[AMERICAN JOURNAL OF SCIENCE, VOL. 253, MARCH 1955, PP. 173-181]

BASALT COLUMN RINDS CAUSED BY DEUTERIC ALTERATION

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ABSTRACT. A late Tertiary columnar basalt flow in southwestern Oregon is characterized by a narrow, dark rind zone around each column. This rind, which was at first attributed to chilling, has instead been found to be a zone of deuteric alteration caused by volatiles escaping toward the joint cracks. Locally the volatiles were trapped within the core of the columns and produced altered patches. The altered patches and rind zone are characterized by the presence of chlorophaeite, a hydrous mineraloid of deuteric origin. Elsewhere, the rock is fresh.

The joint cracks are believed to represent loci of reduced pressure toward which the volatile materials streamed from the interiors of the columns. Volatiles were trapped only locally in the core but uniformly in thin zones around the columns, where they proceeded to convert olivine and glassy base into chlorophaeite and, in some instances, into siderite and chlorophaeite.

Three earlier reports of joint crack control of deuteric alteration are cited. However, in all these cases the rock adjacent to the joint cracks was fresh and the rock farther away was highly altered. This condition is the *reverse* of that observed by the present writers.

INTRODUCTION

In the summer of 1949 a county road quarry in southwestern Oregon was examined. This quarry is located in the Butte Falls quadrangle in Jackson County about four miles west of Butte Falls on the road to Medford (fig. 1).

The rock is a late Tertiary (Pliocene ?) porphyritic olivine basalt flow, the "later intracanyon basalt" of Wilkinson, et al. (1941), that extends westward down the divide between McNeil Creek and Butte Creek valleys. The total observed thickness of this flow is about 40 feet, with columnar joints well developed throughout the total thickness and over an area examined of about 500 square yards. The average diameter of the columns is about two feet, and each column is surrounded by a relatively uniform black rind zone. This paper presents the results of a study of these rind zones.

DESCRIPTION OF THE BASALT

General nature.—The bulk of each column of this olivine basalt flow consists of a core zone of dark gray fresh rock completely surrounded by a narrow black altered rind zone containing the mineraloid chlorophaeite. Most columns exhibit a thin outermost yellowish-brown weathered zone. Vesicular patches occur sporadically throughout the core.

Core.—The core comprises the greatest part of the column and is characterized by clear light gray euhedral to subhedral plagioclase phenocrysts and fewer small grains of yellow olivine and dark brown augite in a black aphanitic groundmass. The phenocrysts are generally random, but locally flow structure, approximately normal to joint columns, is well developed.

Rind.—Surrounding each column is a thin black zone which, upon casual examination, appears to be an aphanitic chilled border. The zone is uniform in thickness around any given column and varies but slightly from one column to another, the average thickness being 1 cm. The contact between this zone and the core is abrupt and regular. Plate 1-A shows such a zone. Identical thin zones have been found cutting through the core in random manner, and

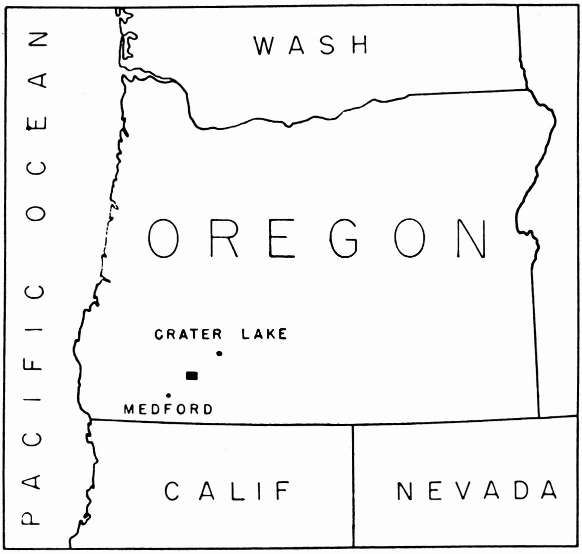


Fig. 1. Index map showing location of Butte Falls quadrangle.

as irregular and branching streaks. These may cut completely through the column or extend for only a short distance. Some are subparallel to the outer rind.

