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WEATHERING RINDS DEVELOPED ON PLUTONIC IGNEOUS ROCKS IN THE NORTH CAROLINA PIEDMONT

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ABSTRACT. The appearance of weathering rinds developed on unmetamorphosed plutonic igneous rocks in the North Carolina Piedmont varies with lithology. Granites and adamellites develop few, but thick, clay-rich rindlets in their weathering rind systems. Gabbros and syenites develop many, thin, limonite-rich rindlets concentric about cores of fresh rock.

Orientation and propagation of solution channels in weathered rock control the appearance of weathering rinds developed on that rock. However, these parameters are greatly influenced by dissolution-produced void space within the rock. Feldspar, especially plagioclase, is susceptible to kaolinization, creating voids. Solution channel development past a void is greatly impeded due to dissipation of stress at the enlarged solution channel terminus. Weathering of relatively unstable mafic minerals also creates void space, but limonite plugs the pores.

Solution channels in granites and adamellites have easy access to plagioclase. Extensive kaolinization in outer rindlets of these rocks disrupts channel orientation, resulting in a few, clay-rich rindlets. In the syenites studied, plagioclase is texturally protected from solution channels by the perthite matrix; hence channelization is unimpeded and many, thin, clay-deficient rindlets are formed. The residence time of labradorite on gabbro weathering rinds is insufficient for extensive kaolinization. Alteration of the less stable ferromagnesian minerals produces many thin rindlets of nearly constant thickness.

INTRODUCTION

A weathering rind is a sequence of altered rocks physically attached to and encircling an inner core of comparatively fresh rock. Weathering rinds are products of physical and chemical weathering, and they are believed to be initiated by exfoliation. Gilluly, Waters, and Woodford (1968) state that two types of exfoliation may be distinguished: (1) giant plates split away from fresh or altered plutonic rocks; and (2) small thin flakes scaled from partly weathered massive rock. These products of exfoliation have been termed "speroidally weathered boulders," "weathering rings," "weathering crusts" (Dennen and Anderson, 1962), "diffusion rings" (Singer and Navrot, 1970), or weathering rinds. That the weathering rind phenomenon has a number of synonyms is testimony to the different appearances of weathered rock in outcrop. This is particularly true of weathering rinds developed on plutonic igneous rocks in the North Carolina Piedmont. Here, weathering rinds assume two general forms: (1) a clay-rich weathering rind consisting of a few thick laminae (hereafter termed "rindlets") which are differentiated into two distinct morphologies and (2) a limonite-rich weathering rind composed of many rindlets of a single morphology. Descriptive terminology for weathering rinds in this study is illustrated in figure 1.

The purpose of this study is to evaluate the relative importance of rock texture and mineralogy in influencing weathering rinds developed

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on plutonic igneous rocks. Parameters other than rock texture and mineralogy, such as topography and climate, may influence weathering rinds developed on igneous rocks. In order to minimize the variables, only unmetamorphosed plutonic igneous rocks in the North Carolina Piedmont were sampled (fig. 2). A total of 17 weathering rind profiles were sampled from the Lilesville and Mt. Airy granites, the East Farrington adamellite, the Concord syenite, and the Pee Dee gabbro. Weathering rinds were sampled only where: (1) faults, planar joints, and dikes are all absent in the outcrop area; (2) the fresh rock was devoid of foliation; and (3) an uninterrupted fresh-to-weathered sequence was visible.

Merill (1906) recognized that although weathering rinds are developed on all rocks the phenomenon is best developed on feldspar-rich igneous rocks. Blackwelder (1925) concurred and stated that weathering rinds are products of exfoliation. Expansion caused by hydration of minerals, insolation, and unloading are often cited as processes respon-

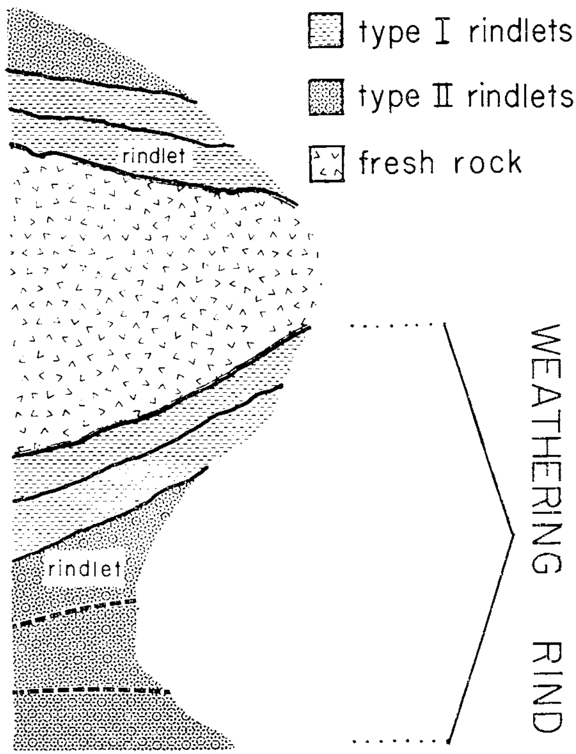


Fig. 1. Cross-section view of a typical weathering rind developed on a granite or adamellite. Bands of altered rock, termed "rindlets," concentrically envelop an inner core of fresh rock. These rindlets have two distinct morphologies, labeled types I and II. Type I rindlets are indurated and retain the structure of the fresh rock. Boundaries between individual type I rindlets are sharp and parallel the fresh rock contact. Type II rindlets are non-indurated sandy rubble. Boundaries between type II rindlets are diffuse and have random orientations.

