SPHEROIDAL WEATHERING OF IGNEOUS ROCKS

RANDOLPH W. CHAPMAN AND
MILDRED A. GREENFIELD

ABSTRACT. Spheroidal weathering is that process by which igneous rocks scale off in concentric shells producing rounded boulder-like forms. Despite recent observations and experimental data, many individuals still misunderstand the true nature of this process. The present paper is an attempt to clarify the matter.

The first part of the paper reviews the several hypotheses which have been advanced from time to time to explain spheroidal weathering. The current views, held by the best authorities, are that spheroidal weathering results from either of two processes: (1) the swelling and spalling of the exterior surface of angular blocks of rock due to the hydration, carbonation, and oxidation of constituent minerals in the outer surface, or (2) the swelling and spalling of the exterior surface of angular blocks which have been subjected to sudden, intense heating of their exterior by forest fires and brush fires.

The second part of the paper describes the mineral alterations observed in the shells surrounding several spheroidally weathered boulders. This study shows that in general the core of each boulder consists of relatively fresh rock, but in the shells surrounding the core the primary minerals are altered by weathering to secondary minerals such as kaolinite, sericite, montmorillonite, serpentine, chlorite, hematite, and limonite. As a result of these changes the altered rock has increased in volume, the rock in the outer shells having suffered a greater increase than that in the inner ones. It is concluded that this increase has caused the rock to scale off in concentric shells.

INTRODUCTION

IT is a commonly observed fact that many igneous rocks tend to scale off along joint faces, especially at corners and edges formed by intersecting joints, and thereby develop rounded boulder-like forms which are often but not always enclosed in concentric shells. These rounded boulders range in diameter from a few inches to several feet, and the shells that bound them are from a fraction of an inch to several inches thick. The outer shells normally show a greater degree of weathering than the inner ones, and the core generally consists of fresh, unaltered rock. These boulders have been observed both at the surface and below the surface down to a depth of approximately 40 feet. Examples of this type of weathering have been reported from such widely scattered localities as California, Montana, Vermont, Oklahoma, Hawaii, Ireland, India, and Southern Rhodesia.

The term "exfoliation" has been applied by various writers to this phenomenon, a word which can be traced to the Late Latin *exfoliare* which means to strip of leaves or to scale or flake off. This term has lost much of its significance, however, since it has been applied in a general way to several types of rock spalling, such as the flat flaking of the pyramids in Egypt (Barton, 1916); to sheeting which is flaking on a much grander scale (Gilbert, 1904; Miller, 1911); and to the type of rock spalling that develops rounded residual boulders (Grabau, 1920, pp. 393-394; Blackwelder, 1925). Other names such as "concentric exfoliation," "concentric weathering," and "spheroidal weathering," have also been applied to the process by various authors. The present writers believe that the term spheroidal weathering is the most appropriate for this type of weathering, since it is expository and describes the type of boulder that is formed by the process. This name, therefore, will be used in the present paper.

During the last 90 years several hypotheses have been advanced to explain the spalling of rocks to produce rounded forms. It appears certain now, however, largely as a result of the careful studies of Eliot Blackwelder (1925, 1926), that spheroidal weathering results from the swelling and spalling of the exterior surface of blocks of rock due either to: (1) the hydration, carbonation, and oxidation of constituent minerals in the outer surface, or (2) the sudden intense heating of the outer surface by forest fires and brush fires. The senior author of the present paper has observed, however, in discussing the matter with others, that in spite of Blackwelder's work some geologists and many students are still confused by spheroidal weathering. Many fail to appreciate the relative importance of the two processes involved or are unable to discern which process operated in a particular case. The confusion is increased by the use of the name "exfoliation" for this type of weathering, a term that has also been applied to other somewhat similar processes. The purpose of the present paper is to clarify the subject and dissipate some of this confusion.

The first part of this paper is an historical review of the several hypotheses that have been advanced to explain the phenomenon of spheroidal weathering. The development of ideas is traced and the current views on the process are summarized. The second part of the paper is a description of the actual mineral alterations that have taken place in the shells surrounding several spheroidal boulders. It is believed that this information is a worthwhile contribution inasmuch as heretofore the mineral alterations accompanying spheroidal weathering have been described rather generally and vaguely, and, so far as the authors are aware, no detailed microscopic description of such changes has ever been published.

DEVELOPMENT OF HYPOTHESES ON THE ORIGIN OF SPHEROIDAL WEATHERING

Many years ago Page (1861, p. 75) in connection with his studies on the structures of igneous rocks, noted that some greenstones present a spherical or globular structure, the weathered cliffs of such a rock appearing like a huge accumulation of bombs and balls varying from a few inches to several feet in diameter. "Such a structure," he said, "from its apparent aggregation round a common centre, is also termed concretionary, and generally exfoliates, on exposure to weather, film after film, like the coats of an onion." Page evidently thought that the spheroids produced by weathering were fundamentally concretionary in nature and were merely brought out by weathering.

Bonney (1876) related that Professor J. Thompson regarded spheroidal "structure" as "the result of a process of exfoliation due to the action of the weather on a tolerably regular-shaped, homogeneous mass" (p. 149) along joint planes. Bonney disagreed with Thompson, however. He was willing to concede that cuboidal blocks of rock obviously tend to weather into rough spheroids; also that further action of the weather might occasionally produce concentric exfoliation in such spheroids; however, he did not believe that any theory of decomposition was adequate to explain the facts. Bonney believed that spheroids could form without the presence of joint planes. He supported his argument by citing the columnar basalt near Le Puy, Central France, in which "spheroids may be seen, . . . enclosed three or four at a time in a columnar shell without any dividing cross joints, so that they are just like Dutch cheeses packed in hexagonal cases (the interstices being filled up). The lid of the box has more or less fallen away and exposed the contained spheroids." (p. 150). He pointed out that since these spheroids are all solid, weathering has not occurred because there are no joints along which it can proceed. Bonney was convinced that spheroidal "structure" is due chiefly to contraction of the mass while cooling. During the discussion which followed the presentation of Bonney's paper before the Geological Society of London, a Mr. Koch told of an experiment in which he had placed fragments of ironstones and quartzite upon the sole of a furnace. These fragments cracked off in shells, leaving spheres. Thus Bonney's paper considers three hypotheses for the origin of spheroidal weathering: (1) Professor Thompson's theory of chemical decomposition caused by weathering along joint planes; (2) Bonney's theory that spheroids are the result of contraction of the rock mass while cooling; and (3) Koch's discovery that spheroids may be produced by the heating of rocks.

Geike (1882, p. 335) interpreted the spheroidal boulders of igneous rock as a result of weathering. He observed that: "In many prismatic massive rocks (basalt, diorite, etc.) segments of the prisms weather into spheroids, in which successive weathered rings form crusts like the concentric coats of an onion. When one of these rocks has been intruded as a dike, it sometimes decomposes to a considerable depth into a mass of brown ferruginous balls in a surrounding matrix—the whole having a resemblance to a conglomerate made of rolled and transported fragments."

Along the Potomac River, outside of Georgetown, Washington, D. C., Spencer (1885) noticed perfectly rounded boulders of gneiss in a large mass of decayed rock of similar composition. The hillside had been cut away in the construction of a road beside the river, and exposed decayed crystalline rock to a depth of nearly 50 feet. Much of the gneiss was disintegrated but contained unaltered masses which had resisted atmospheric decay. Some of the gneiss upon weathering exhibited a schistose structure, yet much was remarkably compact, but traversed by numerous joint planes extending in all directions. As the weathering proceeded from the joint planes it left solid masses which were spheroidal and often showed a banded structure. Surrounding them were concentric zones which he decided marked the progress of decay and were in no way related to concretionary structure.