Close examination reveals phenocrysts of the same size and composition as those in the core, and many are seen to extend across the contact of these two zones (pl. 1-B). This zone, which is so striking in hand specimen, would go unnoticed in thin section except for its alteration products (cf. below). The plagioclase appears dark brown and glassy and shows no contrast with the dark groundmass. The mafics appear the same as in the core.

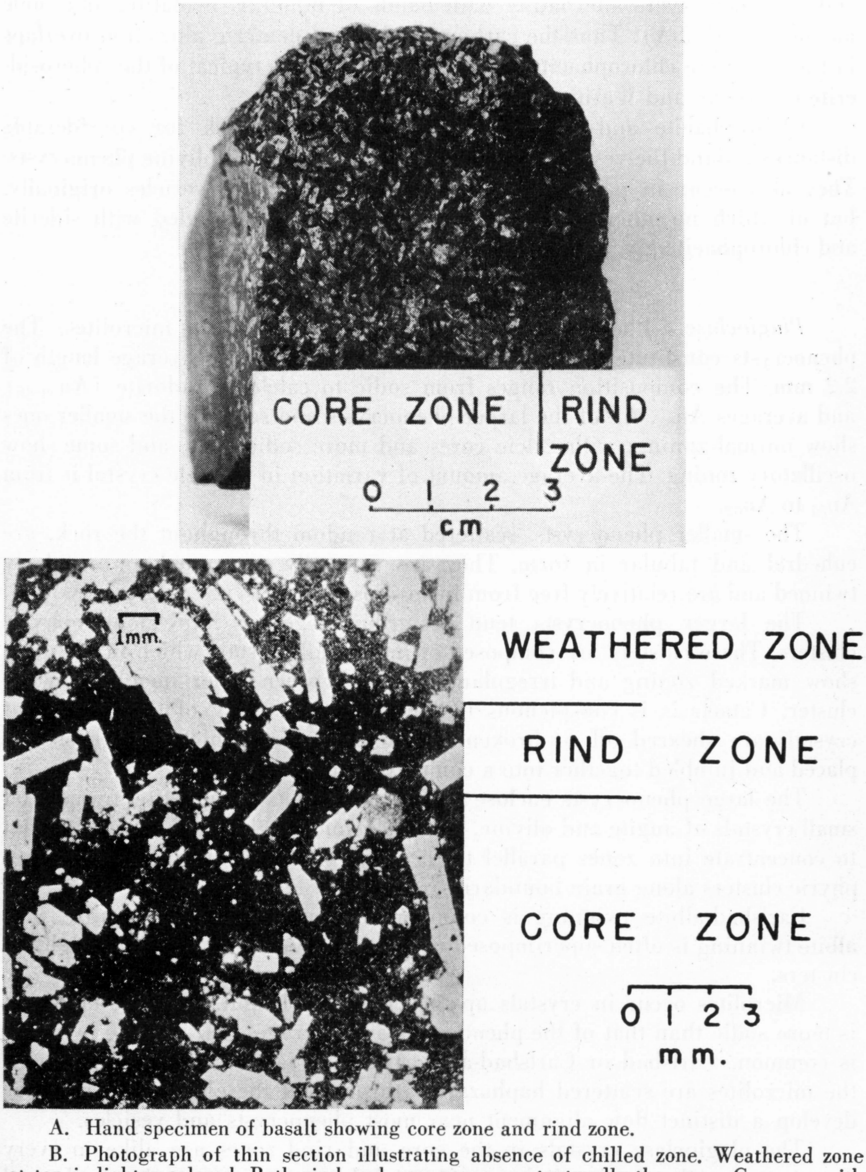
Weathered rind.—A weathered zone, varying from less than 1 mm to 5 mm occurs around the basalt columns. A thin film or coating is the most characteristic form. Weathering has softened the outer part of the rind to a yellowish-brown clay-like rock. In contrast to the unweathered rind, the phenocrysts stand out as clearly visible crystals. Except for the light brown color of the groundmass this zone presents the same appearance as the core. In thin section the rind and weathered rind are clearly demarked. All of the glass and some of the magnetite have been converted to limonite dust. The plagioclase and augite phenocrysts and the plagioclase microlites are unaltered. A few olivine grains remain. Rarely, the entire rind zone has been altered, in which cases the weathered zone is in contact with fresh core material.