sible for exfoliation. Feldspar, especially plagioclase, is susceptible to kaolinization. Alteration of feldspar to clay minerals and swelling of micas result in expansion which could propagate, if not initiate, cracks in the incipiently altered rock. Although insolation involves repetitive heating and cooling of rocks, its effect is negligible. Griggs (1936) conducted a series of laboratory experiments in which he subjected several igneous rocks to temperature differences of 110°C for 3 yrs with no visible effect. Slight expansion by unloading (Jahns, 1943) may initiate exfoliation. Unloading may be particularly effective in initiating cracks, if the outcrop possesses inherited stress patterns. This study is not concerned with how or why the initial cracks in incipiently altered rocks are formed; rather, this study deals with the perpetuation of these cracks by secondary processes and their effects upon appearances of weathering rinds.

WEATHERING RINDS DEVELOPED ON THE FIVE ROCK TYPES

Rindlets on the East Farrington adamellite and the Lilesville and Mt. Airy granites are of two distinct morphologies, and these are designated type I and type II (fig. 1). Type I rindlets are the innermost rindlets; these are indurated and retain the texture of the fresh rock (pl. 1-A). Individual rindlets are from 20 to 40 cm thick and are bounded by small cracks (about 1 mm wide) filled with clay-sized debris. Limonite rims mafic minerals and is also concentrated along cracks separating individual rindlets. Plagioclase appears chalky. Clay-sized material in the rindlets is between 5 and 10 wt percent (table 1) and is amorphous to X-ray diffraction. Contacts between individual rindlets are sharp, and rindlet boundaries are parallel to the fresh rock contact (pl. 1). Type I rindlets grade into type II rindlets at distances of 30 to 80 cm from the fresh rock contact (pl. 1-A and B). The outer, type II, rindlets are structureless, non-indurated sandy rubble. Pebble sized remnants of type I rindlets are embedded in a matrix of silty sand (pl. 1-A). Individual rindlets are 20

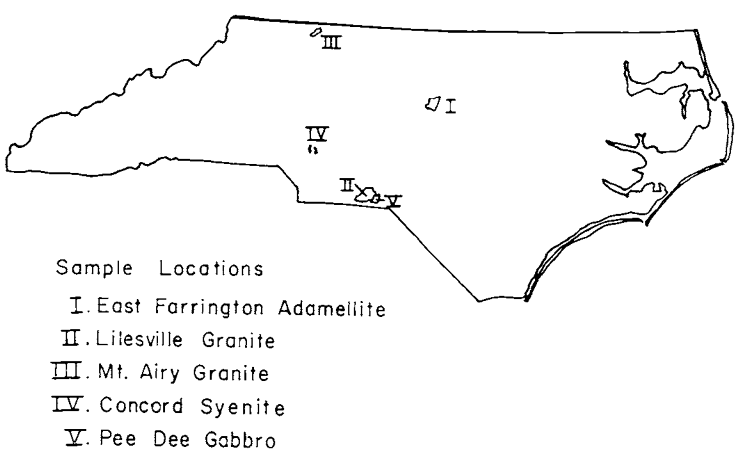


Fig. 2. Map of North Carolina showing sample locations of weathering rinds.

to 70 cm thick. Type II rindlet boundaries lose their definition between 1 and 1.5 m from the fresh rock contact (pl. 1-A). Plagioclase is completely altered to clays. Complete conversion can be evidenced by the disappearance of feldspar. X-ray diffraction shows this clay to be a moderately crystalline dehydrated halloysite.

Weathering rinds developed on Concord syenite and Pee Dee gabbro represent a radical departure from rind morphologies on the granitic rocks. The syenite and gabbro have only one rindlet morphology, which is designated as type III. This morphology consists of many thin rindlets concentric about a core of fresh rock (pl. 1-C and D). Rindlet thicknesses range from 0.5 to 2 cm, and all rindlets are indurated and retain the structure of fresh rock. Type III rindlets are clay deficient but limonite rich. The more altered outer rindlets contain less than 3 percent clay-sized material (table 1). Contacts between individual type III rindlets

