesite was derived, is apparent only where the flow thins to the south as it overlies the more elevated Alvord Creek Beds and the Pike Creek volcanics.

Massive Phase

On the northern side of Alvord Creek a precipitous exposure of massive andesite rises about nine hundred feet. (Figure 60) Towards its base this exposure also shows magnificent columnar jointing. The columns which are predominantly rectangular average nine to ten feet in diameter. Although the jointing may locally be traced almost to the top of the exposure, it is lost to a great measure in

Figure 59. View of the main scarp at Little Mann Creek showing the tuffaceous deposits beneath the andesitic injected breccias. To the right beyond the margin of the picture, the beds dip in the opposite direction, presumably due to their deposition on the inner slope of a crater.

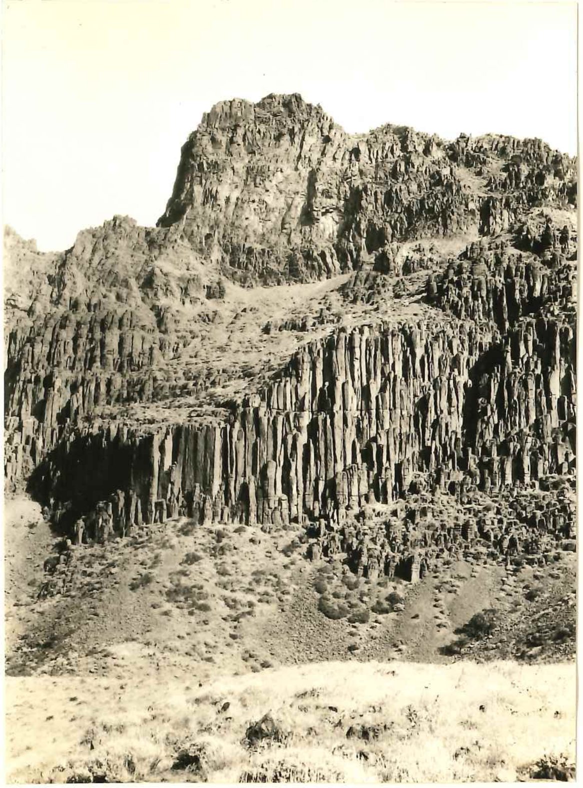

Figure 60. The massive phase of the great andesitic flow north of Alvord Creek. The exposure is about nine hundred feet in height. The columns average at least ten feet in diameter. The local absence of columnar jointing in the upper part is due to deuteric alteration.

irregular zones of alteration in the upper part of the mass.

To the east, for several hundred yards, this massive andesite overlies the well defined lower flow which is capped by the previously mentioned thin bed of tuffs. In general, the columns show here a subsidiary horizontal platy structure that was probably induced by the flowage. To the west, the lava may be traced into the western extension of the previously described columnar andesite exposed on the southern side of the creek. Northward the massive andesite outcrops continuously for about another mile to Cottonwood Creek. Still overlying the lower andesitic flow and the capping tuffs, it is exposed in both forks of the stream. (Figure 61) Here, however, the columnar phase has thinned to about five hundred feet in thickness. Locally it retains this thickness quite consistently. The absence of exposures on the scarp prevent it from being traced northward from Cottonwood Creek. Two miles to the north in Willow Creek it does not occur, although stratigraphically at least the upper part of the horizon should have been exposed.

The only other exposure of this massive phase of the andesite is at Mann Creek, (Figure 62) where the outcrop is truncated by a transverse fault. Although its base is not visible, this exposure has a vertical extent of nearly four hundred feet. The jointing of this andesite is not well defined, but it shows distinctly both columns and horizontal platy joints.

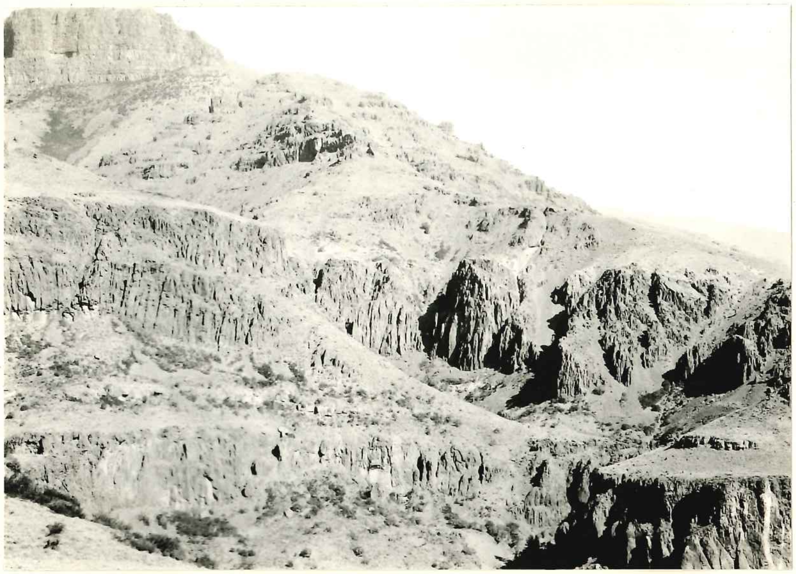

Figure 61. The north fork of Cottonwood Creek. At the base, the upper flow of basic andesite is exposed. Above it the tuffaceous bed is visible beneath the columnar phase of the great flow. The more poorly defined upper exposures are formed by the injected breccias. On the left the basaltic flows form the cliff at the top.

Figure 62. The columnar andesite in the valley of Mann Creek. Above on the left the injected breccias are visible. In the distance the basalt is exposed.

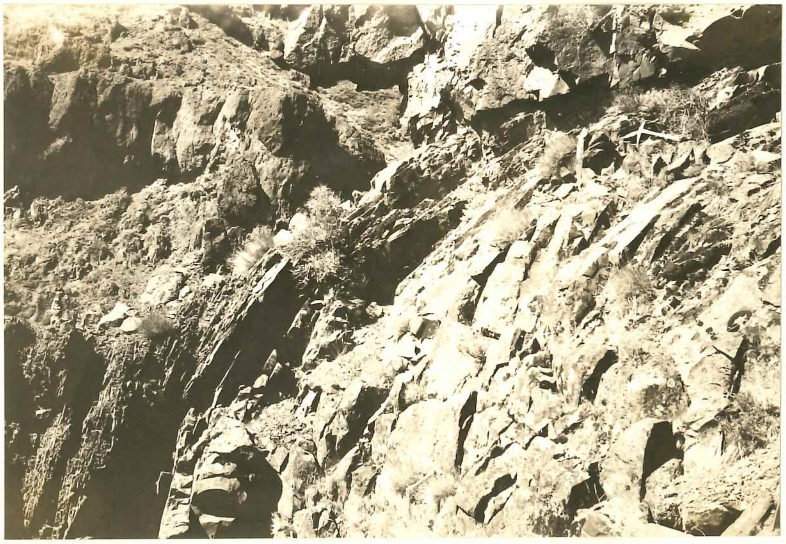

Figure 63. Andesitic injection on the northern side of Little Dry Creek curving to the horizontal.

Aside from a strong similarity in the rock, these exposures of the massive type show at the top a light grey highly kaolinized phase with irregular small cavities, which suggests strong deuteric gas action. Downward this gassed zone grades into the normal rock. Unfortunately this light grey porous rock is easily eroded, so that its contact with the overlying andesite is masked by soil. This overlying phase consists predominantly of reddish vesicular andesitic breccias injected by intrusions of rather glassy dark grey andesite with very platy jointing. These persistent exposures are referred to by the writer as the injected breccias.

In the three localities where the massive columnar type occurs, the rock is extremely similar. In spite of its great thickness it is always remarkably aphanitic throughout. Where fresh it is of a fairly dark grey, but the gassed phases range from light grey to greenish or even reddish shades. Although it shows minor variations both in texture and in the content of small phenocrysts, the variations are almost the same in their relationship in each locality.

The gassed kaolinitic phase at the top of the columns contains megascopic crystals of a brownish amphibole. This mineral, which has many of the properties of barkevikite, forms, at the most, close to five percent of the rock. The largest of these phenocrysts in the great exposure north of

Alvord Creek was about 3 mm. in length. As a rule these crystals are partially replaced by magnetite or the brownish iron oxides. In many instances only the pseudomorphs survive. In the great exposure even these remnants are rarely observed below the upper three hundred and fifty feet. Similar hornblende, however, is present in the andesite exposed in the large vent in the valley of Little Alvord Creek.

A pale greenish augite appears invariably to be present as a minor constituent. It is usually in irregular grains less than .5 mm. in diameter. A few thin sections show an occasional well shaped crystal of hypersthene with a maximum observed length of .8 mm. In contrast to the amphibole, the pyroxene is fresh. The distribution of these mafics has no regularity.

In the upper part of the exposures andesine shows a marked seriate development with individual crystals ranging up to 2 or 3 mm., but with the average more nearly .1 or .15 mm. The plagioclase usually shows irregular alignment. Although the presence of glassy inclusions in the larger crystals frequently renders their zonal growth apparent, the laths as a whole show but slight change in composition. They are predominantly of a fairly acidic andesine.

Although the plagioclase as a rule forms about sixty percent of the rock, the texture can seldom be classed as pilotaxitic for there is usually a cryptocrystalline semiopaque ground, which is probably derived from a decomposed glass. It is formed largely of indistinct feldspathic material filled with opaque dust that 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 at least .2 mm. in length. In most specimens, however, the smaller laths, without increasing in size, become ill defined and irregular in outline. The fine cryptocrystalline groundmass, thus formed, may appear blotchy in thin section owing to local kaolinization, which otherwise does not affect the texture. Near the base of the great columns in Alvord Creek the content of plagioclase phenocrysts locally diminishes. Here the crystals are largely fragmental. In spite of these small variations, analysis of a remarkably fresh specimen from the uppermost hornblendic zone coincides almost exactly with an analysis from the base of the columns about nine hundred feet below. (Table VII)

Injected Breccias

Vesicular breccias and aphanitic lava injected into it form the most persistent phase of the andesite and are exposed continuously for at least eight miles. Usually these injected breccias vary in thickness from about six hundred to a thousand feet. The base, however, is exposed only where it overlies either the previously described massive phase or some andesitic tuffaceous beds exposed low on the scarp between Little Mann and Little Dry Creeks. These beds

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
Phosphorous 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. & P. Herdsman.

I. The base of the great columns.

II. Unaltered andesite from the top of the massive phase.

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.

Table VII - 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".

show a sharp change in inclination which appears to be due to primary deposition at the margin of a crater.

Although these breccias and their injections are very varied in detail, they are in general so similar that they may be described as a unit. Before considering some of their many variations, the writer will present a brief description of their predominant characteristics together with an hypothesis which may explain many of their peculiarities.

Many of the injections are vertical at the base of their exposure, but traced upward they either curve sharply to a horizontal position (Figure 63) or locally end as a fan shaped injection with widely diverging platy jointing. Figure 64) Most of the injections are roughly horizontal. (Figure 65) They consist usually of a thin mass under ten feet in thickness following a slightly sinuous course through the breccia. The platy jointing of these injections renders them susceptible to erosion, while the reddish breccias, which they cut, are as a rule more resistant. Viewed from a distance, the horizontal structure thus formed is very suggestive of a series of flows, although the bulk of the section is usually composed of breccia. (Figure 66)

As a rule the vertical injections can be traced downward for only ten or twenty feet before they are found almost invariably to end abruptly in a vesicular breccia. In the transition the lower extremity of the injection becomes finely vesicular and ends rather abruptly in an

Figure 64. Andesitic fan shaped injection intruding the breccia directly above the shoulder at the top of the massive columnar phase north of Alvord Creek

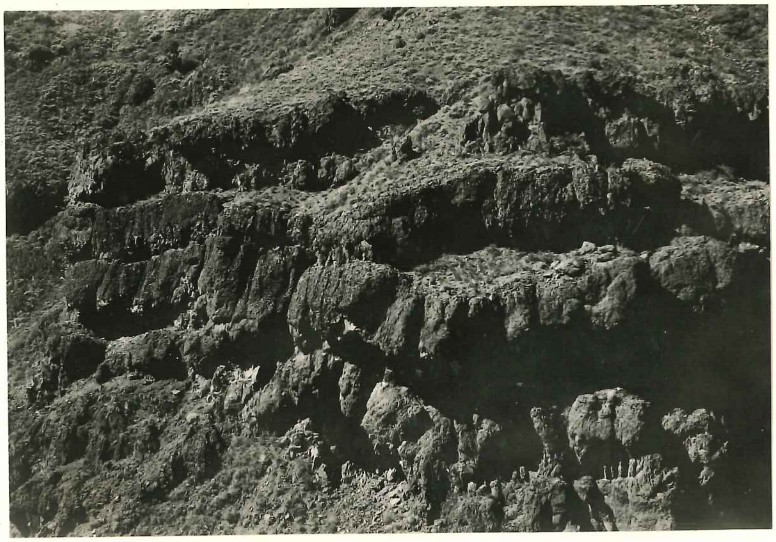

Figure 65. Injected breccias on the southern side of Little Dry Creek. The breccias form the more resistant massive exposures while the slightly sinuous course of the horizontal injections is defined chiefly by their erosion.

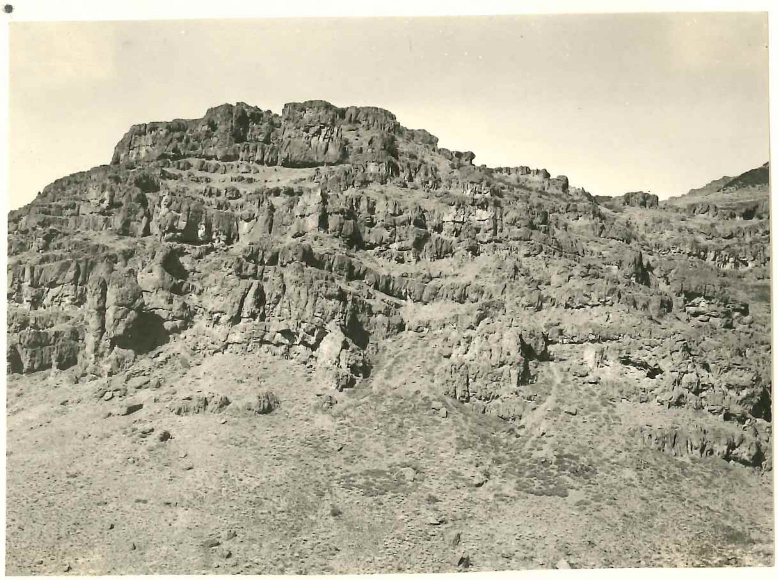

Figure 66. The scarp south of Little Dry Creek. Owing to the roughly horizontal injections the breccia resembles a series of flows.

irregular highly porous surface that usually has been oxidized to a reddish shade presumably by the volcanic gases. In numerous examples the elongation of the vesicles indicates that the flowage came from the position now occupied by the underlying vesicular breccia.