Thus far, geologists had noted spheroidally shaped boulders, enclosed in a series of concentric shells which they believed were caused by weathering, but they had not explained the mechanics of the process.

The importance of oxidation and decay in the production of spheroidal weathering was first clearly outlined by Dana (1895, p. 127). According to him: "This oxidation process, and other methods of decay go on with greatest rapidity in the fissures of rocks below a surface soil, because the descending surface waters keep them almost continuously wet; and it is under such circumstances that a rock which is much fissured or jointed becomes reduced to a pile of great boulders with a rusty earth between. The decay of oxidation at first produces a thin discoloring of adjoining surfaces, and this continues, eating off the angles, which are attacked from three directions, until a bluff of solid rock becomes apparently a pile of great boulders. With the progress of alteration, the discolored portion becomes banded with yellow and brown; and as it deepens, the outer part of the spheroid sometimes separates in concentric shells, precisely corresponding with the concentric structure of a concretion. But these concentric shells are due to the decay that is in progress; and apparently to alterations in the work of decay dependent on climate . . . " Dana thus recognized that this spheroidal weathering is due to a definite type of chemical action related to climatic conditions.

The "niggerheads" of the gabbro area around Baltimore, Maryland, were cited by Merrill (1897, pp. 241-248), as typical examples of spheroidal weathering. These massive rocks, he thought, had been originally traversed by one or more sets of joints, along which moisture and "the accompanying agents of disintegration" had made their way and gradually rounded off the corners until only an oval mass remained, surrounded by concentric layers. Merrill believed that the above process holds true also for huge granite bosses, or domes, such as those in Yosemite Valley, California, and Stone Mountain, Georgia. These domes, he felt, were merely on a much grander scale. He did not elaborate upon the mechanics of the process.

Some years later J. F. Kemp (1909) received from a Mr. J. R. Villars a photograph accompanied by a letter discussing the curious weathering of a diabase dike near Butte, Montana.

This dike, which was exposed to a depth of 20 or 30 feet, showed rounded masses of rock varying in diameter from a few inches to two feet. These masses were separated into concentric layers, a division which was marked in the weathered rock but was wanting or scarcely observed in the fresh rock. Kemp forwarded the photograph and letter to the Mining and Scientific Press stating that: "The dike is a fine illustration of spheroidal weathering . . . the breaking up being in large degree referable to strains produced in cooling. Weathering has brought out the shelly or onion structure, but one cannot well resist the conviction that some internal structure has facilitated the assumption of these peculiar shapes." (p. 443). Although Kemp's conclusions are not at all clear, it appears that he attributed spheroidal weathering of the diabase to a combination of three factors: (1) internal structure, (2) strains caused by cooling, and (3) weathering.

Hobbs (1912, pp. 150-152) was one of the first to recognize two distinct processes in the development of rounded boulders resulting from spheroidal weathering: (1) mechanical disintegration, and (2) chemical decomposition. Hobbs believed mechanical disintegration is due to daily temperature changes. Relative to chemical decomposition he made an effort to analyze its progress. He stressed the importance of jointing in facilitating the progress of chemical decay which he thought was brought about by the process of hydration and carbonation. He emphasized that the newly formed minerals, resulting from hydration and carbonation, are notably lighter and hence more bulky than those minerals from which they have formed. "Strains are thus set up," he argued, "which tend to separate the bulkier new material from the core of unaltered rock. Eventually, the squared block is by this process transformed into a spheroidal core of still unaltered rock wrapped in layers of decomposed material . . . " (p. 151).

Cleland (1916, pp. 31-33, 39-40, 388), like Hobbs, believed that rounded boulder-like forms can be developed by two distinct processes of weathering. One of these he termed "spheroidal weathering" which he considered to be brought about by chemical decomposition occasioned by hydration. The other he called "exfoliation" and explained it as mechanical disintegration brought about by daily changes in temperature.

Grabau (1920, pp. 393-394) believed that rounded boulders are produced in two ways: (1) by "concentric exfoliation" whereby the rock peels off in concentric shells, and (2) by granular disintegration whereby the rock crumbles into grains but leaves a rounded residual boulder. "Concentric exfoliation" he attributed to daily changes of temperature. These changes, he maintained, are especially great in desert regions and have been estimated on the surface of some rocks to be as great as 80°C. The rock, being a poor conductor of heat, is affected chiefly on the surface, although the heat passes inward very gradually. On cooling by radiation in the clear atmosphere, the temperature of the outer layers sinks rapidly and easily passes below that of the inner part of the rock. As a result, the surface portion, for some distance inward, is subjected to a series of stresses which results in the flaking or peeling off of the outer layers. Since the angles of the rock are most exposed, being subjected to heating and cooling from all sides, they peel off first and the result is the production of curved and rounded outlines. Thus, according to Grabau, "concentric exfoliation" or the successive peeling off of layers results, a phenomenon very marked in most dark and fine-grained igneous rocks in desert regions. Grabau illustrates this process by a photograph showing what he calls "concentric exfoliation" in a dike of basic igneous rock taking place at a depth of at least 25 feet below the surface. Most people today would agree, however, that temperature changes are insignificant at such depth. Furthermore, the surface of the ground shown in this photograph is covered by rather dense vegetation, indicating that the climate is reasonably moist and not arid as intimated.

The other process that Grabau believed effective in the development of rounded boulders is granular disintegration, which he attributed also chiefly to daily temperature changes. This process may operate in three different ways: (1) Since different minerals, such as plagioclase and pyroxene, for example, have different coefficients of expansion and contraction, internal stresses are set up in the rock which tend to separate these minerals, one from the other, until a loose sand results. (2) Individual minerals themselves are affected by temperature changes due to the fact that they expand and contract differently in different crystal directions. The stresses thus set up tend to open up minute cracks along cleavage planes into which air and moisture can penetrate and effect decomposition of the mineral. (3) "In moist climates, dark igneous rocks are often reduced to a mass of residual boulders by combined disintegration and decomposition." (p. 397).

The first systematic study of spheroidal weathering was made by Blackwelder (1925) who used the term "exfoliation" for the process. He pointed out that exfoliation, or the development of spheroidal forms, takes place most commonly in the granitoid igneous rocks, and occurs under various conditions. Blackwelder read some 30 standard reference works and special papers on weathering and decided that the majority of writers attributed exfoliation to the daily range of temperature in deserts and on mountain tops where the range is exceptionally great. As a result of intensive field work, however, he concluded that exfoliation is not a simple process, but a combination of processes of diverse origins.

In typical exfoliation, according to Blackwelder, "a series of cracks is formed roughly concentric to a single joint-block . . . The force producing the cracks has been one of tension, with the effective component operating in a radial direction . . . Such radial forces originate either by (a) the internal shrinkage of the block (b) by its external expansion" (p. 794).

In order to test the hypotheses of some writers that temperature changes cause exfoliation, Blackwelder made laboratory experiments in which he subjected sound igneous rocks to sudden changes of temperature, ranging from 15° to 210°C., by plunging the cold rock into boiling oil. In no case did these cause any spalling or cracking or even visible weakening of the rock. Inasmuch as this laboratory range in temperature is greater than any possible temperature range in the desert, the apparent lack of effect is significant.

From field observation Blackwelder noted that rocks in very dry deserts are rarely exfoliated. He examined hundreds of boulders strewn over the great alluvial fans in the Panamint and Salton deserts of California. He climbed many mountain peaks, 1000 feet to 3000 feet above timber-line, but found no evidence of exfoliation. In the humid climates, however, where the diurnal range of temperature is less than in the desert, he found that exfoliation appears abundantly in outcrops of granite, gabbro, and diabase. Furthermore, in these moister regions he found boulders of exfoliation forming at a depth of

20 feet below the surface. He considered these observations as cogent evidence that exfoliation is due to chemical decay.