Vesicular patches.—Sparsely scattered through the core are zones of alteration containing an abundance of vesicles. These irregularly shaped areas range up to 25 cm in diameter and contain vesicles as much as 2 cm in diameter.

All vesicles are lined with chlorophaeite which in turn may be coated with siderite and calcite or natrolite. That portion of the basalt immediately enclosing these vesicles and amygdales is very dark in appearance and resembles the rind zone.

Microscopic examination reveals alteration of the same sort that characterizes the rind zone, which is even more intense locally. The vesicle walls

PLATE 1



A. Hand specimen of basalt showing core zone and rind zone.

B. Photograph of thin section illustrating absence of chilled zone. Weathered zone at top is lighter colored. Both rind and core zones are texturally the same. Compare with A. Large clear laths are plagioclase phenocrysts; minute clear laths are plagioclase microlites. Light gray prisms are augite phenocrysts.

are lined with orange-brown and/or green chlorophaeite layers which grade into a green surface fringe of chloritic fibers. This outer chloritic fringe, which represents the breaking down of chlorophaeite, is lacking in those vesicles which are filled. The carbonate structure is radial and consists of concentric layers with the first few layers alternating with green chlorophaeite and the later layers alternating with bands of limonite, hematite, and some magnetite (pl. 2-A). Thus the carbonate phase of deuteric alteration overlaps in time with the chlorophaeite phase. This structure is typical of the spherosiderite in Oregon and Washington lavas.

Chlorophaeite and siderite permeate the host rock for considerable distances around the vesicles and completely replace many olivine phenocrysts. They also occur in patches that may have been smaller vesicles originally, but of which no other trace remains. Chloritic fibers mingled with siderite and chlorophaeite give a fine felted texture to these patches.

PETROGRAPHY OF THE BASALT

Plagioclase.—Plagioclase occurs as phenocrysts and microlites. The phenocrysts constitute 22 percent of the rock and have an average length of 2.2 mm. The composition ranges from sodic to calcic labradorite (An_{50-68}) and averages An_{63}. All of the larger phenocrysts and some of the smaller ones show normal zoning, with calcic cores and more sodic rims, and some show oscillatory zoning. The average amount of variation in a single crystal is from An_{57} to An_{63}.

The smaller phenocrysts, scattered at random throughout the rock, are euhedral and tabular in form. They are generally not zoned or complexly twinned and are relatively free from inclusions.

The larger phenocrysts tend to group together into glomerophyric clusters. These clusters are composed of individual crystals which in the main show marked zoning and irregular contacts between other members of the cluster. Cataclasis is conspicuous in these clusters. Many of the constituent crystals are sheared off or broken into smaller parts which have been displaced and jumbled together into a complex aggregate.

The large phenocrysts enclose glassy groundmass, magnetite grains, and small crystals of augite and olivine. The inclusions of glass and magnetite tend to concentrate into zones parallel to the clino-pinacoid, and in the glomerophyric clusters along grain boundaries.

Carlsbad-albite twinning is common and pericline twinning rare. The albite twinning is often superimposed upon several grains of the glomerophyric clusters.

Microlites occur in crystals up to 0.1 mm in length. Their composition is more sodic than that of the phenocrysts and averages An_{40}. Albite twinning is common, Carlsbad or Carlsbad-albite twinning is rare. For the most part the microlites are scattered haphazardly throughout the glassy base but they develop a distinct flow alignment near most phenocrysts and vesicles.

The plagioclase crystals in the core and rind zones are alike in every respect except that in the rind zone films of chlorophaeite coat the cracks and surfaces of the crystals.