This irregular alternation of breccias and injections may be repeated continuously in the same section with marked similarity, although varying in detail. Locally, however, the horizontal injections may not be present. Instead in a well defined vertical zone the breccias may be found to be relatively homogeneous for a height of many hundred feet. On the other hand in the upper part of the northern exposures, there are locally masses of andesite that are definitely formed by flows. Other masses, however, show a gradational relationship to the underlying breccia and an outline that appears to be too irregular for a flow. The origin of this type which is not conclusively determined, will be discussed later.

The uppermost injections exhibit characteristically a spinous jointing parallel to the direction of flowage. This phase is of a dark grey color and shows a dull vitreous luster. In thin section it usually shows minute feldspathic microlites, averaging about .05 mm. in length, in a dark opaque ground. In other very aphanitic types an incipient feldspathic crystallization in broader flakes gives the rock in thin section a mottled appearance.

The more common platy types are rather similar petrographically to the massive columnar rock already described. It invariably appears to manifest a seriate development of the andesine laths, the largest of which seldom exceed 1 mm., while in the main mass of the ground they average from .1 to .2 mm. The ground is either glassy or cryptocrystalline. In either case it is high in magnetite dust. As in the columnar type a few small crystals of pale greenish augite and of orthorhombic pyroxene are usually present, but at the most the two together do not constitute as much as five percent of the rock. The brown amphibole characteristic of the uppermost kaolinized zone of the massive andesite was not observed in the injections.

Chemically a specimen from the uppermost injections north of Alvord Creek proved to be very similar to the analyses of the upper and lower phases of the underlying massive andesite. (Table VII) The greatest discrepancy lies merely in the fact that the content of both the iron and the magnesia is slightly more than one half of one percent greater in the platy injection than in the massive phase.

The Mode of Origin of the Injected Breccias

The andesite is considered by the writer to have been extruded from an elongate vent or a series of vents parallel to the present scarp. The lava owing to its great mass and to its high viscosity, is thought to have welled into a thickness of approximately fifteen hundred feet. The upper surface of this lava would have chilled very possibly to a vesicular glass while the extruded material beneath it was still increasing in depth. As in the formation of a flow breccia this surface would have been broken by the movement of the lava.

The increased viscosity of the partially chilled near surface lava would have caused the retention of the volatiles, which, instead of being concentrated above the vent, would have been diffused through the overlying lava. The surface of the flow would have formed the logical release for the increasing gas pressure. This pressure in the opinion of the writer would have caused the injection of the uppermost still fluid lava into the overlying breccia. On intruding the unconsolidated breccias, the injections would have curved into the horizontal position in a manner perhaps similar to the experiments of Chamberlin and Link.(46) These experiments showed that liquid forced upward through artificial strata, not subject to compression, tends to spread laterally in the unconsolidated horizons.

Happening probably with explosive violence the individual injections would have caused a release of pressure

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(46) R. T. Chamberlin and T. A. Link, "The Theory of Laterally Spreading Batholiths," Jour. Geol., Vol. XXXV (1927), p. 342.

in the still fluid lava immediately below. This would have resulted in the expansion of the volatiles. This expansion would have formed a vesicular lava at the base of the injection and at the same time would have induced a reduction of temperature causing immediate solidification. The upper part of the injections would have been too viscous to permit a liberation of the volatiles. The platy jointing alone testifies to great viscosity, which was so extreme that open cavities are present locally between the contorted laminations at the nose of an injection.

The extreme fragility of finely vesicular glassy lava, formed at the base of an injection, would permit it to be easily brecciated by any movement in the underlying lava. With a period of quiescence the volatiles would again have accumulated. Rising into the vesicular breccia they would have tended to alter it to the reddish shades so common in near vent lava. With sufficient increase of pressure, injections into the overlying breccia would again have occurred,forming more vesicles at the base of the solidified cap.

In such manner, the gradual solidification of the great flow progressing downward from the surface might have been accompanied by a periodic repetition of injections and breccias, which would have formed a continuously thickening cap of solidified lava on the still molten underlying mass. The great columnar phase previously described would be formed by the solidification of this underlying mass. The highly kaolinized and porous upper surface of this massive lava is attributed to the retention of volatiles beneath the capping breccias. The presence of these volatiles would also explain the local crystallization of an amphibole.

Subsidiary Activity

From Little Mann Creek to Little Dry Creek at about eight hundred feet above the lowest exposures of the injected breccia a persistent bed of stratified tuffs is exposed at numerous places lying on the top of a breccia. (Figure 67) Although the bedding is well defined the horizon is very irregular in its inclination. In spite of this distortion it retains a relatively uniform thickness varying from about two to five feet.

This thin layer of tuffs is thought to have been formed as a deposit of ash, extruded on top of the injected breccias from satellitic vents on the surface of the great flow. The subsequent movement in the surface of this mass of unsolidified lava, on which it rested, would have caused the distortion of the bed.

Usually the thin undulating horizon of tuffs is directly overlaid by a mass of andesite one hundred to one hundred and fifty feet in thickness. This lava shows approximately horizontal platy jointing, modified towards its base into irregular columnar structure. That this upper mass is later than the underlying tuffs is indicated by the fact that beneath the thin layer of breccia, which marks its base, the

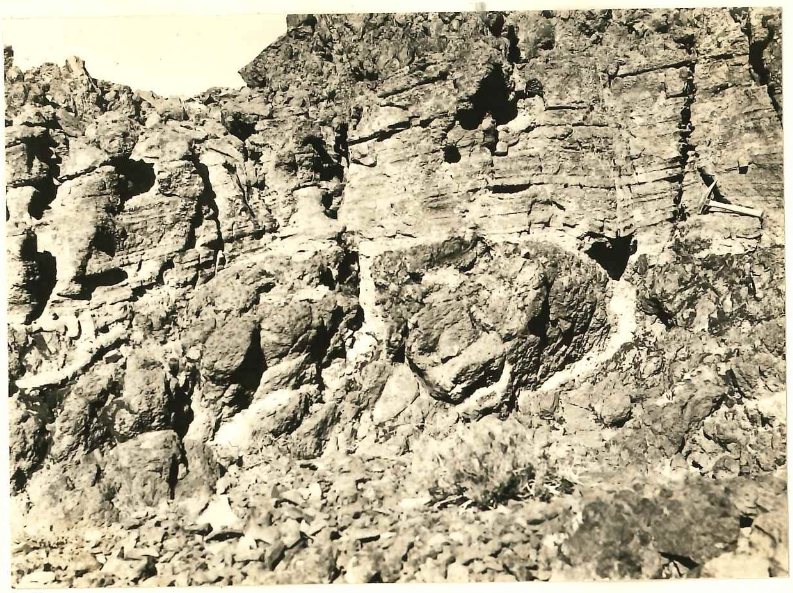

Figure 67. On the southern side of the divide between Mann Creek and Little Mann Creek. The thin bed of tuffs which presumably marks the surface of the great andesitic flow.

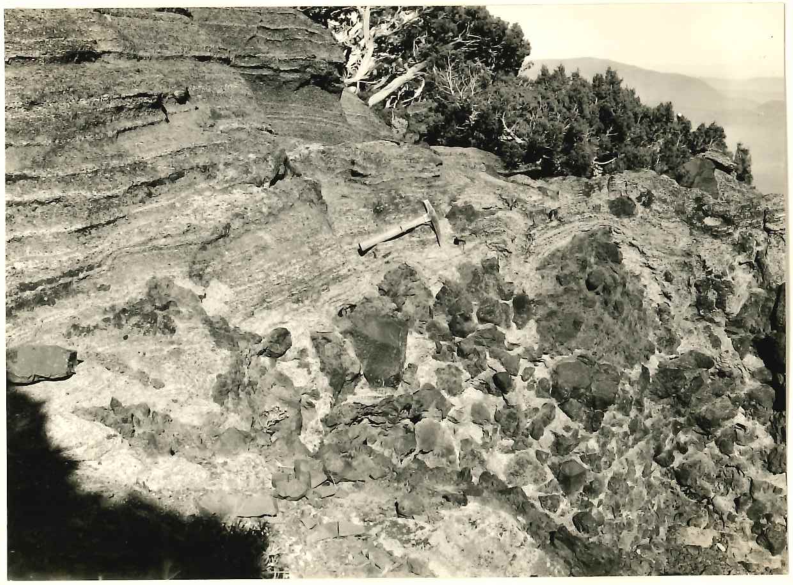

Figure 68. In Little Mann Creek valley, the northern continuation of the tuffaceous beds forming the northern cinder cone. The aeolian bedding is disturbed both by minor injections and by the movement of the underlying breccia.

tuffs are indurated and altered to a shade of orange red that is especially intense at the upper contact.

At its surface this flow shows irregular injections into an overlying coarse vesicular breccia which in turn is overlaid by more stratified tuffs. (Figure 68) This contact is gradational, for the fine greyish buff colored tuffaceous material continues downward between the blocks of the breccia. As in the case of the underlying andesitic flow at Alvord Creek and Cottonwood Creek, small fragments broken from the margins of these blocks are incorporated in this material. Although some of the tuff is thus derived from the breccia, many of the fragments are of a non-vesicular dark glassy andesite, that must be derived from an aeolian origin. In the valleys of Little Mann Creek and Little Dry Creek, the injections from the underlying flow have intruded the breccias (Figure 68 & 69) and the overlying bedded tuffs.

On the north side of Little Mann Creek these tuffs are only about ten feet in thickness. Traced southward, however, they prove to be the direct continuation of the ash from a cinder cone that thickens gradually to the south until it reaches a thickness of several hundred feet on the divide between Little Mann and Little Dry Creek. (Figure 70) The bedding of these tuffs is here inclined northward at about thirty degrees. (Figure 71) To the south of Little Dry Creek the tuffs have been largely stripped by erosion, but the

Figure 69. In the center the upper part of the satellitic flow may be seen injecting the breccias underlying the northern cinder cone in the valley of Little Dry Creek.

Figure 70. A section of the northern cinder cone on the northern side of Little Dry Creek. The cliff on the left is about two hundred feet in height.

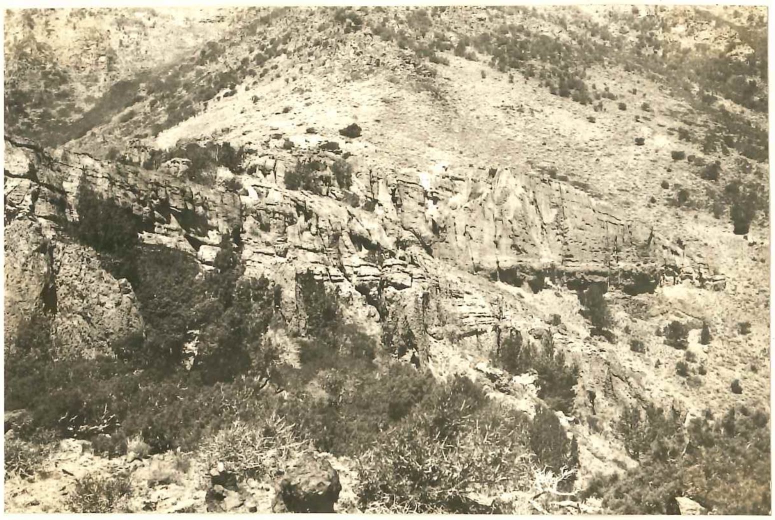

Figure 71. The northern limb of the northern cinder cone on the divide between the valleys of Little Mann and Little Dry Creek. The beds are inclined northward at nearly thirty degrees.

surface of the coarse breccia on which they lie gradually rises on a slope dipping northward at about five degrees. The northern part of the summit of the Little Dry Creek divide probably forms the center of the vent from which these cinders were extruded. On at least three sides the beds dip away from this point. The cone, however, appears to be asymmetrical, for the northern slope is several times more elongate than the southern one which ends immediately to the south in Dry Creek.

The actual vent is not clearly exposed. Evidence as to its position, however, is suggested by a red pinnacle, which rises over a hundred feet above the slope on the southern side of the divide. This pinnacle is formed of tuffaceous material that has been indurated by a broad andesitic dike. The tuff contains coarse elongate masses of vesicular lava that from their irregular shape and from their inclination to the north may be explained as being deposited as semifluid masses on the inner slope of the crater.