A year later Blackwelder (1926) pointed out that in the semi-arid forested mountains of western United States fire seemed to rank first in causing the disruption of boulders and rock outcrops. This statement was supported by a series of experiments in which Blackwelder subjected different kinds of igneous rocks to repeated sudden heatings and coolings with temperatures ranging from 200° to 800°C. There was no visible effect upon the rock unless it approached the extreme temperature range that the rock was capable of withstanding. From these experiments Blackwelder concluded that insolation, or diurnal changes of temperature, are entirely inadequate to cause rock breakage. However, since the temperatures of fires are likely to reach 1200°C. and even above, he believed that forest fires can cause rocks to spall. He stated: "The field evidence is abundant, but has received little notice. On the broad plateau of the Medicine Bow Mountains, as well as in the Sierra Madre and other ranges in southern Wyoming, the writer has found nearly every boulder and outcrop in the forested zone thus cracked and rounded and the adjacent ground strewn with spalls. The effect of all other weathering processes were insignificant in comparison with those of the repeated conflagrations. Similar conditions were noted along the semi-arid eastern flank of the Sierra Nevada in California. In such localities it is probable that fire spalling demolishes exposed rocks much more rapidly than the more common but less violent processes such as chemical disintegration." (p. 138-139).

Like Blackwelder, Grout (1932, pp. 305-307) believed that the change in rock volume caused by daily and seasonal temperature variations is small in comparison with that resulting from forest fires, though the alterations caused by the former are more numerous and may have an effect over a period of years. He believed that: "the spalling produced by a single forest fire is probably comparable to the effects of sun and frost for a thousand years, though the great effect of fire may be partly a result of previous loosening of the grains by frost and other agencies."

The experiment by Griggs (1936) was designed to test the effectiveness of fatigue in rock exfoliation by insolation. Although this experiment dealt with the process of exfoliation in the general sense, the results are significant with respect to spheroidal weathering. Griggs subjected a specimen of granite to artificial temperature changes in a 15-minute cycle varying from 32°C. to 142°C. This experiment was continued for the equivalent of 244 years of diurnal temperature change. Photomicrographs of the surface of the rock before and after the experiment showed that there had been no cracking or spalling as a result of heating and cooling. Griggs concluded that "the effect of temperature changes over a thousand years is not sufficient to cause any exfoliation or disintegration of granite" (p. 796).

The importance of fire was further emphasized by Emery (1944) who investigated the relations of brush fires to rock exfoliation. He studied several square miles of brush and grass land in San Diego, California, where he found that exfoliated rock outcrops are numerous. He observed that: "Spheroidal shapes are characteristic of quartz diorite outcrops in the region and further development of these shapes resulted from the exfoliation by the fire, since the thickest spalls were generally formed at the sharpest corners. Loosely attached to a few of the rocks were older but very similar spalls, suggesting that the spheroidal shapes of the rocks were partly due to previous brush fires . . . Since the heat even of a brush fire can produce extensive exfoliation, and, since large areas of the west have a brush cover, it seems not unlikely that a great deal of exfoliation has resulted from brush fires, with the consequent tendency toward development of spheroidal rock shapes in widespread areas" (p. 508).

Very recently Larsen (1948, pp. 114-119) described and illustrated some granitic rocks in Southern California that have weathered into rounded forms which he called "boulders of disintegration." These boulders are commonly buried 10 to 20 feet below the surface where they are imbedded in a gruss of disintegrated rock. The boulders themselves are fresh and some are surrounded by shells of fresh or partly decomposed rock. Many boulders now project above the surface or lie upon the surface. Larsen believes that at one time these were imbedded in gruss and later the intervening gruss was washed away leaving the boulders on the surface. He made chemical analyses of the fresh boulders and of the gruss surrounding them and from

Figure 1. Spheroidal weathering in porphyritic olivine basalt at the north end of the Koolau Range, Oahu. This exposure is in a steep cut and about 30 feet below the ground surface. Note that the spheroids are arranged more or less regularly in vertical and horizontal rows determined by joint planes. Some vertical joints are still visible. The spheroid in the extreme lower left corner is about 18 inches in diameter.

Figure 2. Detailed view of spheroidal weathering of porphyritic olivine basalt at the north end of the Koolau Range, Oahu. Note how the firm, unaltered rock in the interior of the spheroids grades radially outward through weathered shells into completely disintegrated rock.

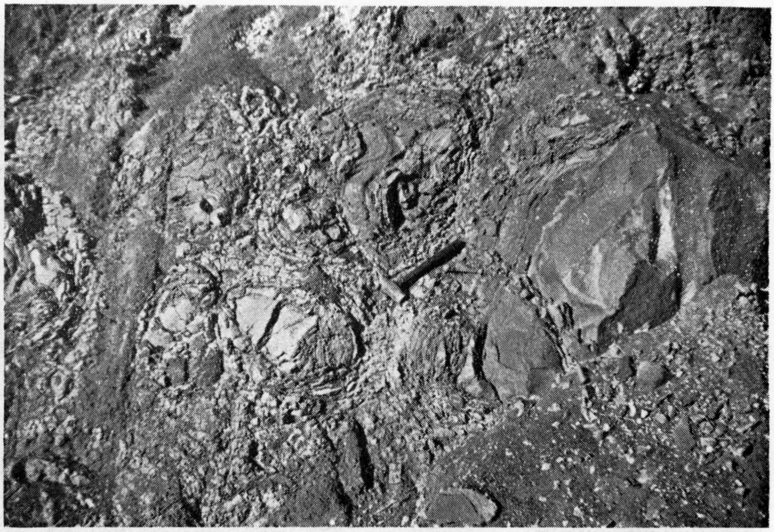

Figure 3. Spheroidal weathering in vesicular basalt on the Schofield Plateau near the west gate of Wheeler Field, Oahu. This outcrop is in a road cut about 12 feet below the ground surface. Note how weathering has taken place along joints which are less regular than in Figures 1 and 2.

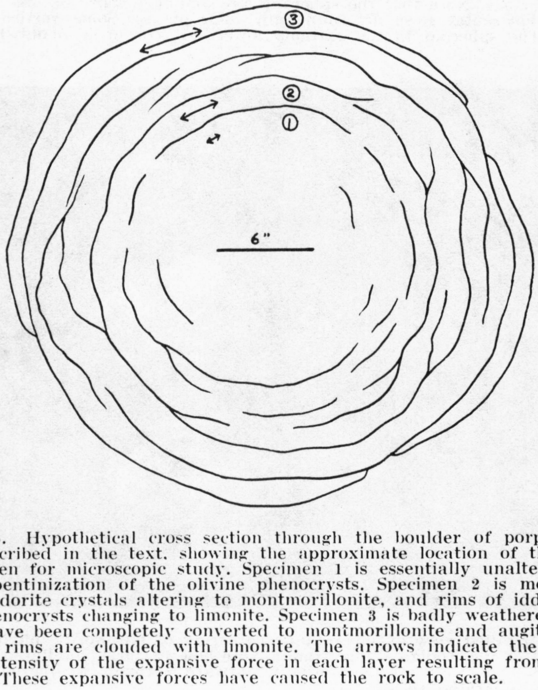

Figure 4. Hypothetical cross section through the boulder of porphyritic olivine basalt described in the text, showing the approximate location of the three specimens chosen for microscopic study. Specimen 1 is essentially unaltered except for slight serpentinization of the olivine phenocrysts. Specimen 2 is more weathered, with labradorite crystals altering to montmorillonite, and rims of iddingsite around olivine phenocrysts changing to limonite. Specimen 3 is badly weathered; labradorite crystals have been completely converted to montmorillonite and augite crystals and iddingsite rims are clouded with limonite. The arrows indicate the direction and relative intensity of the expansive force in each layer resulting from alteration of the rock. These expansive forces have caused the rock to scale.