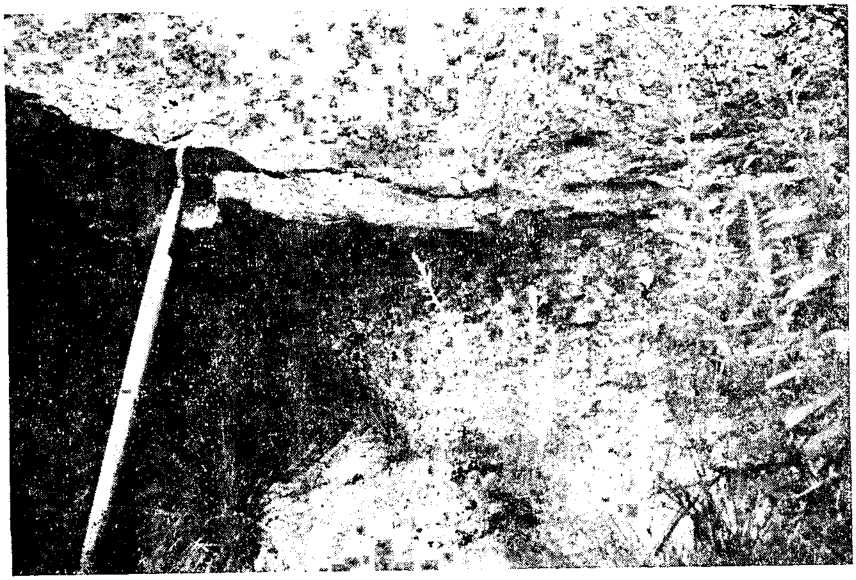
TABLE 1

Modal analyses of selected weathering rind samples from all 5 lithologies (in percent)

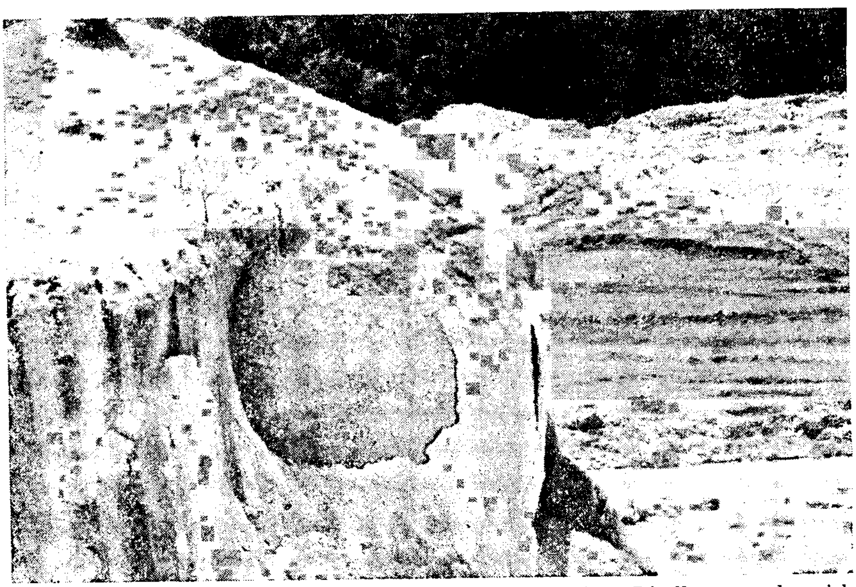
cm from fresh rock contact	Rind morphology	Kaolinized feldspar	Quartz	Unaltered K-feldspar	Unaltered plagioclase	Biotite	Quartz plus perthite	Aegirine-augite	Hornblende	Augite	Olivine	Wt percent of clay-sized fraction*
					East Farrington adamellite							
0	Fresh	0	20	29	48	2						0
55	I	5	24	26	42	1						4.8
90	II	20	26	30	25	tr						13.9
					Lilesville granite							
0	Fresh	0	15	39	35	7						0
50	I	10	13	36	28	11						5.9
100	II	20	19	52	tr	5						15.7
					Mt. Airy granite							
0	Fresh	0	21	36	41	1						0
25	I	22	24	38	15	2						6.2
50	II	26	27	40	tr	1						10.1
					Concord syenite							
0	Fresh	0				2	92	1	3			0
20	III	0				1	94	tr	1			1.4
150	talus	1				tr	97	0	0			4.7
					Pee Dee gabbro							
0	Fresh	8			58	5			12	11	7	0
15	III	tr			60	6			13	8	3	1.1
70	III	3			55	2			11	1	0	2.3
120	talus	75										12.2

* Procedure for determining wt percent of the less than 2μ fraction was patterned after Folk (1968). In some instances this fraction was considerably stained with limonite.