The andesitic dike which trends approximately north and south, is an elongate vertical mass with platy jointing parallel to its margins. This mass which is fifty feet or more in thickness can be traced for several hundred yards; cutting through the inclined tuffs. On being traced downward, it was found to cease abruptly at the margin of the underlying breccia. (Figure 72) The exposure is on a steep slope, but unfortunately it could not be determined if the

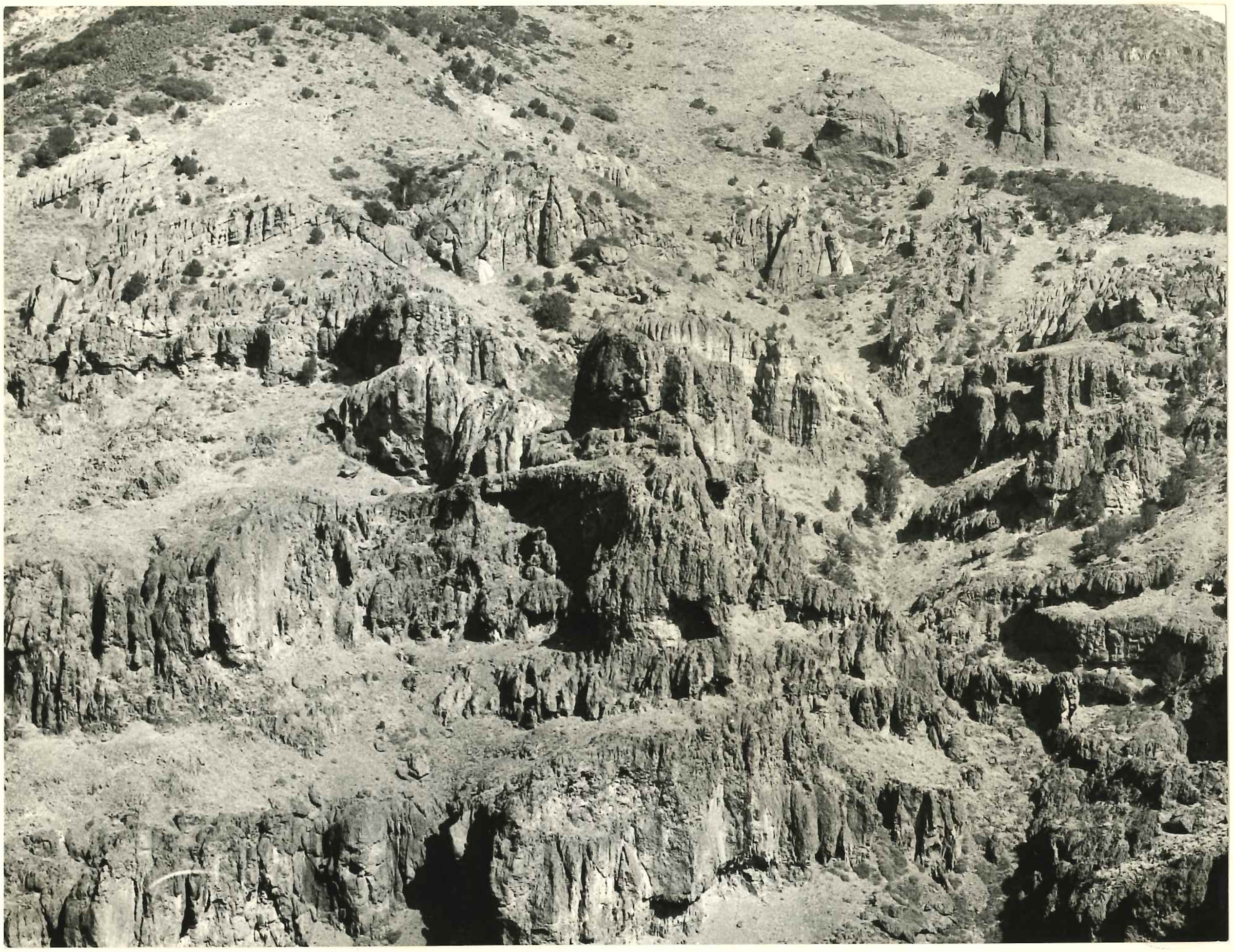

Figure 72. The north fork of Dry Creek is on the right. To the left above the injected breccias, the inclined beds of the northern cinder cone are visible. The dark pinnacle on the divide to the north is a remnant of the inner lip of the crater. The depression to the left of it is formed by the broad andesitic dike that ends abruptly at the top of the breccias. This fact suggests that the surface of the great flow had solidified only to that depth when the satellitic eruption occurred.

intrusive mass ended in depth or in its horizontal extent. It is possible, however, that at the base of its exposure, the dike may have reached the margin of the magmatic source from which it was extruded after the solidification of the surface of the great flow.

To the south between Mosquito Creek and Dry Creek there is another cinder cone which is far more clearly defined. (Figure 73) The coarse tuffaceous beds, rising about four hundred feet in height, dip quaquaversally at about thirty degrees away from a central neck (Figure 74) of vertically jointed platy aphanitic andesite of a dark grey color. The actual vent thus indicated is about one hundred feet wide and three hundred feet in length, with its larger axis at approximately North 30 West. At its northern end two small dikes of glassy andesite cut the cone. These are both roughly parallel to the elongation of the neck. One of these extends for only a short distance, but the other can be traced for a couple of hundred yards.

With the greater localization of the cinders about the vent, the size of the fragments averaged decidedly larger than those previously described. The larger masses range up to a foot or more in diameter, while many of the beds contain fragments two to four inches across. Black andesitic glass was found to be more common than in the northern cone. The inclined beds, like those to the north, rest on a vesicular breccia that caps some massive lava. This lava,

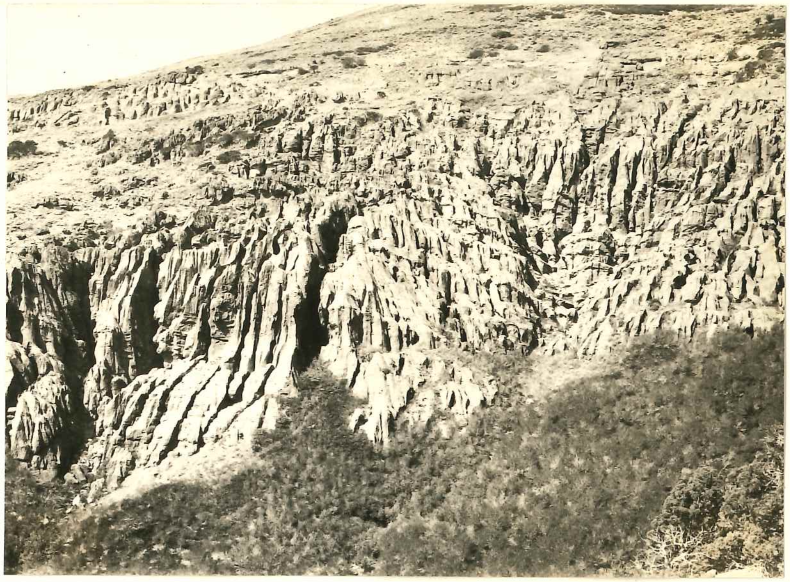

Figure 73. The western part of the southern cinder cone viewed from the neck.

Figure 74. The neck of the southern cinder cone showing the typical vertical jointing.

which is locally close to a hundred feet in thickness, shows a gradational relationship to the underlying injected breccias without the presence of the intervening tuffaceous bed observed to the north.

Between these two cones and slightly to the west, more andesitic lava is exposed in the Dry Creek valley overlying the inclined tuffaceous beds. The top of this andesite is almost at the same elevation as the summit of the two cones. From its stratigraphic position, this lava is evidently due to later extrusion. It consists of an alternation of platy andesite and of vesicular breccias which have suffered minor injections of glassy andesite. Although the injections are small, they were found to grade into underlying vesicular breccias. To judge from limited exposures it would be difficult to differentiate this phase from some of the lower injected breccias. This lava may well have been extruded from the andesitic dike exposed to the north. The proximity of this vent may have permitted a repetition of the periodic formation of injections and vesicular breccias similar to that postulated for the lower horizons.

To the south, in Mosquito Creek and Willow Creek, exposures of the upper part of the andesite are not sufficiently persistent to permit the recognition of flows that may cap the injected breccia. In Cottonwood Creek the evidence does not suggest them. To the north of Alvord Creek at about three hundred feet above the great exposure of massive andesite there is an irregular mass of platy andesite that is locally about three hundred feet in thickness.

This mass (Figure 75) shows an irregular relationship with the typical injected breccias that bound it both above and below. Its lower contact, where observed, shows a vesicular gradation to the breccia with vertical elongation of the vesicles, while the upper contact shows a black glassy andesite with spinous jointing injecting into the overlying breccia. This highly chilled lava was not observed lower in the section. Beneath this phase the mass of lava exhibits irregularly inclined platy jointing which locally is modified by rough columnar structure.

This mass and others similar to it possibly have been formed as flows, but their peculiar contacts and relationship suggest that they may be the chilled near surface phase of the great andesitic flow. In this case the gradation to the underlying breccia might possibly be explained by the raising of a relatively thin cap formed of both solidified and highly viscous lava, by the gradual accumulation of gas beneath it. With the local liberation of the gas, this great blister would have collapsed, but the momentary release of pressure would have permitted the frothing and the solidification of the lava adjacent to the cavity. The immediate slumping of the roof would have brecciated this vesicular mass.

The raising of the cap would thus explain the indications of vertical movement at its lower contact, while the

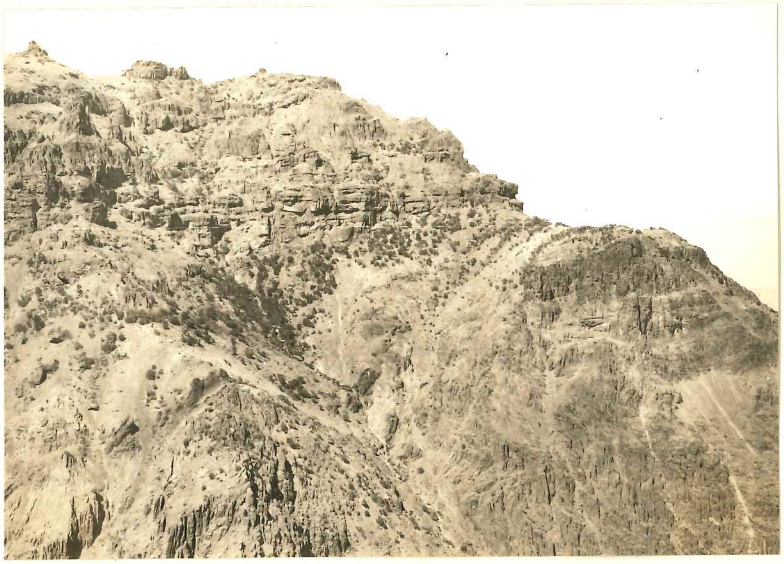

Figure 75. The northern side of Alvord Creek valley viewed from the south. The top of the great columns is exposed in the lower part of the picture. The badly gassed phase is partially clad with juniper. Above the shoulder are the injected breccias. The hypothetical origin of the thick mass of platy andesite, exposed just below the summit, is considered in the text. This mass shows a maximum thickness of about three hundred feet.

tension to which the mass would have been submitted might account for its horizontal platy structure. Adjacent to the hypothetical cavity the lower margin of this chilled cap would have graded into the more fluid phase, which would have become vesicular on the release of pressure.

Foreign Material Associated with the Andesite

Aside from the features already mentioned, the phases exposed in each valley are a repetition of the same general types. In the north fork of Cottonwood Creek, however, at a few hundred yards to the west of the uppermost exposure of the massive columnar lava, stratified acidic tuffs are exposed near the stream bed. These are overlaid nonconformably by a broad inclined mass of andesite, which has indurated them. (Figure 76) The lava, which shows platy jointing parallel to the contact and irregular columnar jointing perpendicular to it, ends above as an injection into an overlying breccia. The tuffaceous sediments are in a tilted mass that is about twenty feet in thickness and seventy feet in length. At their western end these sediments are also indurated by an andesitic breccia, which underlies them.

These isolated sediments are at least seven hundred feet above the uppermost stratigraphic level of the Alvord Creek Beds which they resemble in their content of quartz and biotite. The local presence of these stratified tuffs is considered to be due to a large block of sediments

Figure 76. The block of stratified acidic tuffs found he north fork

Figure 77. The basaltic flows abutting against the surface of the andesite on the southern side of the south fork of Willow Creek.

carried upwards by the andesite rising in the vent, which probably closely underlies them. Within the distance of a hundred yards both the massive basal andesite and the overlying injected breccias show marked vent characteristics. These consist of the vertical jointing in the massive phase and of the presence of a remarkably homogeneous breccia in a persistent vertical zone about a hundred feet in width and nearly a thousand feet in height.

Possibly a somewhat similar explanation may account for the presence of fragmental material of a foreign nature in association with the andesitic tuffaceous beds at the base of the massive phase north of Alvord Creek. There, fragments of rhyolite, fossil wood, and acidic conglomerate, similar to some horizons of the Alvord Creek Beds, occur as float adjacent to the exposures of the tuffs. Although the fragments were not found in situ, they are thought to be derived from the weathering of the tuffaceous deposits. From this interpretation their presence must be due to explosive volcanic action and possibly to that phase which may have immediately preceded the extrusion of the great flow.

Steens Mountain Basalt

Relationship to the Andesite

The andesite and the Pike Creek volcanics are capped by a great series of thin basaltic flows (Figures 7 & 78) that extend to the summit of the mountain, about three thousand feet above. This great thickness, however, is far

Figure 78. The basaltic flows exposed above the cirque of the south fork of Alvord Creek. On the left the cliff rises nearly a thousand feet.

from a maximum figure as the near-vent phases of the earlier volcanics, 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 elevation. To the south, the top of the Pike Creek volcanics is almost at the same level. Traced westward into the glacial cirques, the upper surface of the andesite decreases gradually in elevation on a slope that locally attains an extreme inclination of about twenty degrees. (Figure 77) The thin flows lap against this inclined surface.

Only to the south of Alvord Creek was the actual basal contact of the basalt observed. There the surface of the andesite, sloping westward, was capped by a slight thickness of poorly stratified andesitic tuffs. The contact is somewhat irregular, but showed no suggestion of pronounced erosion. Elsewhere, viewed from a distance, the gently undulating line, demarking the base of the basalt as it abuts against the andesite, suggests that the domed structure, formed by the accumulation of this viscous lava, was relatively unmodified by erosion at the time of the later extrusion.

General Description

This series consists chiefly of thin flows of coarsely holocrystalline olivine basalt of a rather light grey color. This basalt is distinctive in the field both from a peculiar porous texture, that will be described later, and from its local content of phenocrysts of labradorite ranging from about one to four centimeters in length. These flows have been found to vary from about one to seventy feet in thickness, but average close to ten feet. (Figure 79) Although most of the flows retain their thickness at least locally without any marked variations, some of the thinner ones end in contorted vesicular masses. In other places two or more sheets of lava appear to merge together. (Figure 80) A well defined contact may, therefore, disappear on being traced laterally. This is considered to be due to the advance of a sheet before the complete solidification of the surface of a lower flow, which was approximately static.