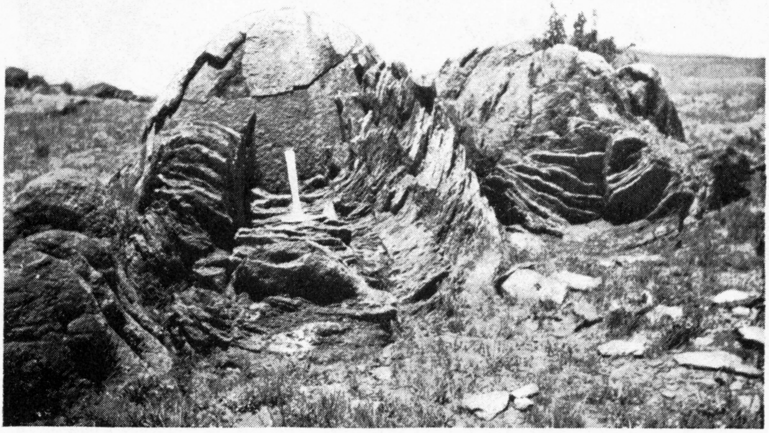

Figure 5. Spheroidally weathered boulders of biotite granite near U. S. Highway 287, about 5 miles south of Virginia Dale, Colorado. Although this is a semi-arid region, temperature variations are not extreme and the shelling of the exterior is due to decomposition and not to temperature changes.

Figure 6. An especially fine specimen of spheroidally weathered biotite granite along U. S. Highway 287, about 5 miles south of Virginia Dale, Colorado. This boulder is a residual that remains after the surrounding rock has weathered away. Microscopic examination reveals that the minerals in the outer shells are more altered than those in the inner ones and that spalling is due to chemical decay.

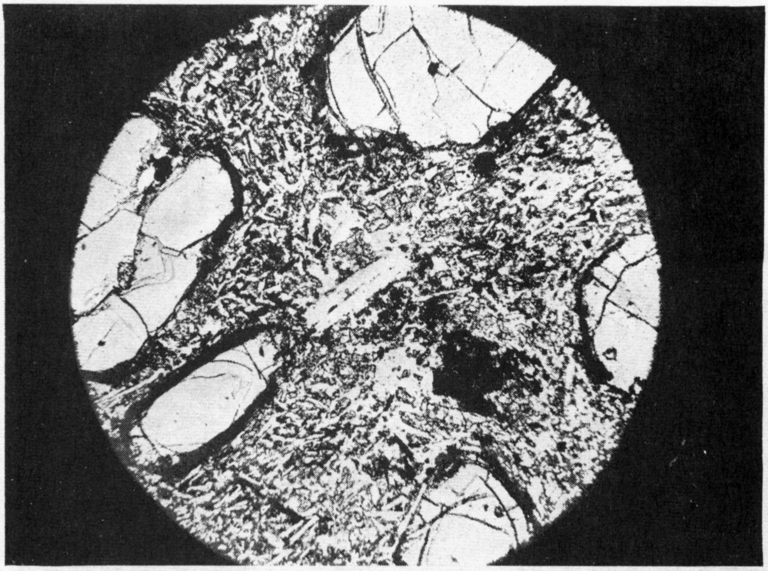

Figure 7. Photomicrograph of slightly weathered porphyritic olivine basalt (specimen 2) from the innermost shell of a spheroidally weathered boulder. This specimen shows slightly more alteration than the fresh basalt (specimen 1) of the interior core. The iddingsite rims about the large phenocrysts of olivine have become nearly opaque by alteration to limonite. In the groundmass the crystals of augite (high relief) and magnetite (black) remain fresh, but the centers of many labradorite crystals (white and lath-shaped) have altered to montmorillonite. Photomicrograph taken in plane polarized light. Diameter of field about 3 mm.

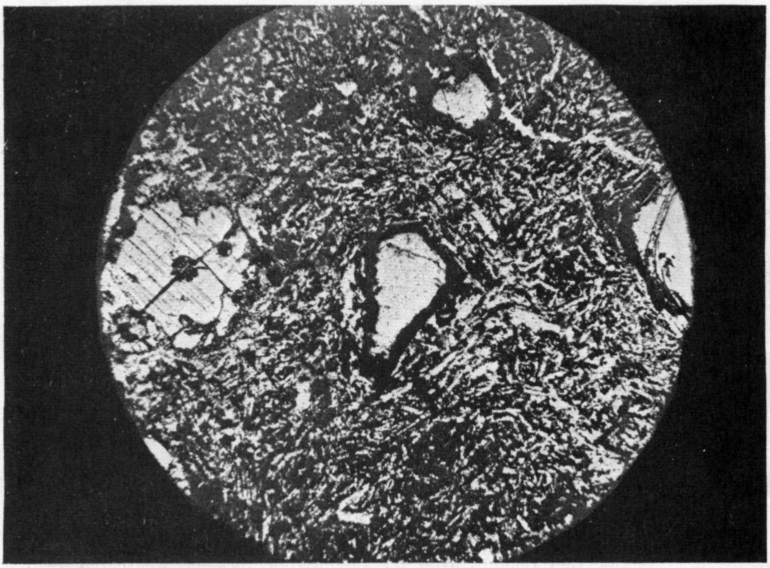

Figure 8. Photomicrograph of badly weathered porphyritic olivine basalt (specimen 3) from the outermost shell of the same spheroidally weathered boulder mentioned in Figure 7. The iddingsite borders on the phenocrysts of olivine are completely oxidized to limonite. The major alteration has been in the groundmass where the augite crystals are now permeated with tiny specks of limonite, making them nearly opaque. The labradorite crystals, although retaining their outlines, have been converted to a lamellar aggregate of montmorillonite. Photomicrograph taken in plane polarized light. Diameter of field about 3 mm.

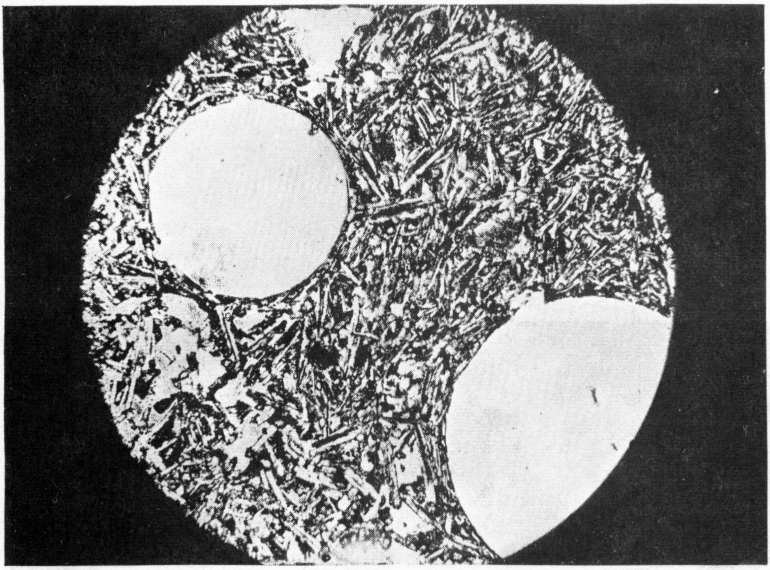

Figure 9. Photomicrograph of relatively fresh vesicular basalt (specimen 4) from the periphery of the interior core of a spheroidally weathered boulder. The rock consists of well-rounded vesicles and a groundmass of labradorite (white laths, some with dark interiors), augite (somewhat clouded, irregular and elongate grains with high relief), magnetite (black grains), and interstitial glass (small colorless areas). The interiors of some labradorite laths are slightly saussuritized and some augite crystals are clouded by limonite. Photomicrograph taken in plane polarized light. Diameter of field about 3 mm.