Augite.—Augite is present both as phenocrysts, as much as 5 mm in length, and as minute granules in the groundmass. The phenocrysts, which appear in thin section as elongate euhedral prisms and subhedral partially resorbed crystals, comprise 5 percent of the rock. The mineral is faintly pleochroic from pale green to brownish green. Much pigeonite "molecule" is present as shown by measurements of the optic angle about Z which range from 39 to 48°. The optic plane is (010) and the maximum extinction ($Z \wedge c$) obtained was 42°. The index of refraction $N_g = 1.715$. All optical data combined indicate an Fe:Mg ratio of about 7:10. Inclusions are common in the phenocrysts and are olivine, plagioclase, grains of magnetite, and more rarely, blebs of the glassy groundmass. The large augite phenocrysts seldom cluster into glomerophyric aggregates.

Augite granules in the groundmass are less than 0.01 mm in diameter and are associated with olivine granules of about the same size. They appear predominantly brownish and are of about the same composition as the augite phenocrysts as judged by measurements of 2V.

Hypersthene.—Hypersthene occurs throughout the rock as a minor accessory and was found in about half of the 18 sections examined. It appears as elongate tabular crystals, the length ranging up to 3 mm and averaging about 1 mm. Pleochroism is distinct with X reddish orange, Y yellowish brown, and Z very light green. The 2V about X is large and appears to be about 60°, indicating an excess of Mg over Fe. There is distinct basal parting.

Olivine.—Olivine occurs as euhedral to subhedral phenocrysts, as much as 2 mm in diameter, and as small granules in the groundmass. The phenocrysts comprise about 3 percent of the rock and tend to unite with augite in cumulophyric aggregates. The olivine is clear except for a few inclusions of magnetite and glass. The grains are colorless in thin section, but pleochroic in thicker fragments from pale grayish yellow to dusky greenish yellow. They are occasionally twinned and frequently have numerous small cracks. Cleavage is distinct (010) and less distinct (100).

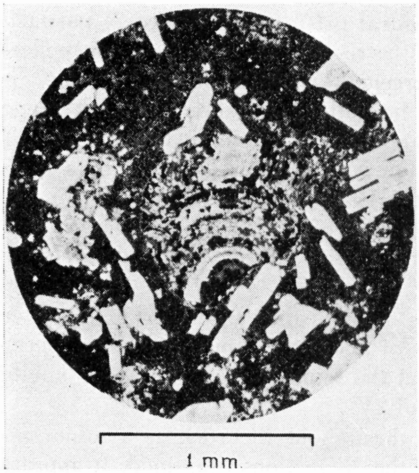
Dr. H. S. Yoder, Jr., very kindly made an X-ray examination of this material and found it to have 31($\pm$2) percent of the fayalite molecule. The following optical properties were determined: $N_m = 1.722 \pm 0.001$, (–) $2V_{Na} = 80°$, $r < v$. These indicate hyalosiderite, in keeping with the X-ray determination.

Groundmass.—The groundmass is characteristically black and comprises about 70 percent of the rock. It consists of opaque black glass and innumerable small microlites and crystallites of plagioclase. Olivine and augite granules make up about 15 percent of the groundmass. Magnetite is also present in scattered grains and in a dusty form so abundant as to make the glass opaque.

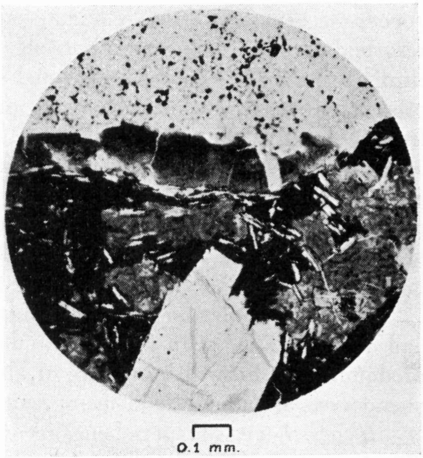
Chlorophaeite.—Chlorophaeite, the hydrous mineraloid which occurs as the alteration product in the rind zone material, was described in detail by Peacock and Fuller (1928). The optical properties of the chlorophaeite determined by the present writers correspond with those given by Peacock and Fuller.

In hand specimen chlorophaeite is reddish brown. When the specimen is freshly broken the chlorophaeite, coating and partly filling some of the

PLATE 2



A.