In the lower cirque of Mosquito Creek at the base of the series there is a bed of well stratified grey tuffs about ten 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 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 showed this rock to be an andesite of intermediate composition. (Table XII) Owing to poor exposures it was not determined if this mass was a

Figure 79. Basaltic flows in the valley of Little Alvord Creek about fifteen hundred feet below the summit. The scale may be realized by a comparison with the figure to the right of the center.

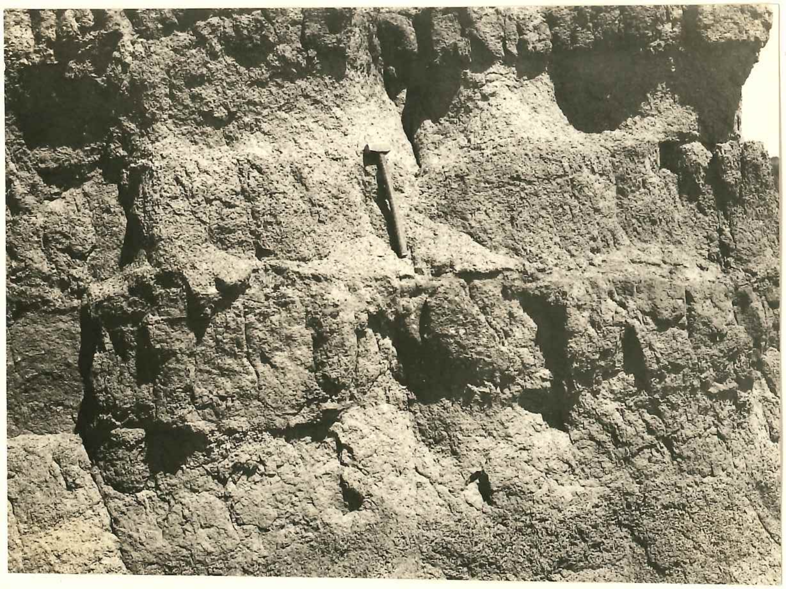

Figure 80. Near the base of the scarp of Northern Steens about a mile to the south of the main fault spur. Thin flows of basalt may be seen partially merging.

flow or a concordant intrusive. Aside from these small units, which probably comprise no more than thirty feet of an entire section, the consecutive flows appear to be in perfect continuity, for flow breccias and basaltic ejectamenta are practically negligible.

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. (Figure 98) Usually in this case they show no topographic expression although continuously exposed. This uniform bevelling is due to the relative softness of the rock. Owing to this variation in erosion, the character of an exposure may change so sharply that it may 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 quite 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 Mountain, 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 in 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.

To the north, in Harney Basin, the fault scarps decrease in height so that only the members capping the basalt are usually exposed. Since lava of a similar character has not been observed by the writer in the Blue Mountains, that extensive range presumably marks the northern boundary of the volcanic series, which filled a broad basin lying 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 increase (Figure 81) owing to the less rigorous erosion at a lower elevation. The series has no analogy to the basaltic flows exposed in the Owyhee Gorge about seventy miles to the northeast. To the southeast of Steens Mountain, the western scarp of the McDermitt Valley depression rises close to fifteen hundred 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 a thousand feet in thickness lie in the intervening space. The upper basalt beneath a thin cap of glassy acidic lava consists of three flows varying in thickness from five to ten 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 volcanics was contemporaneous with the outpouring of the great basaltic floods.

Figure 81. 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.

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 is exposed to a depth of over a thousand 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 kaolinized porphyry forming Lone Mountain. This rock, which contains small feldspathic phenocrysts, is somewhat similar to the upper biotite-dacite of the Pike Creek volcanics, and like it 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 overlaid by a thin layer of basalt, which presumably is a continuation of the Mesa Basalt described by Merriam. (47) 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

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(47) J. C. Merriam, "Tertiary Mammal Beds of Virgin Valley and Thousand Creek in Northwestern Nevada," Univ. Calif. Publ., Bull. Dept. Geol., Vol. VI (1910), p. 36-38.

sufficient magnitude to permit its correlation with that of Steens Mountain. Even in Guano Valley the scarps are low and the exposures unsatisfactory. (Figure 82) 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 fifteen hundred 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 surity. 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 similar, they show predominantly a glomeroporphyritic texture that is quite distinctive. They may therefore be part of a separate series.

The sequence exposed in Warner Valley has bearing on the relationship of this great northern series to the Warner Basalt described by R. J. Russell in his paper on the Warner

Figure 82. Aeroplane view of the eastern scarp of Guano Valley from the north. The volcanic cone of Beatty's Butte is in the foreground.

Range of California. (48) This range forms the eastern wall of Surprise Valley, which is the southern continuation of Warner Valley. Here Russell found a varied sequence of andesitic flows and tuffs to be locally capped by a series of basaltic flows that showed a maximum thickness of six hundred feet. This basalt is in part overlaid by rhyolitic flows.

About forty miles north of Nevada border, the elevated portion of the eastern scarp known as Bluejoint Rim (Figure 83) exposes above the basal talus a thickness of basalt that is close to fifteen hundred feet. 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, (Figure 84) which is bounded by a fairly low scarp on the east and on the west by one that rises over three thousand feet as the eastern boundary of Warner Valley.

Hart Mountain is formed of a complex series of lavas and volcanic intrusions. The lowest member stratigraphically consists of a few badly decomposed basaltic flows of a phenocrystic type that is strongly suggestive of a Steens Mountain type. This lava is overlaid by rather viscous flows of acidic basalt extruded from local vents. Above

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(48) R. J. Russell, "Basin Range Structure and Stratigraphy of the Warner Range Northeastern California," Univ. Calif. Publ., Bull. Dept. Geol., Vol. XVII (1928), pp. 416-425.

Figure 83. Aeroplane view of Bluejoint Rim, which rises about eighteen hundred feet as the eastern scarp of Warner Valley.

R. E. Fuller and A. C. Waters, op. cit., Figure 2, p. 212. Subsequently reproduced in the third edition of L. V. Pirrson's and Charles Schuchert's "Text-Book of Geology" Part I, Figure 269, p. 386.

Figure 84. 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 of it the western scarp of Warner Valley may be seen.

this lava there is a varied sequence of tuffs and andesitic flows. This entire 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 two hundred. The summit of the andesite for a distance of a mile or more rises a few hundred feet above the subsequent basaltic flows that abut against it.

Increasing gradually to the north these flows show a thickness of at least seven hundred 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 basalt. Judging from the evidence of viscosity this lower basalt is of local distribution, but the overlying series from its physical characteristics appears to be the direct continuation of the lava exposed at Bluejoint Rim. At the northern end of Hart Mountain (Figure 85) these flows are locally overlaid by a butte formed of a thickness of approximately one hundred and twenty-five feet of stratified light colored tuffs that are capped by a basaltic flow about twenty feet in thickness. This flow is also indistinguishable from a Steens Mountain type.

To the south the andesite forming the central portion of Hart Mountain is overlaid by basaltic flows that in the southern portion of the mountain are about thirteen hundred

Figure 85. 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 seven hundred feet.

feet in thickness. (Figure 86) These flows strongly resemble the Steens Mountain series aside from the fact that the coarse phenocrysts were not observed. This lava is locally overlaid 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.

The horst forming Hart Mountain ends on the south in a fault. To the south the scarp defining the eastern wall of Warner Valley continues with a height of about twelve hundred feet. (Figure 87) This lower scarp is capped by two thin basaltic flows. Their base is hidden by coarse talus that continues downward for about two hundred 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 discomformably on stratified tuffs about four hundred feet in thickness. Below these beds thin basaltic flows, extending to the talus, show a total thickness of over two hundred 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

Figure 86. Basaltic flows about thirteen hundred 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 three thousand feet in height.

Figure 87. View of the twelve hundred foot eastern scarp of Warner Valley a few miles south of Hart Mountain. The block, is capped by basaltic flows, which again are presumably the Warner Basalt. Beneath them, a thickness of about four hundred feet of tuffaceous sediments is locally exposed. The lower outcrop is formed by basaltic flows that are considered to be the southern continuation of the Steens Mountain series.

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. (49) To the south of Plush the scarp reappears above the alluvium, and exposes a thickness of over two hundred feet of basalt disconformably overlying stratified tuffs that locally show thickness of about one hundred 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 twenty-three hundred feet. (Figure 88) The block, here, is capped by about four hundred feet of basalt, which appears to be the direct 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 three hundred 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.

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(49) R. J. Russell, op. cit., p. 427.

Figure 88. The twenty-three hundred foot scarp west of Warner Lake. About three hundred 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 thirteen hundred feet in thickness. These flows are tentatively correlated with those of Steens Mountain.

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.

Below these tuffs, however, are the precipitous exposures of thin basaltic flows that appear to be practically 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 a thousand feet in height. Although they are not so phenocrystic, they presumably form the southern continuation of those of Bluejoint and Abert Rim, 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 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 (50) "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 the Warner Range volcanics was not determined.

The difficulty in correlating isolated horizons of basalt is well shown on the eastern scarp of Surprise Valley about fifteen miles to the east of Cedarville. (Figure 89) Here basaltic flows about sixty feet in thickness overlie light colored tuffs which are more than twice as thick. These in turn rest conformably on thin basaltic flows about one hundred and twenty-five feet in thickness. Beneath these is another bed of acidic tuffs forming an

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(50) Op. cit., pp. 439-40.

Figure 89. The eastern scarp of Surprise Valley to the east of Cedarville. On the left the butte at the top is formed by about one hundred and fifty feet of tuffaceous sediments, which are capped by a few thin basaltic flows. Beneath these beds in the center of the picture about one hundred and twenty-five feet of basalt overlies a slightly greater thickness of stratified tuffs, which rests on still lower basaltic flows of unknown thickness.

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, 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.

Age Relationship

From fossil leaves, the Upper Cedarville beds beneath the Warner basalt were considered by Chaney (51) 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 still 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 series of the Steens Mountain volcanics apparently lies between them. Although the extrusion of these varied volcanics probably was relatively rapid, the evidence indicates that the Mascall flora was quite persistent and possibly that it continued into the Pliocene.

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(51) R. J. Russell, op. cit., p. 412.

To the east Russell definitely correlates (52) 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. (53) These lower beds in consequence should be older than the Steens Mountain volcanics. 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 (54) 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.

Since the basalt forming these three units at the southern end of Pueblo Mountain is not sufficiently distinctive tO

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(52) Op. cit., pp. 416-7.

(53) Chester Stock, Personal communication.

(54) Ibid.

permit a petrographic correlation, the problem at present cannot be definitely settled. It appears definite, however, 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 with either 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 overlaid by acidic lava and tuffaceous beds, has been intruded by a number of small sills of obsidian. Although, probably 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, an earlier origin than the Mesa Basalt. In consequence the latter may well 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, suggests 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.

Open Texture

The basalts of this region usually show phenocrysts of labradorite and olivine in a rather light grey holocrystalline ground. For the present, however, the textural peculiarities of the ground will be discussed, while the phenocrystic phases are left to a later page. This texture, although typical of the Steens Mountain series, appears to be regional in character, for it is also observed in flows that are distinctly separated stratigraphically.

The peculiarity of this texture lies in the presence throughout the groundmass of innumerable minute drusy cavities, which render the rock extremely porous. These open spaces are usually bounded by the crystal faces of the typical basaltic minerals composing the rock. In the coarsest specimens these minerals are easily visible megascopically. Since similar lava appears never to have been described the writer designates it tentatively as being "open textured".

The most striking feature of these cavities either in the hand or in thin section is the presence of delicate laths of light grey labradorite that projects into them and locally forms a network of conflicting plates. 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 the iron oxide. These mafics, however, are not enclosed in the augite. The olivine crystals and more rarely the augite also come in contact with the drusy cavities.

Some of the open textured rocks, especially those that are more aphanitic, are of a fairly dark grey, although not of as deep a shade as the typical basalt. In the finer grained types the drusy structure is confined to localized points. A seventy foot flow, however, observed low in the series in Mann Creek valley is so coarsely crystalline and of such a light grey color that the rock superficially resembles a granite. With this coarse crystallization the cavities are so general that the rock is extremely fragile.

Disregarding the cavities, which probably form about twenty percent of the rock, this basalt contains nearly seventy percent labradorite, in laths that range from about .5 to 1.5 millimeters in length. With this unusually high content of plagioclase this rock approaches the extrusive equivalent of anorthosite. The mafics consist roughly of about ten percent olivine and a slightly greater content of augite. A little magnetite forms the only accessory. The olivine grains probably average close to .5 millimeters in diameter, but locally they attain about twice that size. Some of the crystals of brownish augite extend for as much as two millimeters.

In these open textured rocks, the cavities were presumably once filled with a mother liquor from which the minerals crystallized. A few rocks locally exhibit skeletal magnetite in a rather opaque base, which in some instances exhibits slight birefringence. This substance is considered to be formed from a decomposed glass. In general, however, the absence of residual material suggests that this liquid escaped as a volatile. In a large measure the porosity of the rock may have permitted this liberation. Field evidence indicates that the major joint cracks also formed an important avenue of escape.

Endomorphic Alteration

In a great many instances in the larger flows of the Steens Mountain series, the fresh open textured rock is confined to a narrow zone adjacent to the major vertical joints. (Figure 90) Away from these cracks the rock changes sharply from a fairly light grey to a dark greenish brown color and simultaneously loses its porosity. In thin section this change proved to be due to the decomposition of

Figure 90. On the divide between Little Alvord Creek and the south fork of Alvord Creek at about a thousand feet below the summit. Adjacent to major joint cracks the resistant unaltered basalt is apparent.

the olivine to a brownish or greenish substance, with which the rock is impregnated. This substance appears to be a colloidal deuteric residual known as chlorophaeite, although the characteristic change in color was not observed. (55)

In some instances the olivine appeared to have been converted into iddingsite. Aside from this alteration of the mafics, which is usually accompanied by the formation of magnetite, the texture of the rock is not affected except for the filling of the minute cavities by the deuteric residual.