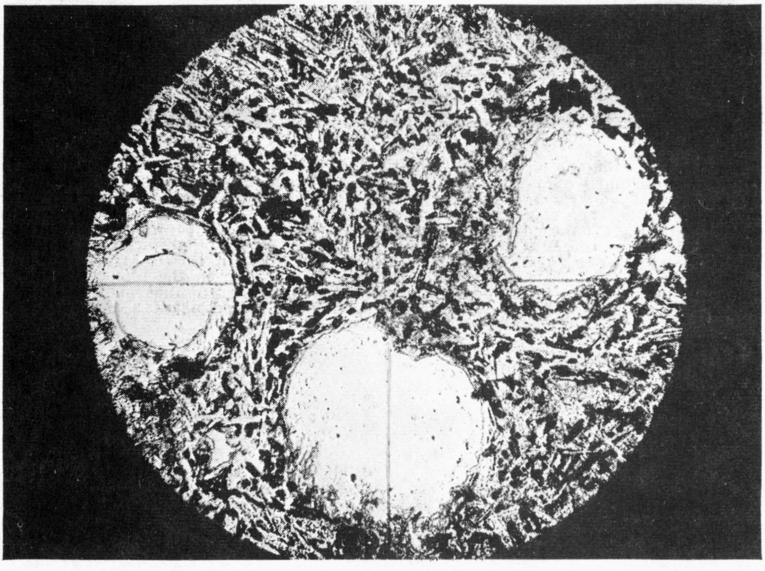

Figure 10. Photomicrograph of weathered vesicular basalt (specimen 5) from the outer shell of the same spheroidally weathered boulder mentioned in Figure 9. Here the augite crystals are badly decomposed and heavily permeated with specks of limonite. The labradorite crystals, although retaining their outlines, are almost completely converted to montmorillonite. Magnetite has partly altered to hematite. The walls of the vesicles have been deformed and pushed inward, apparently by the swelling of the rock through alteration. Photomicrograph taken in plane polarized light. Diameter of field about 3 mm.

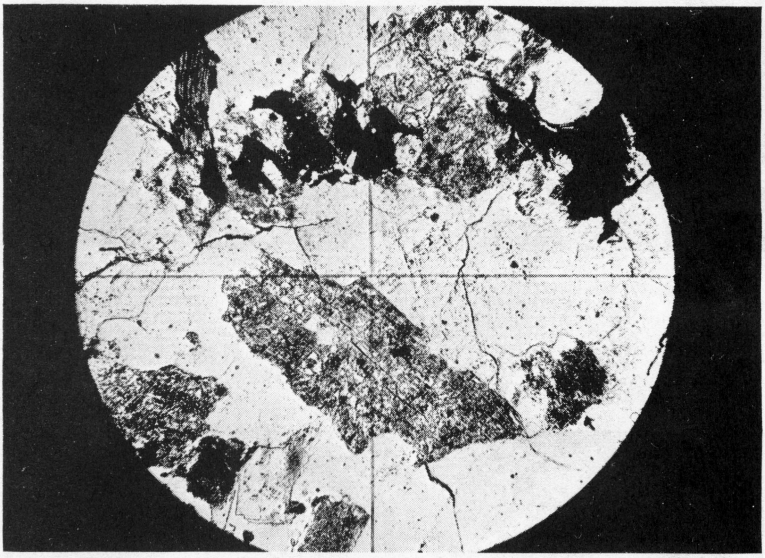

Figure 11. Photomicrograph of slightly weathered biotite granite (specimen 7) from an outer shell of a spheroidally weathered boulder. The white unaltered minerals are chiefly quartz and some microcline. The gray minerals, including the large crystal near the center, are oligoclase, which is deeply clouded with kaolinite and coated with large flakes of sericite (clear areas). The black grains are magnetite, and the dark gray mineral at the lower right edge of the photograph is biotite altering to chlorite. In the oligoclase of this section the flakes of sericite are larger and more abundant, and the kaolinization is more intense than in the oligoclase of the relatively fresh biotite granite (specimen 6) (photomicrograph not shown). Photomicrograph taken in plane polarized light. Diameter of field about 3 mm.

the results concluded that the "boulders of disintegration" were formed by the chemical weathering of the rock and its accompanying disintegration.

SUMMARY OF CURRENT VIEWS ON SPHEROIDAL WEATHERING

From the foregoing it is clear that most writers now consider spheroidal weathering to be caused by either of two processes: (1) the swelling and spalling of the exterior surface of angular blocks of rock due to the hydration, carbonation, and oxidation of constituent minerals in the outer surface, or (2) the swelling and spalling of the exterior surface of angular blocks which have been subjected to sudden, intense heating of their exterior by forest fires and brush fires.

The first process, which may take place in both humid and semi-arid climates, is the more common and operates not only at the surface of the ground but in some cases to a depth of 30 or 40 feet. The other process is undoubtedly local and confined to the surface of the ground since appreciable temperature changes by fires or by other means are not effective at depth. Accordingly, where spheroidal boulders are found forming at depth, it can be safely concluded that the process is one of hydration, carbonation, and oxidation of the minerals in the outer layers and not one of temperature changes. Spheroidal boulders lying on the surface may be the result of either of the two processes. Although it is assumed by many that such boulders located in semi-arid regions are the result of temperature changes, probably most have been caused by hydration, carbonation, and oxidation of minerals in the outer layers. Boulders of this type are well illustrated in Figures 5 and 6 and will be described later in this paper.

MICROSCOPIC STUDY OF SPHEROIDALLY WEATHERED BOULDERS

GENERAL STATEMENT

In the previous section it was concluded that the principal cause of spheroidal weathering is the expansion of the outer surface of a rock due to the hydration, carbonation, and oxidation of its mineral constituents. Although this explanation is now used by many writers, it is stated rather generally and vaguely without specific reference to the exact nature of the mineral changes. As far as the present writers are aware, no microscopic study has ever been made of spheroidal boulders or the shells that surround them. Accordingly, it was deemed worthwhile to undertake a microscopic study of the boulders and surrounding shells in several typical examples of spheroidal weathering in order to determine the nature and intensity of mineral alterations.

Three rocks exhibiting particularly good spheroidal weathering were selected for study (figs. 1 to 6). One of these is a porphyritic olivine basalt from the northern end of the Koolau Range, Oahu, T. H.; the second, a vesicular basalt from the Schofield Plateau, near Wheeler Field, Oahu; and the third, a biotite granite from northern Colorado. In each case an especially good spheroid was chosen and a series of specimens was collected along a radius to represent the fresh rock of the boulder itself and the more weathered rock of the shells surrounding it. Thin sections were prepared from these specimens and mineral alterations were studied (figs. 7 to 11). Modes were determined with a Wentworth integrating stage and grain sizes measured with a micrometer ocular. Microscopic study of these specimens has enabled the writers to draw certain significant conclusions about the relationship of mineral alterations to spheroidal weathering.