PLATE 1

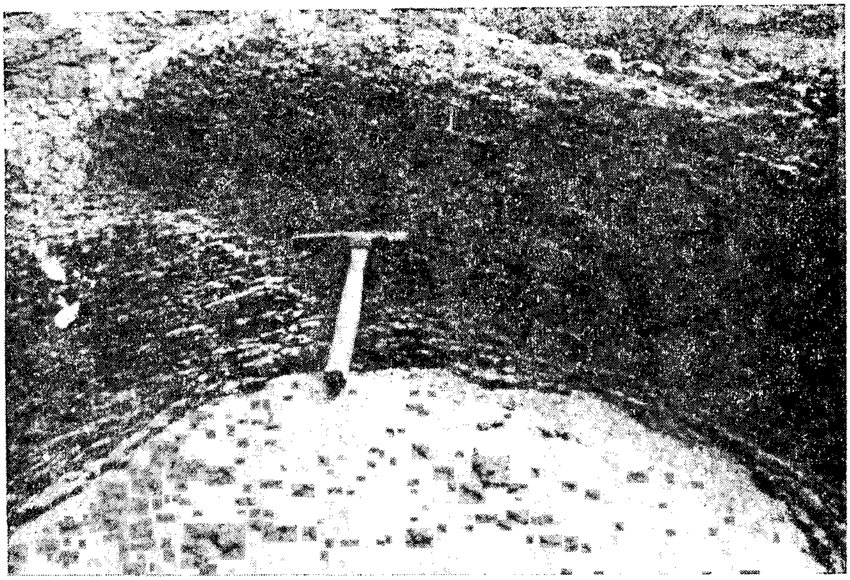


A.

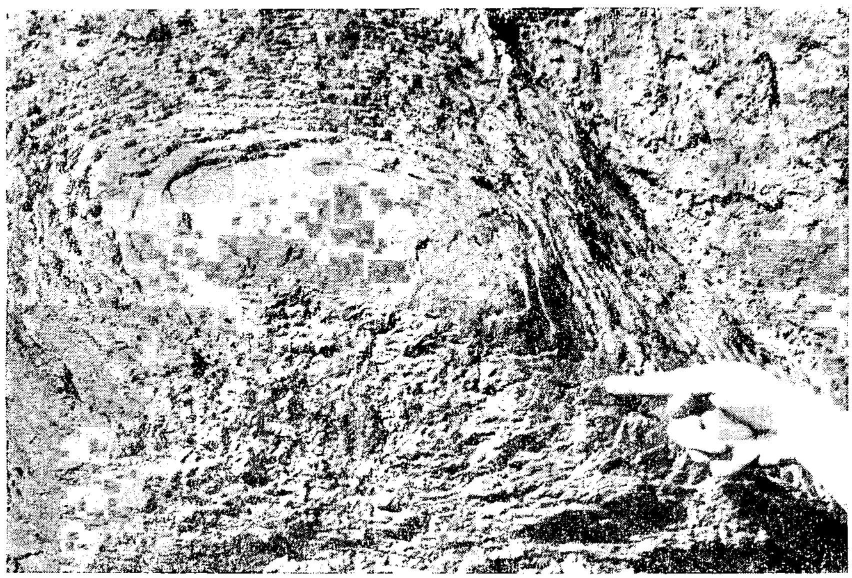


B.

Weathering rinds on granites have a few, thick rindlets. Rindlets are clay rich, and boundaries between individual rindlets are diffuse. In contrast, rindlets developed on syenite and gabbro consist of an "onion skin" morphology, characterized by many



C.



D.

limonite-rich rindlets of nearly constant thickness. A-D show typical weathering rinds developed on (A) Lilesville granite, (B) Mt. Airy granite, (C) Concord syenite, and (D) Pee Dee gabbro. The small pine tree atop the weathered boulder in (B) is about 1 m high.

are sharp and are characterized by limonite concentrations. Table 2 outlines the weathering rind characteristics of all five rock types.

SOLUTION CHANNELS

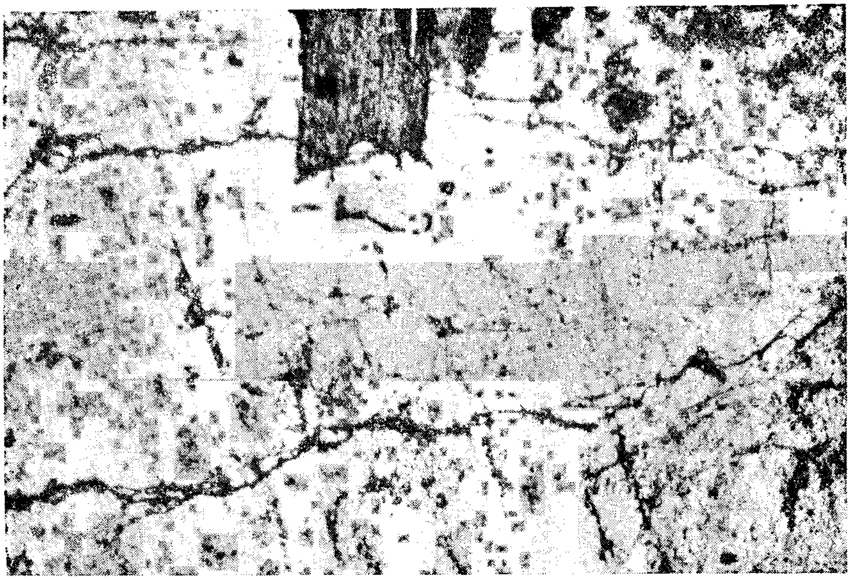
On a micro-scale, physio-chemical weathering is concentrated alongside cracks that are positioned both within mineral grains and along grain contacts (Rodgers and Holland, 1979). When filled with products of mineral dissolution, these cracks are termed "solution channels." Solution channels are presumed to act as conduits for incoming pore water and as outlets for dissolved alteration products like amorphous silica and limonite. Since unfilled solution channels are found in thin sections from cores drilled into fresh rock, it is believed that these micro-cracks are first initiated by unloading or other stress-relieved causes (Johnson, 1970).