Chemical analyses (Table VIII) of both the altered and the unaltered phase of a flow indicate that the altered phase is slightly hydrated and that the iron content has been oxidized to a minor extent. The other constituents change slightly, but they do not suggest an explanation for the variation in color. The alteration is, therefore, attributed to the corrosive action of the volatiles which were unable to escape.

In flows of this type the uppermost lava is usually unaltered for a depth of at least five or ten feet. The top of the altered zone has been observed locally as a fairly level line, but as a rule it rises as a dome in the center of each large roughly vertical block. (Figure 91) In such cases the fresh rock may be traced downwards adjacent

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(55) R. Campbell and J. W. Lunn, "Chlorophaeite in the Dolerites (tholeiites) of Dalmahoy and Kaimes Hills, Edinburgh," Min. Mag., Vol. XX (1925), pp. 435-440.

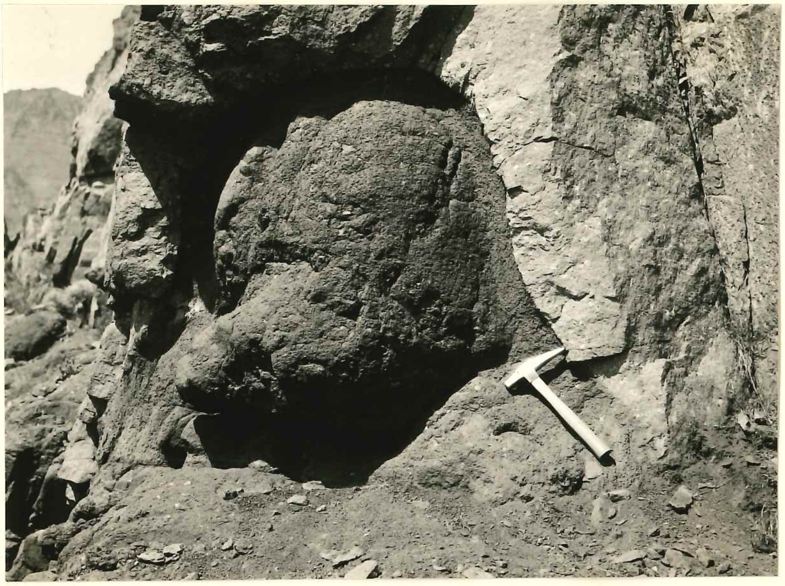

Figure 91. Endomorphic alteration clearly defined in a flow near the base of the basaltic series on the northern wall of Little Alvord Creek. In the center of a block bounded by major joints, the rounded upper margin of the zone of alteration is characteristic.

Table VIII - Part 1

	I	II
Silica	47.60	47.75
Alumina	18.27	18.59
Ferrous Oxide	8.93	7.68
Ferric Oxide	1.91	2.40
Magnesia	6.54	6.18
Lime	8.70	8.25
Soda	3.11	3.22
Potash	1.03	1.03
Water above 105 C.	.80	1.10
Water at 105 C.	.33	.65
Carbon Dioxide	none	none
Titanium Dioxide	2.20	2.42
Phosphorous Pentoxide	.27	.28
Sulphur	trace	trace
Manganese Dioxide	.39	.33
	100.08	99.88

Specimens from a flow on the southern side of the cirque of the south fork of Alvord Creek at about a thousand feet below the summit. Analyst W. H. Herdsman.

I. Unaltered Phase.

II. Endomorphically altered phase.

Table VIII - Part 2

	I	II
Orthoclase	6.12	6.12
Albite	26.20	27.25
Anorthite	32.80	33.18
Diopside	6.80	4.73
Hypersthene	4.45	8.14
Olivine	14.82	10.18
Magnetite	2.78	3.48
Ilmenite	4.26	4.56
Apatite	.67	.67
Water	1.03	1.75
	99.93	100.06

Norms calculated from the analyses in Part 1.

I. Hessose, C. I. P. W. Symbol, II(III).5"."4.4.

II. Hessose, C. I. P. W. Symbol, II".5"."4.4.

to the joint as a thin zone perhaps only a few inches in width, but locally continuous for many feet. The smooth surface and angular fractures of the light grey outer layer forms a marked contrast with the rounded exposures of the easily weathered dark rock within the block.

This same observation was made in numerous localities in the study of the more acidic volcanics. In highly kaolinized acidic lavas chips sufficiently fresh for petrographic examination may frequently be obtained from the surface of the major joint cracks, which usually are coated by a selvage of resistant rock about a half an inch in thickness. Thin sections prove that this is not due to subsequent silicification. In the more viscous lavas the presence of a crack would have liberated the volatile deuteric residuals from a more narrow zone than in the porous open textured basalts. Examples of this phenomenon were observed both in the rhyolite laccolith and in the biotite-dacite flows.

The Origin of the Jointing

On Bluejoint Rim a local accumulation of vesicles was observed at the top of a zone of alteration, while the enclosing unaltered lava was not vesicular. This fact suggests that the lava within a joint block remained sufficiently fluid to permit the rising of volatiles, while the solidification had already occurred adjacent to the surrounding cracks, at least to the depth at which the vesicles were observed. Additional evidence on the same point was observed east of Steens Mountain.

On the northern scarp of Upper Alvord basin north of Alvord Desert a basaltic flow, that appears to have been fairly viscous, shows finely vesicular V shaped zones extending downward from the surface. These zones are bisected by the major joints, while on either side there is massive basalt that shows merely an accumulation of coarser vesicles higher up between the flarings V's. The lava adjacent to the joints is thought to have been chilled by the advancing cracks, while on either side it retained sufficient fluidity to permit the accumulation of the volatiles in the upper part of the joint block. Presumably tension accumulated in a network of solidified lava beneath the cracks and caused the progressive advance of the joints prior to the complete solidification of the flow to that depth. This premature solidification adjacent to the cracks is attributed to the loss of volatiles. The liberation of the gases would not only cause dehydration, but would induce chilling both by the transfer of heat and by the expansion of the volatiles.

Sosman once suggested (56) an origin of columnar structure by convection currents. This hypothesis was found by the writer to be untenable, although it offers an explana-

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(56) R. B. Sosman, "Types of Prismatic Structure in Igneous Rocks," Jour. Geol., Vol. XXIV (1916), pp. 219-224.

tion for the variations in composition between the outer and inner part of a column. In this theory he drew an analogy to the cellular structure produced by the vertical convection currents caused by the surface cooling of a thin layer of liquid. These currents obtain the minimum friction when the liquid is divided into hexagonal cells. The currents descending on the margin of the broad low columnar cell unite at the base and rise in the center. Material in suspension is therefore deposited in each unit at the center of the base. Columnar structure produced in this manner would occur only in very fluid thin horizontal sheets of lava. The jointing should then be principally in broad hexagonal columns with some seven and five sided ones, but rarely with any of three or four sides.

In support of his hypothesis, Sosman quoted (57) from Scropes' description of the volcanoes of central France which states that "occasionally as for example at La Tour d' Auvergne in the Mont Dore the columns show a cylinder of black basalt within a prismatic case of lighter color and looser texture." This description strongly suggests a type similar to the Steens Mountain Basalt.

Owing to the thinness of the flows and to the fluidity of the lava the Steens Mountain series should have been favorable for the development of convection columns. As at

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(57) Op. cit., p. 227.

Mont Dore the variation between the outer and inner portion of the block suggests a change in composition that might be explained by convection. Many of the flows, however, are rich in coarse phenocrysts of labradorite. The flow structure, which these exhibit, is uninfluenced by the position of the major joints and the crystals appear to show no tendency to accumulate in the center of the base of the columns.

The shape of the columns also furnishes definite evidence against the convectional origin. Instead of being predominantly hexagonal and bounded by vertical joints, the blocks are more often four sided and the bounding planes are usually curving or irregularly inclined. (Figure 92) The symmetrical columns which the cells demand are absent. The jointing is therefore preferably attributable to contraction.

Magmatic Segregations

A number of flows on Steens Mountain contain thin sheets or lenses of basalt that are usually more coarsely crystalline and more vesicular than the enclosing rock. (Figure 93) The largest observed of these sheets, which usually occur in flows showing the altered phase, is about five inches in thickness. A maximum lateral extent was not determined, but locally they can be traced for at least thirty or forty feet.

These lenses as a rule give indication of a high volatile content by their open texture and their vesicularity. The gas content in some cases has formed cavities, which may

Figure 92. Coarse jointing typical of the unaltered basaltic flows is here shown by the series at Abert Rim. The gully does not represent a fault. The rapid variation in the sequence is due to the local merging of flows.

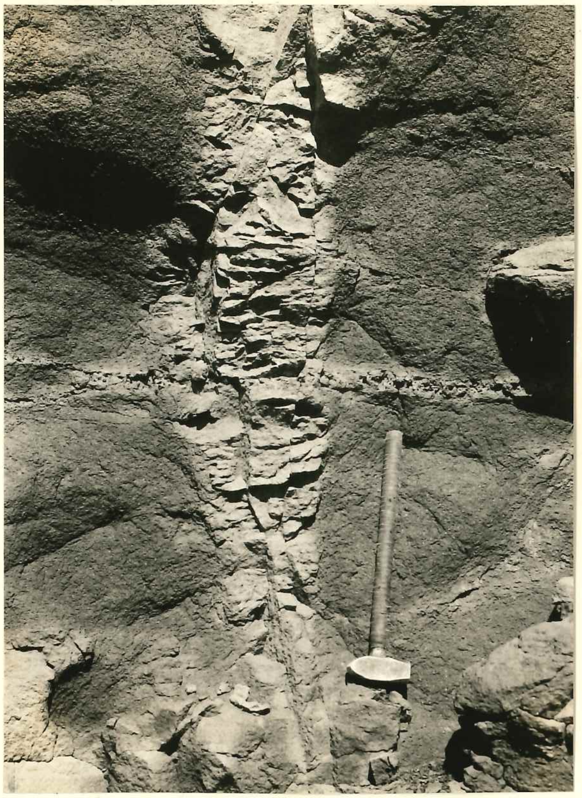

Figure 93. On the divide between Little Alvord Creek and the south fork of Alvord Creek at about a thousand feet below the summit. The resistant vertical zone in the center is formed by unaltered rock adjacent to a major joint crack. Just above the hammer there is a horizontal segregation veinlet, which branches on the left.

reach a length of two feet. The lava at the bottom of the cavity shows a flat surface, while the top forming a low dome only a couple of inches in height exhibits small basaltic stalactites.

At the intersection of major joint cracks the lava forming these sheets in several instances may be traced upwards as a thin veinlet. The surface of these vertical cracks instead of being cemented by this minute intrusive usually exhibits a somewhat aphanitic pitted surface of a rather brilliant red color. These surface features are undoubtedly caused by the escape of volatiles.

The rock forming the small sheets and veinlets is as a rule relatively fresh. The zone adjacent to their lower contacts in some instances also lacks the alteration, perhaps owing to the fact that these horizontal sheets furnished access to the cracks and thereby permitted the escape of volatiles. The freshness of the segregations may in part be explained by the apparent absence of olivine and the accompanying alteration products. The mafics in these masses consist chiefly of augite and magnetite, both of which exhibit an acicular development.

The horizontal sheets show no indication of a possible foreign origin. They are considered therefore to be formed by the segregation of magmatic residuals. This interpretation has been substantiated by chemical analyses (Tables IX & X) of the segregation and the normal rock of two flows.

Table IX - Part 1

	I	II	III
Silica ----------------	47.20	48.60	46.45
Alumina ---------------	18.08	14.00	17.90
Ferrous Oxide ----------	3.29	6.61	5.94
Ferric Oxide -----------	7.77	8.00	5.68
Magnesia --------------	4.15	3.75	4.88
Lime ------------------	9.96	7.65	9.35
Soda ------------------	2.82	3.67	2.84
Potash ----------------	.93	1.94	1.01
Water above 105 C. -----	1.30	1.00	1.60
Water at 105 C. --------	1.55	1.50	1.70
Titanium Dioxide -------	2.60	2.40	2.00
Carbon Dioxide ---------	none	none	none
Phosphorous Pentoxide --	.29	.64	.31
Sulphur ---------------	trace	trace	trace
Manganese Dioxide ------	trace	.29	.27
	99.94	100.05	99.93

Specimens from a flow near the base of the cirque in Mosquito Creek at about twenty-five hundred feet below the summit. Analyst W. H. Herdsman.

I. Unaltered Phase.

II. Segregation veinlet showing marked differentiation by an increase in silica, iron and the alkalies.

III. From the surface of a cavity in the same segregation which here shows a composition almost identical to the flow.

Table IX - Part 2

	I	II	III
Quartz ----------------	3.48	2.64	.42
Orthoclase ------------	5.56	11.12	6.12
Albite ----------------	23.58	30.92	24.10
Anorthite -------------	33.92	16.12	32.80
Diopside --------------	10.58	14.58	9.29
Enstatite -------------	5.70	-----	-----
Hypersthene -----------	----	4.59	11.08
Magnetite -------------	3.02	11.60	8.35
Hematite --------------	5.76	-----	----
Ilmenite --------------	5.02	4.56	3.80
Apatite ---------------	.67	1.34	.67
Water -----------------	2.85	2.50	3.30
	100.14	99.97	99.93

Norms calculated from the analyses in Part 1

I. Hessose, C. I. P. W. Symbol, II"."5."4.4.

II. Camptonose, C. I. P. W. Symbol, (II)III.5.3"."4.

III. Hessose, C. I. P. W. Symbol, II(III).5."4.4.

Table X - Part 1

	I	II	III	IV
Silica --------------	46.10	44.40	43.60	46.50
Alumina -------------	14.90	13.86	11.09	14.43
Ferrous Oxide --------	8.28	5.53	8.36	6.31
Ferric Oxide ---------	1.54	5.47	2.92	6.56
Magnesia ------------	8.60	11.17	19.12	5.09
Lime ----------------	12.24	10.50	7.60	9.60
Soda ----------------	1.80	1.70	1.02	2.36
Potash --------------	.51	.45	.33	.80
Water above 105 C. ----	3.75	3.90	3.90	3.90
Water at 105 C. -------	.50	1.50	.90	.60
Titanium Dioxide ------	1.60	1.38	1.05	3.35
Carbon Dioxide -------	none	none	none	none
Phosphorous Pentoxide -	.12	.12	.16	.36
Sulphur -------------	none	none	none	trace
Manganese Dioxide -----	.24	.18	trace	.22
	100.18	100.16	100.05	100.08

Specimens from the olivine-rich flow near the base of the cirque of Willow Creek at about twenty-five hundred feet below the summit. Analysts W. H. & F. Herdsman.