PORPHYRITIC OLIVINE BASALT

General nature. This rock, belonging to the Koolau volcanic series, outcrops at the northern end of the Koolau Range, Oahu, about 3 miles southwest of the village of Kahuku. At this point about 1,000 feet above sea level, the lavas have been deeply dissected by streams, and one section is well exposed in a steep cut nearly 30 feet high where an old road follows a canyon wall. The basalt is so thoroughly weathered into spheroidal masses that the outcrop simulates a sedimentary deposit of rounded boulders (figs. 1 and 2). Spheroidal weathering extends from the surface to a depth of at least 30 feet.

The spheroids are lined up in more or less regular rows, arranged approximately vertically and horizontally, and individual spheres are spaced on centers ranging from 8 inches to 3 feet. At the contact between any two spheroids the line of demarcation is generally planar and suggests that a joint plane served as a starter. In many places the original joints are still visible. The spheroids themselves range from 6 inches to 3 feet in diameter, and are larger and less weathered near the base of the cut. They are bounded by concentric shells which are concavo-convex with a maximum thickness near their centers ranging from half an inch to 3 inches, and which taper toward their edges.

The interior of the spheres is composed of fresh, firm rock consisting of a blue-green groundmass set with rounded, yellow-green phenocrysts of olivine. As one progresses from the fresh rock of the interior toward the outer shells, the groundmass becomes brownish yellow and eventually the olivine turns brown, loses its luster, and falls out of the specimen. The final weathering product surrounding the outer shells is a buff, brown, or red, friable rock which crumbles to a powder. The complete zone of alteration, i.e., from fresh rock to completely weathered material, takes place within a zone from 3 to 6 inches wide.

One particular spheroid, 2½ feet in diameter, was selected for microscopic study. The solid interior is 9 inches in radius and its rim of concentric shells is 6 inches thick (fig. 4). Three specimens were collected along the radius of the spheroid as follows: (1) fresh basalt (specimen 1) from the outer edge of the solid interior, 8 to 9 inches from the center; (2) slightly weathered basalt (specimen 2) from the innermost shell, 9 to 10 inches from the center; and (3) badly weathered basalt (specimen 3) from the outermost shell, 14 to 15 inches from the center.

Fresh basalt (specimen 1). This is a porphyritic rock consisting of a dense, light-gray groundmass set with abundant sub-rounded phenocrysts of yellow-green olivine. In thin section it was found to consist of sub-rounded, embayed phenocrysts of olivine and much smaller microphenocrysts of hypersthene, set in a dense groundmass of labradorite, augite, magnetite, and volcanic glass. Many of the olivine phenocrysts contain alteration rims of yellow-brown iddingsite averaging 0.4 mm. thick. The microphenocrysts of hypersthene have an average diameter of 0.22 mm. and all appear to have crystallized later than the olivine. The labradorite ($Ab_{40}An_{60}$) forms slender laths 0.1 mm. long which show random orientation except adjacent to olivine phenocrysts where they trend parallel to the borders. Small rounded grains of augite and magnetite are scattered among the labradorite, and colorless, slightly birefringent volcanic glass fills the interstices between grains. The mode of this rock, in volume per cent, determined with an integrating stage, is shown in Table I together with the grain sizes of the constituent minerals.

TABLE I

Modes, in volume per cent, and grain sizes of porphyritic olivine basalt.

Minerals	*Modes*		*Grain Sizes*	
	Specimen 1	*Specimen 2*	*Range*	*Average*
Olivine	47.1%	46.9%	0.4–3.5 mm.	1.8 mm.
Hypersthene	8.7	9.5	0.1–0.3 "	0.2 "
Augite	15.8	16.9	(uniform)	0.02 "
Labradorite (ca. An_{60})	21.3	19.8	"	0.1 "
Magnetite	1.7	2.0	0.02–0.2 mm.	0.04 "
Glass	5.2	4.9	——	——
Miscellaneous	0.2	——	——	——
	100.0%	100.0%		

Except for slight serpentinization of some olivine phenocrysts along fractures, the rock is essentially unaltered. The labradorite, augite, and magnetite of the groundmass are quite fresh. The development of iddingsite rims is believed to be a late magmatic phenomenon.

Slightly weathered basalt (specimen 2). In this specimen the groundmass has turned light gray or buff and some of the olivine phenocrysts have lost their brilliant luster. The rock is less firm than specimen 1 and crumbles readily under a blow of the hammer. In thin section (fig. 7) this specimen is texturally similar to specimen 1 and its minerals are qualitatively similar (table I). The apparent small quantitative mineral differences between the two rocks are due partly to limitations in accuracy of the Rosiwal method and partly to actual original differences in the two specimens. The volcanic glass in specimen 2 is olive-green instead of colorless, possibly due to weathering. Tiny acicular microlites penetrate the glass.

This specimen shows slightly more alteration than specimen 1. All iddingsite rims about the olivine have been partly altered to limonite and have become nearly opaque. The olivine itself, however, remains relatively fresh as do the augite and magnetite of the groundmass. The centers of many labradorite laths have been altered to a fine-grained aggregate with low birefringence which is believed to be montmorillonite, but the borders of the laths remain fresh.

Badly weathered basalt (specimen 3). In this specimen the groundmass has become yellow-brown. Although most olivine phenocrysts retain a high luster internally, their surfaces have turned dull and brown. These phenocrysts can be easily removed with the fingers and the rock can be crumbled in the hand. In thin section (fig. 8) the texture is found to be similar to that in the previous specimens and it is apparent that the original mode was also the same (table I).

This rock is highly altered. Iddingsite borders on the olivine phenocrysts are completely oxidized to limonite, but the olivine itself is still relatively fresh although slightly more serpentinized than in specimen 2. The major alteration has taken place in the groundmass. Augite crystals have been weathered and are now permeated with tiny grains of limonite which effectively obscure the crystals and prevent more thorough optical study. Labradorite crystals have been intensely altered throughout to a lamellar aggregate of montmorillonite, and only locally may the original laths be recognized. Most magnetite granules appear completely unaltered.

VESICULAR BASALT

General nature. This rock, a fine-grained, bluish gray, vesicular basalt of the Koolau volcanic series, is exposed in a deep road cut on the Schofield Plateau near the west gate of Wheeler Field, Oahu. The cut reveals spheroidal weathering of the basalt to a depth of 12 feet below the surface (fig. 3).

In general the spheroids are spaced on centers from 1 to 3 feet apart, but are not as well aligned as those in the porphyritic olivine basalt in the Koolau Range. The spacing of spheres and the arrangement of shells of adjacent spheres show clearly that the weathering began along joint planes. The shells are thinner than those in the basalt from the northern end of the Koolau Range. Generally they range in thickness from an eighth of an inch to 2 inches but the average is between a quarter and three-quarters of an inch. Furthermore, the thickness of an individual shell is more uniform throughout than in the porphyritic olivine basalt and the shell extends farther around the interior boulder; thus the shell is less lenticular and the interior boulder is more completely surrounded by it.

The interior residual boulders are fresh and unjointed. The first apparent evidence of weathering is seen in the innermost shells that have maintained their texture but have turned grayish. In the outer shells the rock turns brown to yellow-brown and starts to fall apart. Surrounding the outer shells is a zone of brown or red-brown, completely decayed rock. The width of the weathered zone, i.e., from the fresh rock to the completely decayed rock, ranges from 6 to 12 inches.

Two specimens of this basalt were selected for microscopic study from one spheroidal mass, 2 feet in diameter: (1) relatively fresh basalt (specimen 4) from the periphery of the interior spheroid, 5 to 6 inches from its center; and (2) weathered basalt (specimen 5) from an outer shell surrounding the solid interior, 11 to 12 inches from its center.