TABLE 2

Summary of weathering rind habits for all lithologies

	TYPE I RINDLETS	TYPE II RINDLETS	TYPE III RINDLETS
East Farrington Adamellite	Indurated, retaining structure of fresh rock; rindlet borders are sharp and thicknesses range from 20 to 40 cm. Clay contents from 2 to 5 percent.	Non-indurated sandy rubble with matrix containing rock fragments of type I. Rindlet borders diffuse and thicknesses of 20 to 60 cm. Up to 15 percent clay.	
Lilesville Granite	Indurated, retaining structure of fresh rock; rindlet borders are sharp and thicknesses range from 10 to 20 cm. Clay contents from 2 to 7 percent.	Non-indurated sandy rubble with matrix containing rock fragments of type I. Rindlets borders diffuse and thicknesses of 20 to 40 cm. Up to 20 percent clay.	
Mt. Airy Granite	Moderately indurated; rindlet borders are slightly diffuse, and thicknesses range from 10 to 30 cm. Clay contents from 5 to 10 percent.	Non-indurated clayey-sand containing no rock fragments of type I. Rindlet borders barely discernible. Up to 25 percent clay.	
Concord Syenite			Indurated, retaining structure of fresh rock; rindlet borders are sharp and thicknesses range from 0.5 to 2 cm. Clay contents range from nil to 2 percent in outer rindlets.
Pee Dee Gabbro			Indurated, retaining structure of fresh rock; rindlet borders are sharp and thicknesses range from 0.5 to 1 cm. Clay contents range from nil in inner rindlets to 3 percent in outer rindlets.

PLATE 2



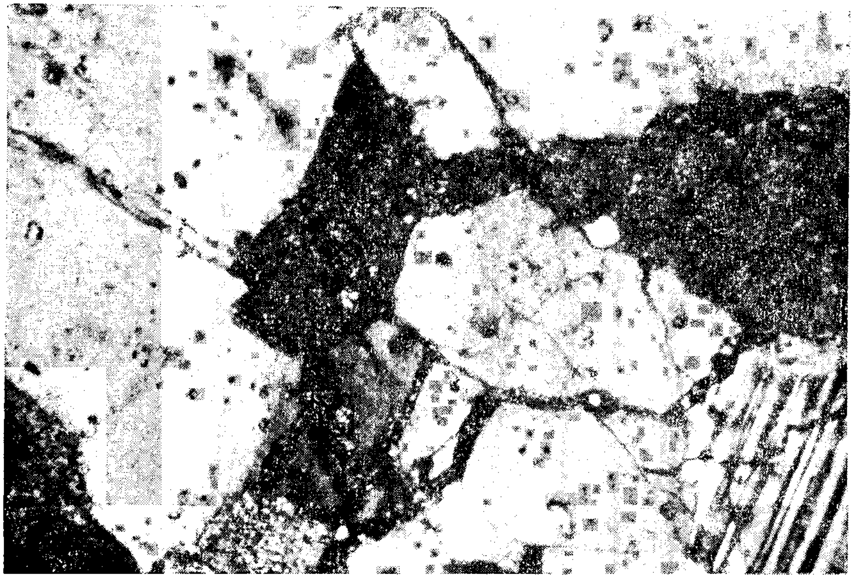
An oriented thin section of fresh Lilesville granite. The long dimension of the photograph is parallel to the outcrop surface and hence to the boundary of type I rindlets. Small cracks, herein termed solution channels, connect centers of mineral alteration and, when enlarged, become the boundaries of weathering rindlets.

Type I, II, and III rindlets all contain solution channels. Solution channels developed in type I rindlets of granitic rocks are typically 0.05 mm wide, and the channels are parallel to one another. Sub-parallel networks of solution channels cut through all minerals, with the orientation being uninfluenced by cleavage or twinning planes (pl. 2). Mineral alteration is visibly evident along channel banks. Plagioclase alteration to clay minerals is especially evident in this regard. Solution channels intersecting mafic minerals are filled with limonite.