I. Upper zone impoverished in olivine and therefore lower in iron and magnesia.

II. The chilled base, presumably representing the original Magma.

III. The olivine-rich zone, greatly enriched in magnesia and to a minor extent in iron.

IV. Segregation veinlet in the olivine-rich zone. Low in magnesia, but higher in the other constituents.

Table X - Part 2

	I	II	III	IV
Quartz	---	----	-----	5.82
Orthoclase	2.78	2.22	1.67	5.00
Albite	15.20	14.15	8.38	20.44
Anorthite	31.14	29.19	25.02	25.85
Diopside	23.42	18.15	9.48	14.81
Hypersthene	7.01	13.85	18.26	6.83
Olivine	10.80	6.24	25.98	----
Magnetite	2.09	7.89	4.18	9.51
Ilmenite	3.04	2.74	1.98	6.39
Apatite	.34	.34	.34	1.01
Water	4.25	5.40	4.80	4.50
	100.07	100.17	100.09	100.16

Norms calculated from the analyses in Part 1

I. Auvergnose, C. I. P. W. Symbol, III.5".4".4.

II. Auvergnose, C. I. P. W. Symbol, III".5".4".4.

III. Hilose, C. I. P. W. Symbol, (III)IV.1.2.2".

IV. Auvergnose, C. I. P. W. Symbol, (II)III.5.4.4.

In both instances the differentiate shows a marked increase in the content of iron, potassium, sodium, titanium and silica, while there is a loss of magnesium, calcium and aluminum. A single segregation, however, was not homogenous, for the analysis of its massive phase differed from that of the flat surface of the lava in its domed cavity. (Table IX)

Otherwise the change coincides with that expected from the fractional crystallization of a magma. The formation of olivine and the calcium rich plagioclase would deplete the mother liquor in magnesium, calcium and aluminum and thereby cause an increase in the other constituents. The increase in the iron content is explained by the fact that the magnesium rich pyroxene, being more refractory, crystallizes first and thereby enriches the residual liquor in iron. Fenner has recently shown (58) that pyroxene forming from a melt, exhibits a reaction series in the magnesium-iron content, which is analogous to the changing ratio of calcium and soda in the crystallization of plagioclase. Unfortunately no explanation is offered of the mechanism by which the residual liquor was concentrated.

The small differentiates are analagous, however, to segregation veinlets in the Dalmahoy sill described by Campbell. (59) These occur in thoeliite as roughly hori-

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(58) C. N. Fenner, "The Crystallization of Basalts," Am. Jour. Sci., Vol. XVIII (1929), pp. 226-237.

zontal anastomosing veinlets of a far more acidic composition. In another phase of this sill, lenses and persistent layers, from their coarse crystallization, were considered to be doleritic pegmatite. Petrographically they showed a slightly more acid composition than the surrounding rock and a high content of chlorophaeite, which is a greatly hydrated mineraloid. Both this doleritic pegmatite and the segregation veinlets are considered by Campbell to be differentiates of the enclosing rock.

The Concentration of Phenocrysts

On Bluejoint Rim at about three hundred feet below the summit there are a number of thin flows which show segregations of phenocrysts, apparently caused by the gravitational settling of the labradorite during flowage. The flows which range from about five to ten feet in thickness, had sufficient fluidity to attain remarkably smooth surfaces. Except for a thin line of reddish glass the contacts are noticeable chiefly from the change in vesicularity. The upper surfaces have spherical vesicles, while at the bottom, organ pipe vesicles extend upwards for as much as six or eight inches. These are formed by the rising of air imprisoned beneath the advancing flows. At the base at least

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(59) R. Campbell and J. W. Lunn, "The Tholeiites and Dolerites of the Dalmahoy Syncline," Trans. Royal Soc. Edinburgh, Vol. LV, (1927), pp. 501-3.

for an inch or two these vesicles are usually inclined in the direction of flowage.

Platy crystals of labradorite averaging two or three centimeters in diameter are concentrated near the base of the flow and upwards show a gradation into a zone free from phenocrysts. (Figure 94) Proof that they settled is furnished by the fact that a few crystals as a rule are retained in the flat glassy surface of the flow usually for a depth of not more than an inch. The phenocrysts generally show a pronounced horizontal alignment and are, therefore, considered to have settled during flowage. Locally, however, the alignment curves into swirls.

On Steens Mountain and Abert Rim there are also some flows that show various types of segregations of phenocrysts, but the mechanism entailed is not so clearly defined. The concentrations were found to be very irregular and not confined to the base. The basal concentrations, however, appeared to be the most common, but as a rule they showed a sharp contact with the overlying lava rather than a gradation. Some of these segregations have a very irregular curving outline and are extremely crowded with coarse crystals, which may be accompanied by vesicles, although the overlying lava is free from them. (Figure 95) Both the irregular outline of the segregations and the absence of gradations may be due to the flowage of the overlying lava over the less mobile phenocrystic mass. The presence of the

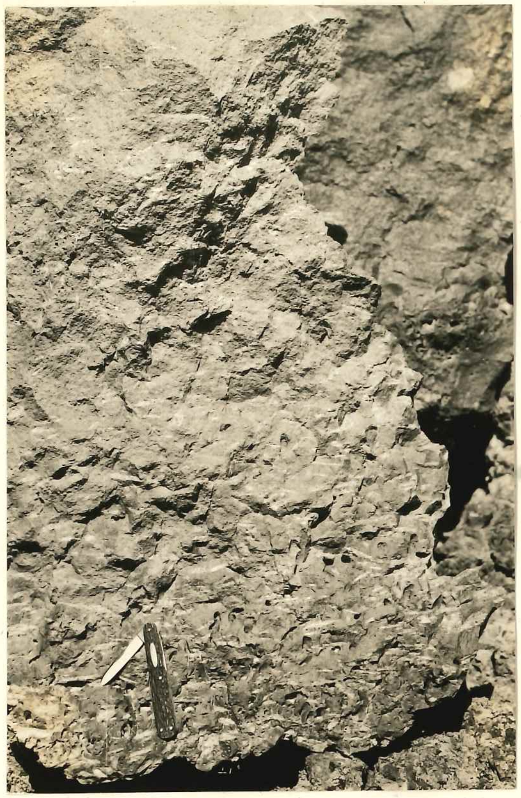

Figure 94. The gravitational concentration of labradorite at the base of a basaltic flow at Bluejoint Rim. The horizontal alignment of the phenocrysts proves that the settling occurred during flowage.

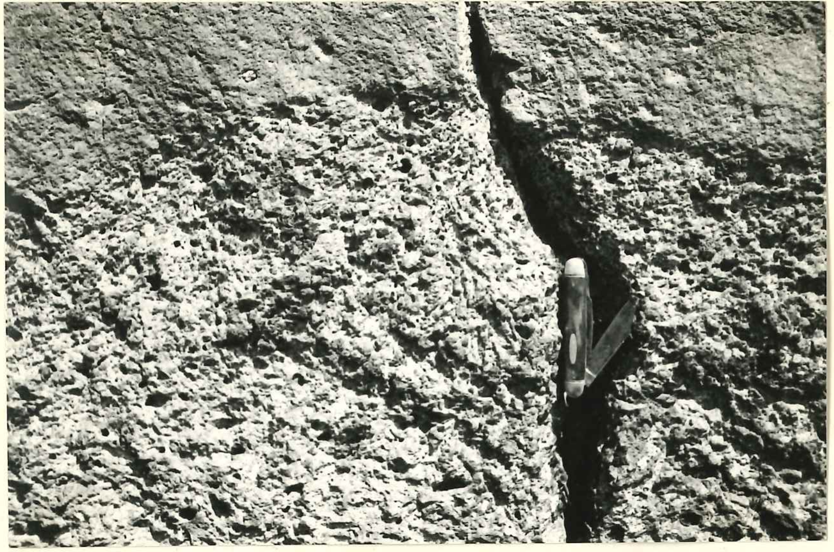

Figure 95. A sharply defined concentration of irregularly massed labradorite phenocrysts near the top of the basaltic series in the valley of Mosquito Creek. Presumably the phenocrysts, by retarding the escape of volatiles, rendered the basal zone vesicular.

vesicles may be explained by the fact that the large platy crystals may have obstructed the rising of volatiles liberated by the crystallization.

In several cases, the coarse labradorite occurs in horizontal streaks a foot or more in width with a barren zone both above and below. In one instance the major concentration was at the top. On Abert Rim a flow with two horizontal concentrations of phenocrysts contains smaller crystals in one zone than in the other. As a rule these horizontal bands show fairly well defined flow structure. In one locality near the top of Steens Mountain, a thin contorted sheet of lava shows labradorite crystals in vesicular swirls. (Figure 96)

It has been previously mentioned that a number of flows appear to have been formed by the merging of successive thin sheets that have advanced prior to the complete solidification of the surface of a stationary lower flow so that the contact is locally distinct, but usually blended. (Figure 80) The concentration of phenocrysts varies frequently from flow to flow. It seems possible to the writer that the concentration may have varied in the successive thin sheets, and that some of the bands of phenocrysts may be due to the merging of sheets of different composition. The necessary differentiation might have occurred before extrusion or during flowage. Unfortunately no locality was found to prove this hypothesis.

On both Steens Mountain and Abert Rim the flows that

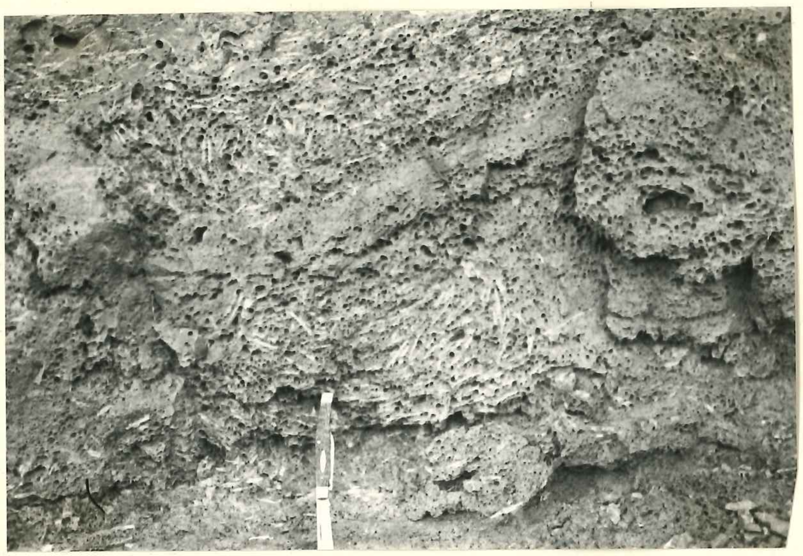

Figure 96. A swirl of vesicular lava showing irregular concentrations of coarse crystals of labradorite in a thin basaltic flow about eight hundred feet below the summit in the south fork of Alvord Creek.

show the most marked variations are usually thin and frequently appear to have been relatively fluid at the time of consolidation. The thicker phenocrystic flows were found to be homogeneous. These flows usually lack horizontal flow alignment, although some exhibit broad swirls of labradorite crystals. This fact combined with their flatness of surface and their coarseness of texture indicates that they were also comparatively fluid when they came to rest. To explain the absence of crystal settling, it seems probable that the thin flows had greater fluidity during flowage.

This evidence of differentiation during flowage renders it impossible to correlate flows stratigraphically by their content of coarse crystals of labradorite. At the southern end of Warner Valley the flows, which the writer correlates with the Steens Mountain Basalt, appear to be free from phenocrysts, yet it is probable that the crystals had settled before the flows reached that region. At Bluejoint Rim and at the northern end of Hart Mountain, a series, which in the writer's opinion is undoubtedly the same, is in part phenocrystic, but the crystals were in the process of settling at the time of solidification.

The Concentration of Olivine

Olivine is present in practically all the Steens Mountain Basalt that has not suffered endomorphic alteration. In many flows it is megascopically visible and usually appears as dark irridescent grains, which attain a diameter of one to two millimeters. The iridescence is due to a thin film of reddish brown alteration, coating the surface.

Near the base of the cirque in Willow Creek there is a flow that is remarkable from its high concentration of olivine grains, some of which even exceed two millimeters in diameter. The base of the flow, which shows the typical organ pipe vesicles, is relatively low in olivine for about six inches, but upwards it grades rapidly into the olivine rich rock, which appears to be uniform in its texture for a thickness of about twenty feet. In this part the dark grains of olivine, contrasting strongly with a mottled ground of light grey and white, compose at least thirty or forty percent of the rock. Capping this phase is a basalt which is almost free from the coarse grains. The contact between these two phases is locally gradational, but for the most part it is defined by a sharp horizontal line, which is accompanied usually by the presence of zeolites. In one place this line curves upwards in a low symmetrical arch about a foot in length and three inches in height. (Figure 97) The massive phase capping the basalt is only about five feet in thickness and then grades into an amygdaloidal lava, which represents the surface. The vesicles are partially filled with a zeolite whose properties coincide with that of a fairly siliceous phillipsite.