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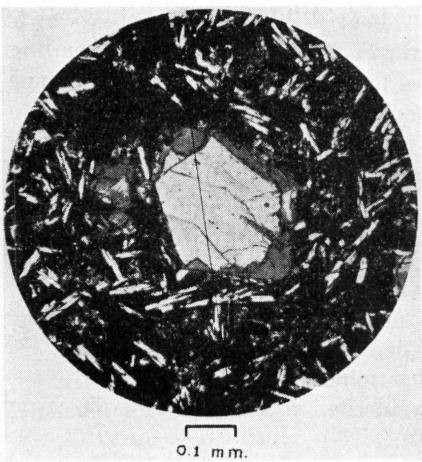

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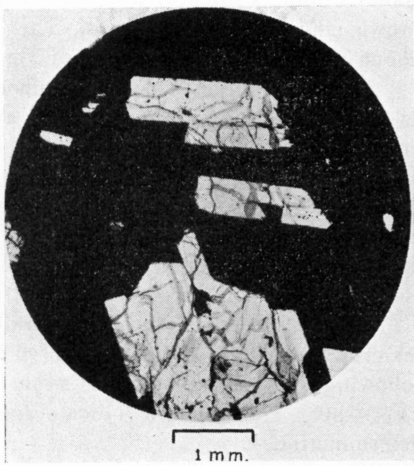

D.

A. Photomicrograph of amygdale of banded siderite, chlorophaeite, magnetite and limonite. Groundmass has many patches of chlorophaeite, chlorite and siderite in felted masses (light gray irregular areas). Clear laths are plagioclase phenocrysts. Plane light.

B. Photomicrograph showing margin of vesicle lined with chlorophaeite. Outer edge of chlorophaeite crust is brown, inner portion and groundmass material are light green. Color change caused by oxidation. Large plagioclase phenocryst in lower middle; small clear laths are plagioclase microlites. Plane light.

C. Photomicrograph of olivine phenocryst partially replaced by chlorophaeite (dark gray). Surrounded by plagioclase microlites. Rind zone. Plane light.

D. Photomicrograph showing plagioclase phenocrysts with chlorophaeite coating cracks. Rind zone. Plane light.

vesicles, is green and distinctly pitch-like in luster. After a brief exposure to the air the green color changes to reddish brown.

In thin section, chlorophaeite is seen to be confined to the rind zone material and to local vesicular patches in the interior of the columns. The chlorophaeite is isotropic and is mostly reddish brown and green, and sometimes brown. The average index of refraction of a dozen grains tested is 1.51. The brownish material apparently represents an oxidized phase of the green unaltered chlorophaeite. Evidence of the color change by oxidation is shown in thin section in which a vesicle lining of the green material is coated by the reddish brown chlorophaeite (pl. 2-B). The green chlorophaeite tends to develope minute fibers commonly oriented in a spherulitic manner, but may occur as a confused mass in which the fibers are diversely oriented. These fibers, which exhibit low birefringence, are probably chlorite.

The cholorophaeite is commonly associated with olivine which it replaces along cracks and cleavages. Usually olivine is only partially altered (pl. 2-C), although all stages of alteration are found, even to complete pseudomorphic replacement. Some irregular patches of alteration occur in the groundmass and have resulted from a replacement of both the vitreous base and the groundmass olivine granules. The augite was nowhere observed to be more than incipiently replaced by chlorophaeite, although in the rind zone its cracks are commonly coated with chlorophaeite. Hypersthene was not observed in the rind zone, consequently its susceptibility to alteration is unknown. Chlorophaeite does not replace plagioclase but is found as coatings and thin films lining cracks in the plagioclase (pl. 2-D). In some cases very thin stringers or veinlets filled with chlorophaeite traverse the rind zone.

Inclusions of glassy base and olivine have been altered in some cases, while the enclosing plagioclase or augite phenocrysts are not altered even though they are traversed by chlorophaeite-filled cracks.