Relatively fresh basalt (specimen 4). This specimen is medium gray, aphanitic, and contains abundant spherical vesicles averaging 1 mm. in diameter. Microscopically (fig. 9) its texture is intersertal, the rock consisting of a mat of labradorite laths (An_{64}) and augite and magnetite granules with colorless to brownish basaltic glass filling interstices. The labradorite is randomly oriented except adjacent to vesicles where the expanding gas bubbles forced the adjacent laths into a concentric arrangement. The labradorite shows albite twinning and conspicuous zoning. Augite and magnetite granules are scattered among the plagioclase. Many of the augite grains are long and slender like the labradorite, with an average length of 0.1 mm., but some are equidimensional with an average diameter of 0.04 mm. Irregular grains of reddish-brown iddingsite, developed from olivine, are scattered throughout the rock, and in some of these, cores of olivine still remain. A few microphenocrysts of hypersthene were noted. The mode of this rock and the grain sizes of its mineral constituents are shown in table II.

Although relatively fresh, this rock shows two effects of weathering. In the first place, many labradorite cores are altered to a very fine-grained birefringent aggregate which appears to consist of sericite, kaolinite, and epidote, although the positive identification of these minerals is not certain. In the second place, some augite crystals have become brownish by oxidation to limonite.

TABLE II.

Modes, in volume per cent, and grain sizes of vesicular basalt.

Minerals	*Modes*		*Grain Sizes*	
	Specimen 4	*Specimen 5*	*Range*	*Average*
Vesicles	23.0%	22.3%	0.3–2.1 mm.	1.1 mm.
Augite	22.6	24.1	0.02–0.2 "	0.1 "
Labradorite (An$_{64}$)	33.5	47.9*	0.1–0.4 "	0.2 "
Glass	14.1		——	——
Magnetite	6.3	5.4	——	0.4 "
Olivine (altering to iddingsite)	0.5	0.3	0.04–0.3 mm.	0.1 "
Hypersthene	tr.	——		
	100.0%	100.0%		

* The labradorite has been almost completely altered to montmorillonite. The ratio of montmorillonite to glass is difficult to determine.

Weathered basalt (specimen 5). The vesicular basalt from the outer shell of the weathered boulder has turned pinkish or yellowish and can be crumbled readily between the fingers. Under the microscope (fig. 10) it is texturally like the fresher material and its mode was probably originally about the same (table II). The rock has been conspicuously altered by weathering, however. Augite crystals are badly decomposed and have lost their birefringence, and many are now heavily permeated with specks of limonite. In some crystals serpentine appears to have developed but the clouded character makes this identification somewhat questionable. The labradorite crystals have been almost completely converted to lamellar aggregates of montmorillonite, and only locally do relics of the original mineral remain. In many places, however, the outlines of the laths are preserved. The volcanic glass can still be recognized but its ratio to montmorillonite is difficult to determine. Magnetite has partly altered to hematite.

The vesicles are not as smoothly circular as those in specimen 4. Practically all have been deformed and crystals of augite, altered labradorite, and magnetite have been pushed inward, forming irregular projections. It appears that the walls of the vesicles have been jammed inward by the swelling of the rock through alteration.

BIOTITE GRANITE

General nature. Many residual boulders of spheroidally weathered pre-Cambrian biotite granite lie upon the surface in northern Colorado (figs. 5 and 6). One particularly fine example (fig. 6), along U. S. Highway 287 about 5 miles south of Virginia Dale, Colorado, was chosen for study. This boulder, approximately 3 feet in diameter, has a solid interior surrounded by from 5 to 10 concentric shells ranging in thickness from 1 to 4 inches. For the most part the shells have uniform thickness throughout and appear to have completely surrounded the interior sphere at one time.

The interior boulder is composed of pink, medium-grained, non-foliated granite, without joints. The rock in the shells is deeper pink and somewhat more crumbly, but is otherwise megascopically similar to the interior. Two specimens were selected from microscopic study from this spheroidal body: (1) relatively fresh granite (specimen 6) from the innermost shell, about 10 inches from the center of the spheroid; and (2) slightly weathered granite (specimen 7) from an outer shell, 6 to 8 inches outward radially from specimen 6.

Relatively fresh granite (specimen 6). This specimen, from the innermost shell of the weathered boulder, is a pink, medium-grained granite, relatively fresh and strong. Microscopically it is allotriomorphic and generally even-grained, although some portions tend to be seriate. One large perthite phenocryst 6.3 mm. long was seen. Perthite, microcline, oligoclase, quartz, and biotite are the essential constituents and magnetite is an accessory. Sericite and kaolin have formed from the feldspars. The mode of this specimen in volume per cent, together with the grain sizes of the modal minerals, is shown in table III.

TABLE III

Modes, in volume per cent, and grain sizes of biotite granite.

Minerals	*Modes*		*Grain Sizes*	
	Specimen 6	*Specimen 7*	*Range*	*Average*
Perthite and microcline	36.5%	41.0%	0.07–2.1 mm.	1.0 mm.
Oligoclase (An_{10-14})	23.1	25.2	" " "	" "
Quartz	31.1	24.6	" " "	" "
Biotite	6.2	4.7	——	0.7 "
Sericite	1.6	3.3	(see note below*)	
Magnetite	1.5	1.2	——	0.09 "
Apatite	—	tr.	——	——
	100.0%	100.0%		

* In specimen 6 this mineral ranges from tiny specks to flakes 0.4 mm. across, with an average diameter of 0.1 mm. In specimen 7 it ranges from tiny specks to flakes 0.6 mm. across, with an average diameter of 0.2 mm.

Perthite and microcline, in subhedral to anhedral crystals, comprise 36.5 per cent of this specimen, and twinned oligoclase (An_{12-14}), also subhedral to anhedral, makes up 23 per cent. The quartz grains, somewhat larger than the feldspars, are exceedingly irregular in outline and all are severely strained. Biotite, pleochroic in deep olive-green and yellow-brown, is scattered evenly throughout the rock. Primary magnetite is an inconspicuous accessory.

The minerals of this rock are slightly weathered. Perthite and microcline show meager kaolinization and sericitization, but oligoclase is conspicuously more altered and generally clouded with specks of kaolinite and flakes of sericite. The sericite ranges from tiny specks to large flakes 0.4 mm. in diameter, with an average diameter of 0.1 mm. It comprises 1.6 per cent of the granite. Some biotite has changed to chlorite with the concurrent separation of magnetite along cleavages, and some of this magnetite has weathered to hematite.

Slightly weathered granite (specimen 7). This specimen is from an outer shell and 6 to 8 inches outward radially from specimen 6. Megascopically it resembles closely specimen 6 except that it is slightly deeper pink as a result of more intense weathering. In thin section (fig. 11), specimen 7 is texturally nearly identical with specimen 6 but its mode differs somewhat. Perthite and microcline are greater by about 5 per cent but quartz is nearly 6 per cent less. The modes may be compared in Table III.

The most significant difference between this specimen and the preceding one lies in the intensity of alteration of the oligoclase. Nearly all grains are deeply clouded with kaolinite so that their twin lamellae are generally obscured, and flakes of sericite are both more abundant and larger. Reference to table III indicates that there is twice as much sericite in this rock as in specimen 6. This mineral ranges from tiny specks to flakes 0.6 mm. across, with an average diameter of 0.2 mm.