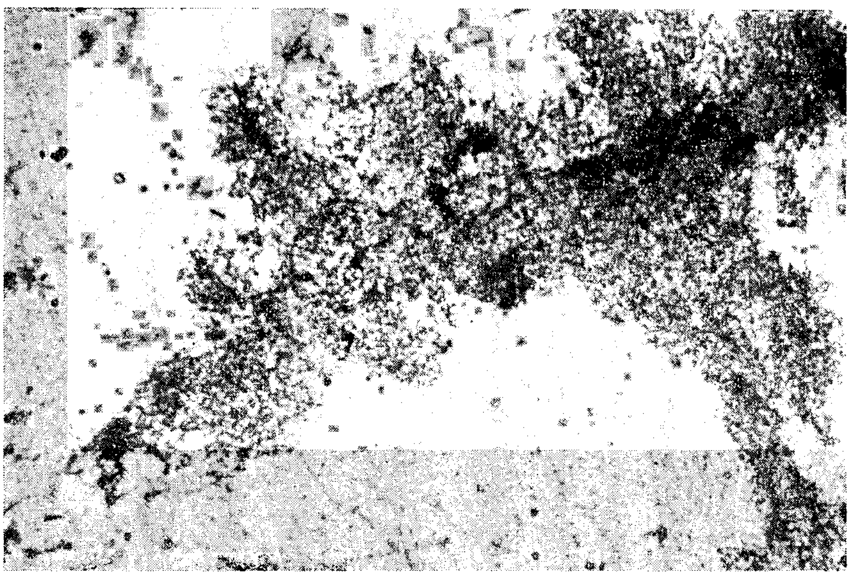
Channel development in type II rindlets is more extensive. Thin sections show that channels are more numerous and wider. The relatively chemically resistant minerals in the granitic rocks, quartz, and K-feldspar, host the highest density of solution channels, as channels in these minerals break up into anastomosing patterns. These channels are filled with amorphous silica. The widest channels (0.1-0.2 mm) lead to and from plagioclase. The incongruent dissolution of plagioclase to clay minerals results in a volume reduction, creating void space. These voids appear to serve as centers for channel confluence (pl. 3-A).

The morphology of solution channels in type III rindlets of gabbro and syenite is very similar to that developed in inner (type I) rindlets of the granitic rocks. Type III solution channels are mainly filled with limonite, reflecting the higher proportion of mafic minerals in these rocks. Dissolution-induced void space is noticeably absent in type III rindlets. In the syenite, plagioclase is within the perthite matrix, a struc-

PLATE 3

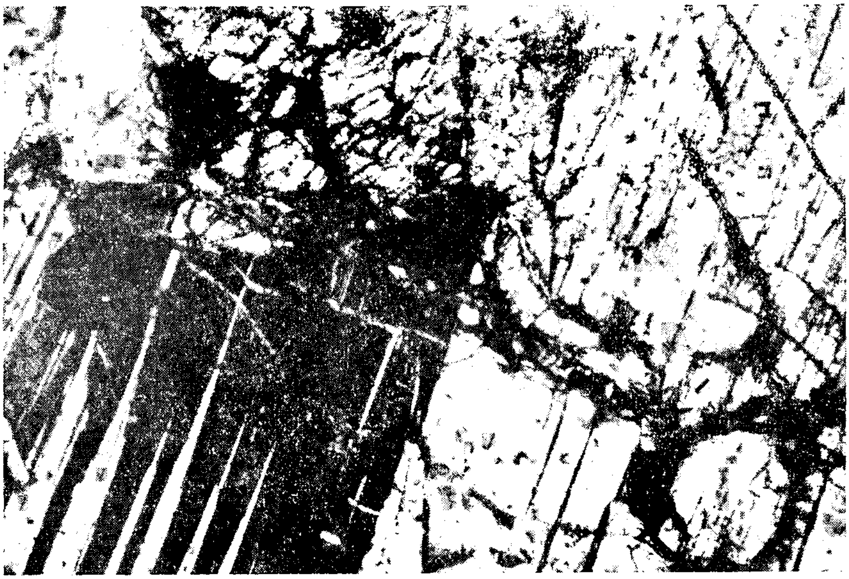


A. Photomicrograph of a type II rindlet of Mt. Airy granite. *In situ* kaolinization of plagioclase (dark areas of slide) produce voids which naturally occur at the terminus of solution channels. Stress is greatly relieved at these solution-induced voids and continued channel propagation along this route is greatly impeded. These kaolinization centers serve as centers for solution channel confluence. Width of these solution channels are about 0.1 mm.



B. Photomicrograph (in plane light) of a Concord syenite rindlet sample. Long dimension of photograph is equivalent to 10 mm. Dark areas are solution channels filled with limonite. These connect altered mafic minerals. Solution channels are not effective in penetrating the perthite matrix (white areas). Continued advancement creates islands of stable mineralogies (perthite) which form the bulk of the talus when the rindlet totally disaggregates.

PLATE 4



Photomicrograph of an outer rindlet from a Pee Dee gabbro weathering rind. Limonite-filled solution channels (about 0.05 mm wide) are seen traversing plagioclase (lower left), pyroxene (upper right) and on olivine grain in the upper left. Plagioclase retains mineralogical identity in gabbro rindlets and alters to clay minerals only after the rindlet disaggregates to form talus.

ture that appears relatively impermeable to solution channels (pl. 3-B). In gabbros, solution channels have access to plagioclase, as thin sections show the labradorite traversed by limonite-filled channels (pl. 4). Yet the plagioclase is visibly unaltered, even in the outermost rindlets. Olivine and pyroxene are the most altered minerals in gabbro rindlets, and these minerals have the highest density of solution channels (pl. 4). Even in advanced stages of alteration, solution channels in gabbro and syenite retain their senses of parallelism.