ORIGIN OF THE RIND ZONE

The concentration of chlorophaeite in the rind zone suggests the manner in which is was formed. Subsequent to the outpouring of the basaltic lava, the flow began to solidify at its surface by the loss of heat and gaseous material to the atmosphere. Stress, initiated by the cooling of the mass, caused centers of contraction to form near the cooling surface producing typical columnar joints. Joint cracks thus formed created loci of reduced pressure and a streaming of volatiles took place from the interior of the columns towards the outside. The basalt had cooled so that it was partially crystallized, yet fluid enough to allow a transfer of gaseous materials. That small amounts of volatiles were trapped in the columns is shown by the scattered vesicular patches; however, most volatiles probably reached the joint cracks and escaped into the air. The residual volatiles that did not quite reach the cracks were trapped in the thin zones surrounding the columns. These residual volatiles, unable to escape, attacked the olivine and glassy base and partially or completely altered them to chlorophaeite and/or siderite. The alteration appears as rims surrounding the partially altered olivine, as pseudomorphs of the completely altered minerals, and as minute films coating and filling cracks in the plagioclase phenocrysts.

This is in agreement with Peacock (1930, p. 172) who states, "Chlorophaeite, on the other hand, according to every careful study, has been formed in doleritic rocks by the reaction of late magmatic, therefore internal, fluids, with newly crystallized ferromagnesian minerals in the rock, most commonly olivine, or sometimes perhaps, with ultrabasic vitreous residue of similar composition. The resulting gel-like product has thus a strongly basic composition corresponding roughly with that of chlorite."

SOME OTHER OCCURRENCES OF CHLOROPHAEITE ROCK

A deuteric process similar to that postulated by the present writers has been reported by Fuller (1938) in a Tertiary basalt flow that caps Steens Mountain in southeastern Oregon. Although the processes were essentially the same, Fuller indicated that the basalt columns show a marked deuteric alteration in the *central portion* of the columns and that the basalt is fresh adjacent to the major joint cracks. Fuller postulates that, as the jointing proceeded, gases escaped along the joint cracks, permitting the basalt to crystallize adjacent to the column walls before final consolidation within the columns.

In an investigation of the Iron Springs district of Utah, Mackin (1947, p. 43-47, summarized 1954) outlined a mechanism of origin of emanations similar to that of Fuller (1938). In the Three Peaks, Granite Mountain, and Iron Mountain laccoliths studied by Mackin, monzonite was completely "stewed" and deuterically altered except where tension joints penetrated into the partly consolidated crystal mesh and allowed iron-rich deuteric emanations to escape from a narrow zone of the adjacent wallrock. This escape halted the alteration and left the selvage rock relatively fresh and also lower in mafics, lower in iron content and lighter in color. He found that mineralizing emanations had been given off from the monozite only where cross joints provided channels of escape for deuteric volatiles.

Fuller has more recently (1950) described the olivine-rich zone of the Palisades diabase sill which appeared to him to be identical to the Steens Mountain flow (Fuller, 1938).

In all three instances cited above, the position of unaltered and altered zones is the *reverse* of that observed by the present writers. To the authors' knowledge no comparable examples have been described before.

SUMMARY

There are at least three processes that might have formed the altered rind of the present study: (1) weathering, (2) exomorphic alteration, and (3) endomorphic alteration. The writers have discarded weathering because of the existence of a true, vastly different weathered zone in which limonite and clay have formed, and because of the presence of completely isolated rind zone material in the fresh core. These same isolated patches prompt them to dismiss the possibility of any other exomorphic origin of the alteration and to accept the endomorphic process described above.

The most unusual feature of this basalt flow is the presence of a thin black zone surrounding each column. At first sight the rind appears to represent a thin chilled margin. However, upon examination of thin sections it was found that the two rock units are identical in texture. ***These rinds are joint-controlled zones of deuteric alteration.*** The pseudo-chilled effect can be attributed directly to the decomposition product chlorophaeite, which coats the light-colored plagioclase phenocrysts and causes them to blend in color with the black groundmass.

ACKNOWLEDGMENTS

The authors wish to thank Dr. H. S. Yoder, Jr., of the Geophysical Laboratory for his X-ray examination of olivine; Prof. Lloyd W. Staples of the University of Oregon; and Prof. Randolph W. Chapman of Trinity College who critically reviewed the manuscript.

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