SIGNIFICANCE OF MICROSCOPIC OBSERVATIONS

Microscopic study of the spheroidal boulders described above leads to the following general conclusions regarding their development:

1. In general the cores of the spheroidally weathered boul-

ders consist of relatively fresh rock, but the shells surrounding the cores are more highly weathered. The intensity of this alteration increases outward more or less regularly through the successive shells. In the porphyritic olivine basalt, the interior boulder is fresh, but the inner shells are slightly weathered and the outer ones intensely so. The major alteration has occurred in the groundmass, the augite granules having partly oxidized to limonite, and the labradorite laths weathered to montmorillonite. Iddingsite rims around the olivine phenocrysts have also oxidized to limonite. Weathering of the vesicular basalt is even more marked. As one progresses from the fresh core outward, the augite crystals lose their birefringence, become clouded with specks of limonite, and locally seem to have altered to serpentine. Labradorite first shows alteration to sericite, kaolinite, and epidote on the periphery of the interior spheroid, and is finally converted to a fine aggregate of montmorillonite in the outer shells. Alteration of the biotite granite is less intense, but it is clear that the outer rims are more weathered than the inner ones. The chief changes are kaolinization and sericitization of the oligoclase. In the outer shells sericite is twice as abundant as in the inner ones and the flakes average twice the size.

2. In the weathering process, oxygen, water, and possibly some carbon dioxide were added to the rocks. New minerals, namely kaolinite, sericite, montmorillonite, serpentine, chlorite, hematite, and limonite were formed, most of these having specific gravities that are lower than those of the original minerals from which they altered. The result of these changes appears to have been an increase in the volume of the altered rock, the outermost shells suffering a more marked increase than the inner ones (fig. 4). Positive evidence of this increase is furnished by the outer layers of vesicular basalt in which the walls of the vesicles were apparently crowded inward by the increasing pressure. The amount of volume increase that took place in any of these rocks cannot be computed accurately, since the amount of material removed in solution is not known. Larsen (1948) found that the gruss surrounding spheroidally weathered boulders in Southern California, "has had some of its iron oxidized, has gained some water and much SiO_2 [leached from above], has lost a little K_2O, and gained a little Na_2O." (p. 119). Although these differences are small,

he concluded that they were adequate to expand the rock and cause it to crumble. He states: "A slight hydration of biotite and other minerals is probably sufficient to effect the change in volume that produces the disintegration and formation of the boulders." (p. 115). Leith and Mead (1915, p. 5-19) calculated that the weathering of a Georgia granite had caused a volume increase of 51 per cent, but since this rock was deeply decomposed, its volume increase must have been unusually large. The rocks discussed in the present paper probably suffered a much smaller increase, even in the outermost shells.

3. It appears probable that the spheroidal scaling of these rocks resulted from the oxidation and hydration of silicate minerals (fig. 4). In each case the fresh rock was first subdivided by joint planes into rectangular blocks, thus enabling subsurface water to attack each block from all sides. Weathering or alteration ensued along all faces of a block, and especially at edges and corners where the specific surface was greater. As a result, swelling of the outer surface of the block took place and internal stresses were set up. When these stresses had reached sufficient intensity, the rock split along a curved surface at a certain depth within the block where the cohesive strength of adjacent grains was exceeded. A concentric shell was thus produced. Further weathering along this new fracture produced additional shells within.

SPHEROIDAL BOULDERS WITHOUT SHELLS

Upon weathering some igneous rocks crumble to grains rather than scale off in shells, and the solid interior spheroid is bounded externally by a gruss of mineral fragments rather than by concentric shells. This is also spheroidal weathering. Whether a rock splits into shells or crumbles into grains appears to depend upon the cohesive strength between the mineral constituents of the rock. If this strength is great, adjacent grains will cohere, and, instead of crumbling, the rock will split along a curved surface at a certain depth within the boulder where the cohesive strength of the grains is exceeded by the shearing stress set up in the expanding outer portion. On the other hand, if cohesion is weak, due either to alteration along crystal boundaries or to the non-interlocking character of adjacent grains, the rock will crumble rather than separate as distinct shells. Fine-grained tough rocks, such as basalts and diabases which have well-developed ophitic texture, generally have sufficient cohesion between grains to develop distinct shells upon weathering. Coarse-grained granites and basic rocks, however, whose grains are less firmly interlocked, generally crumble to a coarse angular gruss surrounding a spheroidal core.

REFERENCES

Barton, D. C., 1916. Notes on the disintegration of granite in Egypt. Jour. Geology, **24**, 382-393.

Blackwelder, E., 1925. Exfoliation as a result of rock weathering. Jour. Geology, **33**, 793-806.

————, 1926. Fire as an agent in rock weathering. Jour. Geology, **35**, 134-140.

Bonney, T. G., 1876. On columnar, fissile, and spheroidal structure. Geol. Soc. London, Quart. Jour., **32**, 149-154.

Branson, E. B., and Tarr, W. A., 1941. Introduction to geology. McGraw-Hill Book Company, 67-69.

Chamberlin, T. C., and Salisbury, R. D., 1927. College textbook of geology. **1**, Henry Holt and Company, 40-41.

Cleland, Herdman T., 1916. Geology, physical and historical. American Book Company, 31-33, 39-40, 328.

Dana, J. D., 1895. Manual of geology. American Book Company. 127.

Emery, K. O., 1944. Brush fires and rock exfoliation. AM. JOUR. SCI., **242**, 506-508.

Geikie, Archibald, 1882. Textbook of geology. The Macmillan Company, 335.

Gilbert, G. K., 1904. Domes and dome structure of the high Sierra. Geol. Soc. America Bull., **15**, 29-36.

Grabau, Amadeus W., 1920. A textbook of geology, Part I, General geology. D. C. Heath and Company, 393-394.

Griggs, David T., 1936. The factor of fatigue in rock exfoliation. Jour. Geology, **44**, 783-796.

Grout, Frank F., 1932. Petrography and petrology. McGraw-Hill Book Company, 305-307.

Hinds, N. E. A., 1943. Geomorphology. The evolution of landscapes. Prentice-Hall, Inc., 358.

Hobbs, William H., 1912. Earth features and their meaning. The Macmillan Company, 150-152.

Holmes, Arthur, 1946. Principles of physical geology. Thomas Nelson and Sons, Ltd., 118-119.

Johannsen, Albert, 1939. A descriptive petrography of the igneous rocks, University of Chicago Press, **3**, 278-279.

Kemp, James Furman, 1909. Spheroidal weathering of dikes. M. Sc. Press, **98**, 443-444.

Lahee, Frederic H., 1941. Field geology, McGraw-Hill Book Company, 46-47.

Larsen, Esper S., Jr., 1948. Batholith and associated rocks of Corona, Elsinore, and San Luis Rey quadrangles, Southern California. Geol. Soc. America, Mem. **29**, 114-119.

Leith, C. K., and Mead, W. J., 1915. Metamorphic Geology. Henry Holt and Company, 5-19.

Longwell, C. R., Knopf, A., and Flint, R. F., 1946. A textbook of geology. John Wiley and Sons, Inc., 31-32.

Merrill, George P., 1897. A treatise on rocks, rock-weathering and soils. The Macmillan Company, 241-248.

Miller, Wm. J., 1939. Elements of geology with reference to North America. D. Van Nostrand Company, Inc., 64-65.

———, 1911. Exfoliation domes in Warren Co., N. Y. N. Y. State Museum Bull., **149**, 187-194.

Page, David F. G. S., 1861. Advanced textbook on geology. Wm. Blackwood and Sons, 75.

Ries, H., and Watson, Thos. L., 1936. Engineering geology. John Wiley and Sons, Inc., 232-242.

Spencer, J. W., 1885. Boulders of decomposition. Am. Naturalist, **19**, 163-165.

DEPARTMENT OF GEOLOGY
THE JOHNS HOPKINS UNIVERSITY
BALTIMORE, MD.