The upper massive phase, which is low in olivine, shows in thin section an even distribution of small laths of

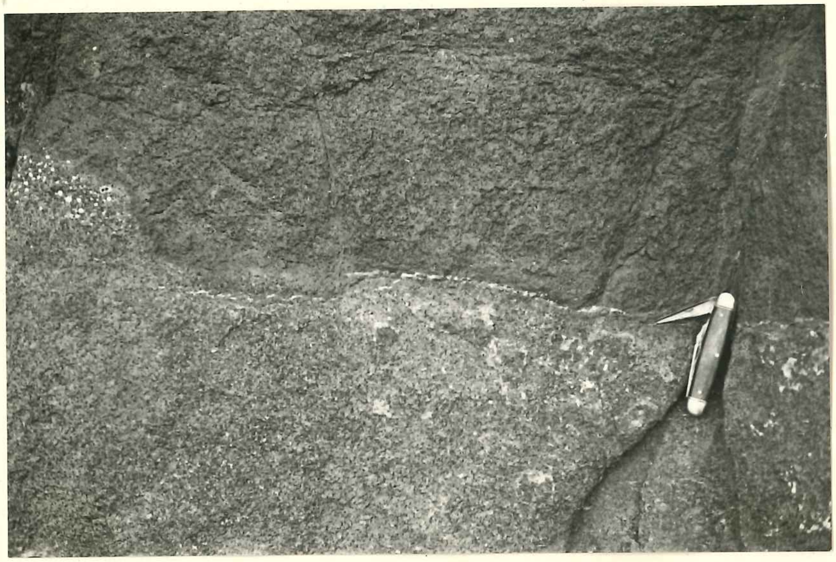

Figure 97. The irregular white line marked by the blade of the knife defines the sharp upper limit of the olivine rich zone of the basaltic flow in the north fork of Willow Creek. The dome is on the left. The line is formed by zeolitic material which is also largely responsible for the light color of the lower zone.

feldspar, which for the most part are enclosed in ophitic augite. Between many of the crystals of augite, however, small grains of partially altered olivine are intersertal to the labradorite. This feldspar is highly fractured and decomposed to material of lower index of refraction and birefringence. This material, which also occurs in larger masses bounded by the faces of the adjacent crystals, appears identical to the coarsely crystalline zeolite that lines the vesicles. Judging from the low potassium content of the rock, however, it must be of a variety of phillipsite poor in potash. The distribution suggests that it is derived from the decomposition of the feldspar and that it fills drusy cavities in an open textured rock.

The field relationship indicates that the concentration of olivine is due to the gravitational settling of the coarse grains. The decrease in olivine at the base may be easily explained by the chilling of the contact prior to differentiation. Additional support lies in the fact that the upper phase is very similar petrographically to the olivine rich zone except for the absence of the phenocrysts.

From this interpretation, the basal six inches of the flow should represent the undifferentiated lava. The gravitational separation of crystals should have depleted the upper zone in the same constituents that enrich the lower. In chemical analyses of the capping phase, the olivine rich zone and the chilled base, the latter shows a percentage of each constituent lying between that of the other two phases. (Table X) The olivine zone is found to be greatly enriched in magnesia and to a minor extent in the iron oxides, while the other constituents all show a general decrease. On the other hand, aside from a loss in hydration and a negligible decrease in manganese oxide, the upper phase shows a loss only in magnesia and the iron oxides, while the other constituents increase. The low olivine content in the calculated norms of both the basal phase and the segregation is obviously due to the oxidation of the mafics.

Presumably the change in magnesia and iron is the controlling factor and is explained by the variation in the olivine content. Since the magnesia greatly predominates, the olivine should approach forsterite in composition. The indices of refraction for its three ray directions, however, range approximately from 1.710, to 1.690, and, therefore, according to Winchell (60), it should be close to an iron rich variety. This discrepancy is not explained.

The capping zone, including its vesicular surface, is only about ten feet in thickness. Judging from chemical analyses the depletion of this zone cannot account for the extreme concentration of olivine beneath it. Considering the initial composition to be represented by the chilled basal phase, the loss in magnesia in the upper zone is

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(60) N. H. and A. N. Winchell, "Elements of Optical Mineralogy, Part II, p. 167.

only a third of that gained in the lower phase of twice the thickness.

The gradation to the thin basal margin practically precludes an explanation demanding the merging of successive sheets of varying composition. An analogous result, however, might have been attained in the advance of a very fluid homogeneous flow. Owing to basal chilling the flow would have been more viscous near its lower margin and a differential rate of flowage would have thus been induced. Into this basal phase the olivine crystals would have settled. The friction caused by their presence would have decreased the rate of flowage. With the progressive advance of basal chilling and the slow accumulation of olivine, the viscous zone would have gradually increased in depth, while the upper more recently extruded lava might have continued to flow at the original speed. If this occurred near the vent where the fresh lava would have been still very fluid and high in olivine, the differential movement between the two zones would have permitted the local accumulation of phenocrysts from an indefinite volume of basalt.

The progressive advance of viscosity upwards from the base would explain the even distribution of olivine instead of the extreme basal concentration. The differential movement would account for the sharp contact between the two phases. The local gradations might be accounted for by the friction between the two layers and by the rise of gases liberated by the lower phase. The vesicular segregations testify to the local accumulation of volatiles, while vertical concentrations of zeolites in cylindrical zones an inch or two in diameter were presumably caused by the rise of gases through the rather viscous lava high in olivine.

Periodic Differentiation

Upper Alvord Basin

Although the successive flows frequently vary in both the concentration and the size of phenocrysts, as well as in the crystallinity and the alteration of the groundmass, no marked distinction as a whole was observed between the upper and lower members of the series. Chemical analyses would undoubtedly show a fluctuation in composition, but probably a rather irregular one.

On the north side of Upper Alvord basin, the scarp, which is about a thousand feet in height, exposes basaltic flows that are considered to correlate with the top of the Steens Mountain series. These flows appear to show a periodic repetition of several types. These types consist namely of coarse basaltic ejectamenta at the bottom followed by dense glassy basalt, then more fluid open textured lava and finally the very fluid type high in phenocrysts of labradorite. Chemical analyses indicated the glassy rock to be decidedly more acidic than the open textured variety. (Table XI)

This repetition is thought to be due possibly to the

Table XI - Part 1

	I	II
Silica ------------------	48.46	51.30
Alumina -----------------	18.09	16.06
Ferrous Oxide -----------	8.59	9.17
Ferric Oxide ------------	2.20	1.95
Magnesia ----------------	4.26	3.58
Lime --------------------	9.75	7.44
Soda --------------------	2.99	3.15
Potash ------------------	.92	1.63
Water above 105 C. ------	.50	.74
Water at 105 C. ---------	.40	.40
Titanium Dioxide --------	3.05	3.25
Carbon Dioxide ----------	none	none
Phosphorus Pentoxide ----	.46	1.20
Sulphur -----------------	.06	.05
Manganese Dioxide -------	.22	trace
	99.95	99.92

Specimens from the highest scarp bounding Upper Alvord Basin on the north. Analyst W. H. Herdsman.

I. Open textured non-porphyritic flow about two hundred feet below the top.

II. The capping flow showing the more acidic type.

Table XI - Part 2

	I	II
Quartz	.24	5.16
Orthoclase	5.56	9.45
Albite	25.15	26.72
Anorthite	32.80	25.02
Diopside	9.83	3.93
Hypersthene	15.10	16.84
Magnetite	3.25	2.78
Ilmenite	5.78	6.08
Apatite	1.34	2.69
Sulphur	.06	.05
Water	.90	1.14
	100.01	99.86

Norms calculated from the analyses in Part 1.

I. Hessose, C. I. P. W. Symbol, II".5."4.4.

II. Hessose, C. I. P. W. Symbol, II"."5.(3)4."4.

differentiation of a dike during periods of quiescence. The surface lava presumably would chill and thereby cause a retention of the volatiles beneath it. While the magma was static, the phenocrysts of labradorite are thought to have formed and to have settled to a zone of equilibrium, where, owing to pressure, the density of the liquid would equal that of the crystals. This hypothetical sinking of the labradorite demands a high volatile content to reduce the specific gravity of the magma. In this magma, the volatile content would probably have been relatively homogeneous and yet, with greater depth, the temperature might well be expected to have increased. If the accumulation of volatiles or tensional forces caused a renewal of activity, the chilled cap might have been ejected explosively. With continued activity the hotter lava from a greater depth would have formed the open textured flows, which would have been followed by the ones rich in phenocrysts. From this hypothetical interpretation, the open texture with its more coarse crystallization is attributed to a relatively high temperature as well as to the still more essential high volatile content.

Dikes

Basaltic dikes are frequently encountered on the eastern scarp of Steens Mountain. 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. The size and orientation of these dikes varies greatly. Most of them, however, are vertical and the larger ones are confined to an approximate north and south axis. (Figure 7)

Many of these dikes show coarse phenocrysts of labradorite and presumably form the feeders for the overlying basaltic series, although some may be of later origin. They usually, however, lack the open texture, and resemble the altered phases of the flows, for the retention of volatiles has resulted in the impregnation of 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 confined to vertical bands. The marked contrast in the resistance of the two phases 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. Locally these bands appear to be explained by marginal chilling, but the evidence is not conclusive.

A number of the larger dikes exposed in the glacial cirques are formed by successive intrusions and hence are true multiple dikes. The largest of these multiple dikes occurring at the base of several of the lower cirques may be traced for many miles as a wall which usually is about fifty feet in width and locally rises close to one hundred feet in height. (Figure 98) Although the exposures are not

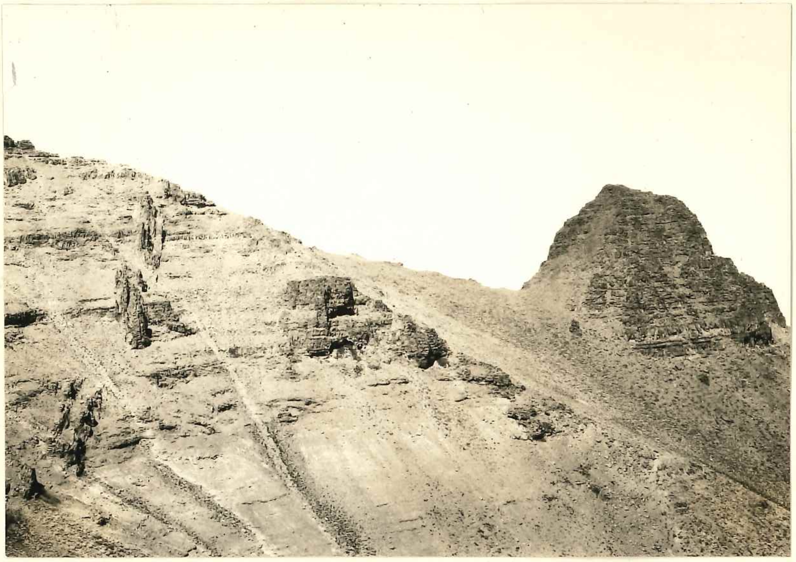

Figure 98. On the left may be seen the broad multiple basaltic dike cutting the basaltic series in the cirque of the south fork of Alvord Creek. The saddle marks the position of the two hundred foot high angle normal fault with the downthrow of the main mass of the mountain. The prominence on the right rises about five hundred feet above the saddle. The exposures to the west have been bevelled by sliding talus. This fault is viewed from the north in Figure 17.

continuous, Waring (61) considered the southern continuation of this large dike to form a prominent exposure near the southern end of the eastern scarp bounding Smith Flat.

Most of the dikes are approximately vertical. In the fault zone between Toughey Creek and Pike Creek, however, two small basaltic dikes follow an inclined course parallel to the planes of the step faults and dip eastward at about sixty degrees. The exposures unfortunately were not sufficiently distinct to prove if either dike were displaced. It is possible that these dikes may have been contemporaneous with the initial movement on the faults. One of these dikes, on coming in contact with a tuffaceous bed, follows it for about a hundred 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 cut the lower tuffs in Pike Creek.

Only on the northern side of the Mosquito Creek cirque (Figure 99) was an exposure observed that suggested the actual extrusion of basalt caused by a dike passing into a flow. Unfortunately the locality is largely covered with talus and morainal material. The exposure shows a coarse basaltic breccia enclosed in a reddish vesicular lava, some of which

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(61) G. A. Waring, "Geology and Water Resources of the Harney Basin Region, Oregon," U. S. Geol. Survey, Water-Supply Paper 231, p. 22.

Figure 99. Looking westward at the basaltic series in the lower cirque of Mosquito Creek. The basaltic vent is exposed in the lowermost outcrops on the northern side of the cirque. On the opposite side of the valley, small normal faults, which dip both to the east and to the west, are obvious from the displacement of interbedded stratified tuffs.

is of a brilliant shade. At its western margin this lava crosscuts the previously mentioned bed of grey stratified tuffs, which is interbedded in the series. (Figure 100) Upwards to the west the basalt appears to merge into thin flows some of which are less than a foot in thickness. Jointing and differential weathering causes the flat sheets, (Figure 101) which are principally under two feet in thickness, to be very apparent, but on examination the actual contacts may be difficult to see, and the change in appearance may be found to be due to a variation in vesicularity. These sheets are considered to have been formed by thin tongues of very fluid lava advancing from this minor vent, which is not exposed to a sufficient depth to prove if it is a fissure eruption.

The Later Series

On top of Northern Steens some fragments of acidic lava suggest that a capping flow may have been removed by erosion. In High Steens the basaltic flows form the surface of the block. South of Smith Flat, however, the rugged crest of Southern Steens is formed by a flow of dense reddish brown lava which caps the basaltic series. This flow, which is at least one hundred and fifty 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.

Figure 100. 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.

Figure 101. Thin basaltic sheets extruded from the vent in the Mosquito Creek cirque.

In the southern part of Pueblo Mountain a flow of grey rhyolite caps the basaltic series. This flow, which is about three hundred feet in thickness shows partially resorbed phenocrysts of quartz about two millimeters in diameter in a cryptocrystalline groundmass. It was once suggested by Merriam (62) 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 XII)

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 disappears beneath the alluvium, an overlying series of tuffs and lavas are exposed above them. This series, which shows a thickness of almost six hundred feet, forms a butte about four miles in length. (Figure 102) 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. They are eroded when the underlying basalt is again exposed by transverse faults.

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(62) J. C. Merriam, "Tertiary Mammal Beds of Virgin Valley and Thousand Creek in Northwestern Nevada," Univ. Calif. Publ., Bull. Dept. Geol., Vol. VI (1910), p. 32.

Table XII - 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
Phosphorous 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 fifteen hundred feet below the summit. Analyst W. H. Herdsman.

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

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

Table XII - 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 1.

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.