Oriented thin sections of inner rindlets of all rock types reveal that solution channels are parallel to the contact between the fresh rock and the innermost rindlet (pl. 2). This strongly suggests that parting (spallation) occurs along solution channels, and that a rindlet is produced when solution channel development becomes sufficiently advanced.

Residual stress within the rock at or near the outcrop surface augments and probably directs the force exerted as a result of a chemical reaction at the crack terminus of the solution channel. That residual stress is the dominant factor in controlling the orientation of solution channels in inner (types I and III) rindlets is partly supported by petrographic evidence. Solution channels in inner rindlets cut through grains of all minerals. Jahns (1943) reported the same orientation of micro fractures in his study.

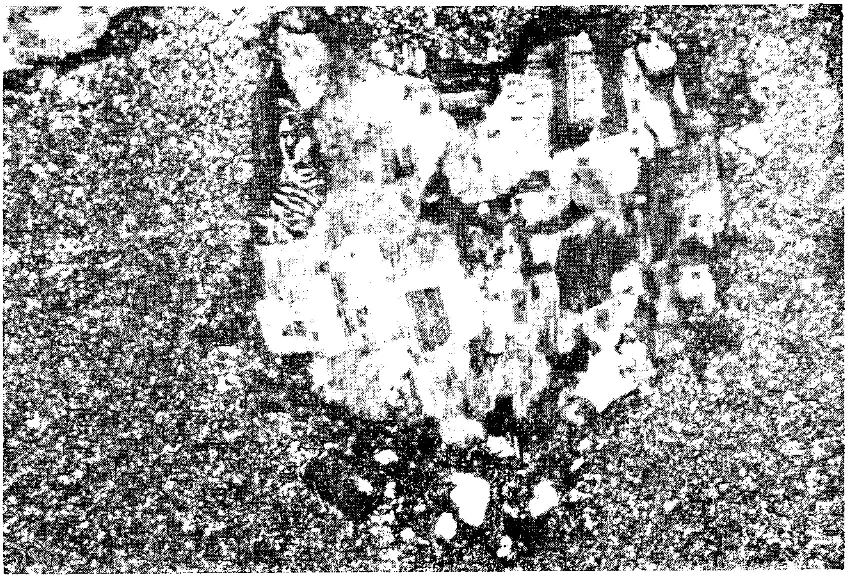
As long as solution channel orientation is parallel with the fresh rock contact, rindlet boundaries will also maintain that geometry. When this internal geometry of the solution channel system is disrupted, the corresponding rindlet boundaries lose their parallelism and become diffuse. This is typical only of the Type II rindlets of the granitic rocks. In these rindlets, *in situ* kaolinization of plagioclase produces a volume decrease with the void becoming saturated with pore water. Thin sections of these rindlets show that kaolinized plagioclase are centers of solution channel convergence, presumably because channel propagation takes the path of least resistance. In the absence of void space, channel propagation must occur at the leading edge of the crack. This is the point of greatest stress concentration. A dissolution-induced void will dissipate the stress, and crack propagation should then be greatly retarded (Neuber, 1958). A neighboring solution channel, unimpeded by extensive kaolinization, presumably continues its propagation into the rock's interior.

Creation of void space by dissolution reactions within an altered rock then appears to be very important in solution channel development. Alteration of mafic minerals does not appear to create sufficient void space to disrupt the continued orientation of solution channel advancement. Biotite alters to dioctahedral vermiculite, creating a volume increase. In the outer type III rindlets of gabbro, olivine and pyroxenes are severely altered, but whatever pore space created has been filled with relatively insoluble iron hydroxides. Feldspars, and especially plagioclase, are then the prime candidates for creating void space upon chemical alteration of the rocks studied. The question must then be addressed as to why plagioclase-bearing rocks like syenites and gabbros have "onion skin" rindlets and not type II rindlets so typical of granitic rocks.

Rock texture controls the weathering rind habit of syenite. Plagioclase is contained within the perthite matrix, and thin sections show this matrix in relatively impenetrable to solution channels. Main solution channels connect mafic minerals rimming the periphery of perthite blebs (pl. 3-B). A thin section of impregnated talus sampled at the foot of a syenite weathering rind reveals subangular rock fragments composed almost entirely of perthitic intergrowths (pl. 5). The exsolved plagioclase and microcline are as fresh as those in the fresh rock. All perthite rock fragments in the talus possess limonite rims of varying thicknesses (pl. 5). This strongly suggests that channelization within an individual rindlet becomes so extensive that it creates islands of stable mineralogy (like perthites) which ultimately disaggregate to form talus.

In comparison to the other lithologies, the rate of rindlet production on gabbros has an important bearing on the weathering rind habit of that rock. In the gabbro, plagioclase is traversed by solution channels; yet, the labradorite retains its identity even in the outermost rindlets (pl. 4). Other minerals (notably olivine, pyroxene, and biotite) are less stable than plagioclase. These minerals alter readily to limonite which effectively fills all voids created by mineral dissolution (pl. 4). The rate

PLATE 5



Photomicrograph of an epoxy-impregnated pebble sampled from talus at the foot of a Concord syenite weathering rind. The pebble, about 1 cm across, is rimmed with limonite. Feldspar of the pebble is as fresh as that in the fresh rock. The limonite rim of the pebble corresponds to the limonite-filled solution channels (pl. 3-B) which served as rindlet border.

at which rindlets are produced should be proportional to the rapidity of alteration of these ferromagnesian minerals. It is postulated that the rate of alteration of these minerals exceeds that of plagioclase. Hence, the residence time of labradorite on gabbro rindlets is insufficient for *in situ* kaolinization to occur. Once gabbro rindlets disaggregate to form talus, plagioclase then alters to clay-sized material (table 1). This assertion is further supported by comparing the relative alteration of plagioclases in gabbro and granite. Figure 3 compares the stability of oligoclase in Lilesville granite rindlets with that of labradorite in gabbro rindlets. In the innermost rindlets of Lilesville granite, oligoclase readily alters to a gibbsite–kaolinite assemblage. Labradorite is fresh even in outer gabbroic rindlets. For similar conditions of weathering, Ca–plagioclases should be less stable than Na–plagioclases (Goldich, 1938). The Pee Dee Gabbro and Lilesville granite are contiguous, and thus weathering conditions should be similar for both outcrops. This apparent contradiction of the stability series is explained if gabbro rindlets are produced at faster rates than rindlets on granitic rocks.

SUMMARY

The boundaries between individual rindlets on a weathering rind of a given lithology are thin cracks containing high concentrations of limonite and/or clay-sized material. Petrographic examination of fresh rock, inner, and outer rindlets reveals that progressive alteration in

weathering rinds is accompanied by solution channels. Because oriented thin sections show these solution channels are parallel to rindlet boundaries, it is believed that rindlet boundaries are formed by coalescence of these channels. The weathering rind of a rock is controlled by the orientation and propagation of these solution channels. In the absence of any appreciable void space solution channel orientation is maintained, with the channels always aligned parallel to the fresh rock contact. In this situation, many thin rindlets of nearly constant thickness envelop the central core of fresh rock in an "onion skin" fashion. If, however, void space is created by kaolinization processes, the parallel geometry of channel propagation is disrupted, and the rindlet boundaries are diffuse and non-parallel to the fresh rock contact. This leads to formation of few, but thick, weathering rindlets.

In syenites, plagioclase is texturally protected from solution channels by the rock texture. The least stable minerals in syenite are ferromagnesians, and the presence of these minerals promote the development of solution channels. These channels coalesce with increasing alteration in the weathering rind, and channel development is not retarded by kaolinization.

Plagioclase is not texturally protected from solution channels in gabbro, but, plagioclase is not the most unstable mineral in that rock. Alteration of ferromagnesian minerals produces rindlets at a fast rate. The residence time of plagioclase on the weathering rind is too short for kaolinization-induced void space to occur.

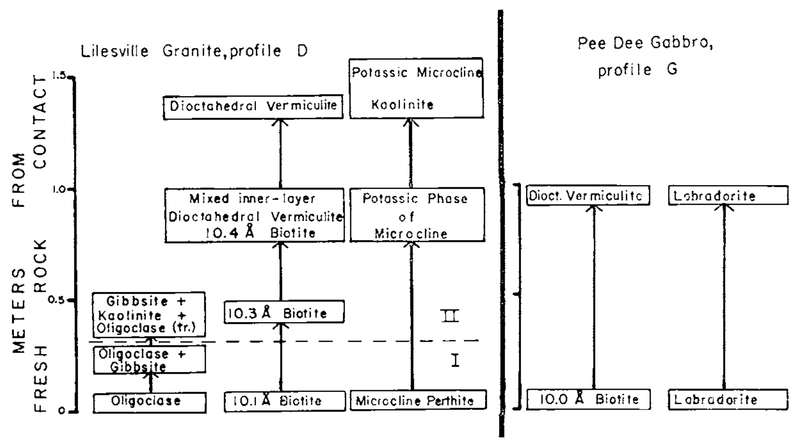


Fig. 3. Diagram depicting the physical and mineralogical changes occurring during progressive alteration of some primary minerals in a Lilesville granite and a Pee Dee gabbro profile. The dashed line in the Lilesville granite separates type I and type II morphologies. The Ca–plagioclase of the gabbro retains its identity even in the outermost rindlets. In contrast, the oligoclase of the granite alters in the innermost rindlets of that system. Mineralogical identification of these samples were performed by X-ray diffraction.

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