Figure 102. 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 lowermost exposures above the basalt are formed of a black rather vitreous lava, which was proved by chemical analysis to be a latite. (Table XIII) In thin section it shows roughly aligned feldspathic microlites in a glassy ground. This latite forms an exposure about two hundred 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.

The surface is formed of vesicular breccias, which fluctuate gently at least fifty feet in elevation. In a manner rather similar to that of the Steens Mountain andesite, the breccias are injected by aphanitic lava showing irregular platy jointing that is predominately 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 fifteen feet of the surface of the uppermost member of the basaltic series and at the same level, suggests that the latite is crosscutting. In addition an adjacent open textured flow is highly altered. Although the relationship is not distinct, the latite is considered to have welled from an elongate

Table XIII - Part 1

	I	II
Silica	62.30	78.55
Alumina	15.22	9.82
Ferrous Oxide	2.73	.92
Ferric Oxide	3.56	1.11
Magnesia	.82	.14
Lime	3.32	.68
Soda	4.00	3.57
Potash	3.49	4.34
Water above 105 C.	2.30	.50
Water at 105 C.	1.40	.30
Titanium Dioxide	.34	.18
Carbon Dioxide	none	none
Phosphorous Pentoxide	.19	trace
Sulphur	trace	trace
Manganese Dioxide	.23	none
	99.90	100.11

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

II. Rhyolite flow about three hundred feet below the top of the series exposed in the scarp east of Alvord Desert. Analysts W. H. & F. Herdsman.

Table XIII - Part 2

	I	II
Quartz ------------------	17.04	40.74
Orthoclase --------------	20.57	25.58
Albite ------------------	34.06	26.20
Anorthite ---------------	13.07	----
Acmite ------------------	----	3.23
Diopside ----------------	2.04	3.13
Hypersthene -------------	3.35	----
Magnetite ---------------	5.34	----
Ilmenite ----------------	.61	.46
Apatite -----------------	.34	----
Water -------------------	3.70	.80
	100.12	100.14

Norms calculated from the analyses in Part 1

I. Toscanose, C. I. P. W. Symbol, I".4".2".3".

II. Alaskose, C. I. P. W. Symbol, I.3".1."3.

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 overlaid by stratified coarse sediments, which are probably of tuffaceous origin. These contain much orthoclase and a minor amount of biotite. This bed, which is only about ten feet in thickness, is indurated at its upper surface by a basaltic flow which is about fifty feet thick. This flow is highly decomposed apparently from deuteric alteration.

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 forty 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 XIII) Quartz phenocrysts one to two millimeters in diameter form less than five percent of the rock.

Above the rhyolite there are light colored stratified tuffs, which at the southern end of the butte, are close to two hundred feet in thickness. To the north, these beds thin gradually to about half that figure. These sediments are overlaid by a small series of basaltic flows. Viewed from the desert this capping seems to be slightly nonconformable towards the north, for the sediments and the underlying series dip southward at about two degrees, while the flows appear to be 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 seventy-five to two hundred feet in thickness. Individually the flows range from ten to twenty-five feet in depth. Although they attained a fairly flat surface they were relatively viscous in comparison to the Steens Mountain series.

The increased viscosity is apparent in the field not only from the absence of an open 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 permitted 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.

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 the low scarp, which rises about four hundred 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 upthrown side.

This northern series was found in several sections 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 open textured 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 one degree. Here it has been roughly bevelled by erosion to an irregular horizontal surface and has been unconformably overlaid 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 twenty miles to the north in Buzzard Canyon a similar lava may possibly be part of the same flow. This, however, is overlaid by two thin basaltic flows, which are capped by a well consolidated breccia consisting largely of coarse pumiceous and glassy fragments.

The Differentiation of the Volcanic Series

The thickness of the great volcanic series strongly suggests that the extrusion occurred in a structural basin, the depression of which may have both preceded and accompanied the volcanic activity. If this sagging took place in the form of a downwarp, there would have been a local distension of the crust at depth, as in the case of the convex side of a bent beam. Following the same analogy, this subsidiary tensional effect would have decreased upwards to the level of no strain and above that point there would be increasing compression. The effect of the latter might be neutralized by regional tension.

The subsidiary tension at depth might logically have resulted in the formation of fissures tapering upwards. The basaltic magma liquified by this release of pressure would have risen simultaneously into these wedge shaped magmatic chambers. The subsidiary compressional effect, however, increasing towards the surface, would have prevented the extrusion of this basalt as fissure eruptions. Instead, with fractional crystallization, possibly aided by assimilation, this magma would have differentiated into more acidic types. Then regional tension or perhaps merely the gradual increase of gas pressure would have caused these elongate magmatic chambers to become the loci of volcanic activity.

On Steens Mountain, the sequence shows, in general, a decided progression in composition from acidic to basic, while the theoretical course of differentiation by the fractional crystallization of a single magmatic mass should have proceeded in the reverse direction. The vents of the Pike Creek volcanics and of the andesite are almost in conjunction and from all geological evidence appear to be confined to a very short span of geologic time. In this instance it is, therefore, rather difficult to conceive of a number of separate chambers, so closely distributed both in time and area, being unrelated, especially since the great mass of extruded material demands a relatively large source. With the renewal of the crustal sagging, which caused the initial formation of the hypothetical wedge, it seems possible to the writer that the differentiating magma might have suffered gradual or periodic contamination by the addition of fresh basalt, causing it temporarily to revert to more basic composition.

Although these local variations may represent stages in the differentiation of a single magmatic chamber, the variety exhibited in the great volcanic sequence of southern Oregon is attributed to unrelated centers of activity and not to a wide spread regional batholith. Conditions controlling local differentiation, however, might have been so general that similar results were attained, perhaps simultaneously, in widely separated regions.

This hypothesis coincides with the fact that the visible volcanic activity is confined largely to the vicinity of the major scarps, although other centers may be hidden. The presence of great discordant wedge-like masses, however, would have caused the localization of the major lines of tensional weakness. It is possible that the subsequent elevation of the acidic volcanics is in part due to the isostatic adjustment of these lighter differentiated masses.

CONCLUSION

The great volcanic series of Steens Mountain was extruded between the Middle Miocene and the latter part of the Pliocene. Aside from the crystalline rocks exposed in Pueblo Mountain, the oldest formation in the region consists of stratified acidic tuffs, which, from paleobotanical evidence, correlate with the Mascal Formation of the Middle Miocene and, therefore, overlie the Columbia River Basalt of northern Oregon and Washington. Before the extrusion of the succeeding members, these beds were deformed both by a basaltic sill and by a rhyolitic laccolith.

The lower part of the overlying series consists locally of fifteen hundred feet of acidic lavas interbedded with stratified tuffs. The lowest flows are of highly acidic rhyolite, while the upper ones are of biotite-dacite. They were followed by the extrusion of andesite to a maximum depth of nearly two thousand feet. Capping this andesite, which consists chiefly of a single huge extrusive mass, are thin basaltic flows forming a thickness of approximately three thousand feet.

The vents for all the major extrusives on the mountain are exposed in the deep valleys eroded in the scarp. The lava invariably appears to be derived from either fissures or elongate vents that roughly parallel the major fault zone. The successive vents occur progressively farther from the base of the scarp and nearer to the main mass of the mountain.

In the lower fault blocks of the region, a varied series of acidic, intermediate, and basaltic lavas, interbedded with tuffs, cap the great thickness of basalt to a depth of about six hundred feet. These show a few minor intervals marked by an angular or an erosional unconformity. Except for these features and the deformation of the basal tuffaceous beds, there is no obvious indication of an unconformity in this great series.

Although this thesis furnishes a fairly detailed report on the areal geology of a section of southeastern Oregon, it is hoped by the writer that the major importance of these observations lies in their testimony regarding a number of geological principles. Many factors render this region almost ideal for the elucidation of the mode of origin of various phenomena both of a structural and petrological significance. The relative simplicity of the geologic sequence, the youthful stage of the erosion, and the absence of vegetation, all contribute to a more precise interpretation of the origin of the structure, while the excellence of the exposures and the absence of weathering aid in the solution of local petrogenetic problems.

The region is structurally important in as much as it permits the establishment of definite criteria which indicate a tensional origin for the local horst and graben structure. The faults defining the blocks are merely the northern continuation of those delineating the ranges of the

Great Basin. Additional testimony is thereby furnished for the tensional origin of the basin range structure.

The petrogenetic data obtained from the region give evidence on many problems of varying importance. To follow the chronological sequence of events, the first point of major interest lies in the various types of alteration suffered by the acidic tuffs at the base of the series. These consist of the extreme optalic metamorphism at the contact of the major basaltic dikes, the green coloration due to the acidic intrusions, and the formation of bedded opal by secondary alteration. The latter is of especial interest since the beds strongly resemble the chert usually ascribed to the deposition of colloidal silica.

In the acidic lavas, the principal importance lies in the interpretation of the vent characteristics, which consist chiefly in the inclined platy jointing and in the localization of spherulites. The usual alteration of the perlite adjacent to the spherulites is attributed to the volatiles expelled by this feldspathic crystallization. In the massive lava, the rock bordering the major joint cracks is locally less kaolinized, due presumably to the liberation of the deuteric volatiles.

Probably owing to its unprecedented magnitude, the great flow of andesite exhibits several phases that demand an original interpretation. In brief, the evidence indicates that the very extensive injected breccias overlying the columnar phase are merely a surface feature formed during the gradual consolidation of an extruded mass, which was so vast that it even developed prominent satellitic activity.

The basaltic series shows many interesting phenomena. The peculiar "open texture", which is attributed to the high volatile content of the lava, has apparently never been previously described, although the basalt otherwise is comparatively normal both in its mineralogical and its chemical composition. This volatile content has resulted in other peculiarities in the series. In these flows, as well as in some of the acidic lavas, the rock adjacent to the major joint cracks is locally fresh, although the central portion of the blocks may have suffered extreme endomorphic alteration. This corrosive action of the deuteric residuals occurs only where the volatiles were unable to escape along the cracks. Although many of the flows are of a type that should have been ideal for the development of convectional columns, that theory was found to be untenable. This fact suggests a contractional origin for the jointing.

This series also exhibits various types of differentiation. Small horizontal magmatic segregations are relatively common in flows that have been high in volatiles. These segregations, following the laws of fractional crystallization, show an increase in silica, potash, soda and ferrous oxide. Local concentrations of coarse phenocrysts of labradorite were attributed in part to gravitational settling during the flowage of a fluid lava, the relatively low specific gravity of which was due to a high volatile content. In one flow an extreme basal accumulation of olivine grains is considered to have been caused by the gradual settling of this mineral during the long continued flowage of a more mobile upper zone.

Aside from the variations in the series due to the local settling of the phenocrysts during flowage, some flows are decidedly finer in texture and more acidic in composition. This phenomena is especially noticeable in Upper Alvord basin where the various types of basalt show a periodic repetition of their sequence. This variation is attributed to the differentiation of a dike during periods of quiescence. The postulated origin, however, is of a hypothetical nature.

The sagging of the structural basin, which this volcanic series fills, demands the local distension of the crust at depth. This tension is considered by the writer to have permitted the rising of basalt as a primary magma, into fissures which tapered upwards. The isolated magmatic wedges, thus formed, might have differentiated both by fractional crystallization and assimilation. These wedges would have paralleled the major axis of the sag and also would have been normal to the predominate tensional stress. Volcanic activity might be due either to the accumulation of volatiles or to tensional forces.

The fact that the series in a single locality frequently reverted to a more basic composition is attributed either to eruptions from unrelated magmatic chambers, or to the periodic contamination of the differentiating magma by the addition of fresh basalt. It is also suggested that the localization of the acidic differentiates may have resulted in isostatic adjustment at the time of the major faulting and thereby may explain the extreme elevation both of High Steens and of Hart Mountain.

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VITA

Richard Eugene Fuller was born in New York City June 1, 1897. His early education was obtained in private schools in that city. Subsequently he attended the Hill School of Pottstown, Pennsylvania. After four years, he received a degree in science from that institution in 1915. He then entered the Yale Sheffield Scientific School, and enrolled in the department of chemistry.

He left college in April 1917, and enlisted as an Ambulance Driver in the American Field Service. He resigned from that service when it was taken over by the American Army and returned to the United States. He then enlisted in the Coast Artillery. After attending the school at Fort Monroe, he was commissioned as Second Lieutenant and was sent to France. There he graduated from the Heavy Artillery School at Angers and was assigned to Battery B of the 42nd Artillery, C.A.C.

After receiving his discharge, he spent one year travelling in the Orient. On returning he enrolled at Yale as a senior, and in June 1921 received a degree of Bachelor of Philosophy, *honoris causa*. After graduation, he worked for a year in a bank in Salem, Oregon before returning to scientific activities.

In the autumn of 1923, he entered the University of Washington as a student of geology, and received a degree of Bachelor of Science in 1924, and that of Master of Science in 1925. Except for two quarters in 1925, which he devoted to travel, his time has subsequently been divided principally between research and outside activities, which are chiefly connected with the Art Institute of Seattle. He was elected trustee of that institution in 1928, Vice-President in 1929, and President in 1930. When necessary, however, he has served in the department of geology as a teaching fellow. For the last year he has held the rank of Associate. For the coming year, the University has appointed him Assistant Professor of Geology with a research appointment. He has been an active member of Sigma Xi since 1928.

While attending the University of Washington, he published the following articles:-

"The Closing Phase of a Fissure Eruption," American Journal of Science, Vol. XIV, (1927), pp. 228-230.

"The Mode of Origin of the Color of Certain Varicolored Obsidians," The Journal of Geology, Vol. XXXV, (1927), pp. 570-573.

"The Asotin Craters of the Columbia River Basalt," The Journal of Geology, Vol. XXXVI, (1928), pp. 56-74.

(With Martin A. Peacock) "Chlorophaeite, Sideromelane, and Palagonite from the Columbia River Plateau," American Mineralogist, Vol. 13, (1928), pp. 360-383.

(With Aaron C. Waters), "The Nature and Origin of the Horst and Graben Structure of Southern Oregon," Abstract, Bulletin of the Geological Society of America, Vol. 40, (1929), p. 187; The Journal of Geology, Vol. XXXVII, (1929), pp. 204-238.