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THE CONTACT METAMORPHISM OF THE ONAWA PLUTON, PISCATAQUIS COUNTY, MAINE.

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ABSTRACT.

The Onawa region, on the southern edge of the heavily forested region of central Maine, is underlain by a belt of tightly folded Silurian slate into which was intruded, sometime in the Devonian (?), a small mass, about 27 square miles in area, of acid to intermediate granitic rock. Accompanying and following the intrusion, the slate was metamorphosed with the production of a three-zoned contact aureole composed of andalusite schist, hornfels, and injection hornfels, named in the order in which these zones occur inward toward the pluton. Several dikes and many aplitic veinlets were injected into the aureole. The structure of the region was somewhat modified with the production of folds trending across the regional strike. Faulting was not common. This paper describes the geology of the region in an attempt to determine the character and degree of the metamorphism produced by the Onawa pluton.

INTRODUCTION.

The geology of the Onawa region presents a picture of a well-formed metamorphic aureole, produced within the borders of a single wide sedimentary formation, completely surrounding a small intrusive mass of granodioritic rock. It has been the purpose of the writer to map the geology of the region (Fig. 1) and to describe the petrography of the aureole in some detail. The Onawa region, named from Onawa post office and station on the Canadian Pacific Railway, is a densely forested, mountainous area of 200 square miles, dotted with numerous lakes, lying between the villages of Monson and Katahdin Iron Works in the southern part of Piscataquis County in the center of the State of Maine. It is a less known part of the State, touched on the west only by an automobile

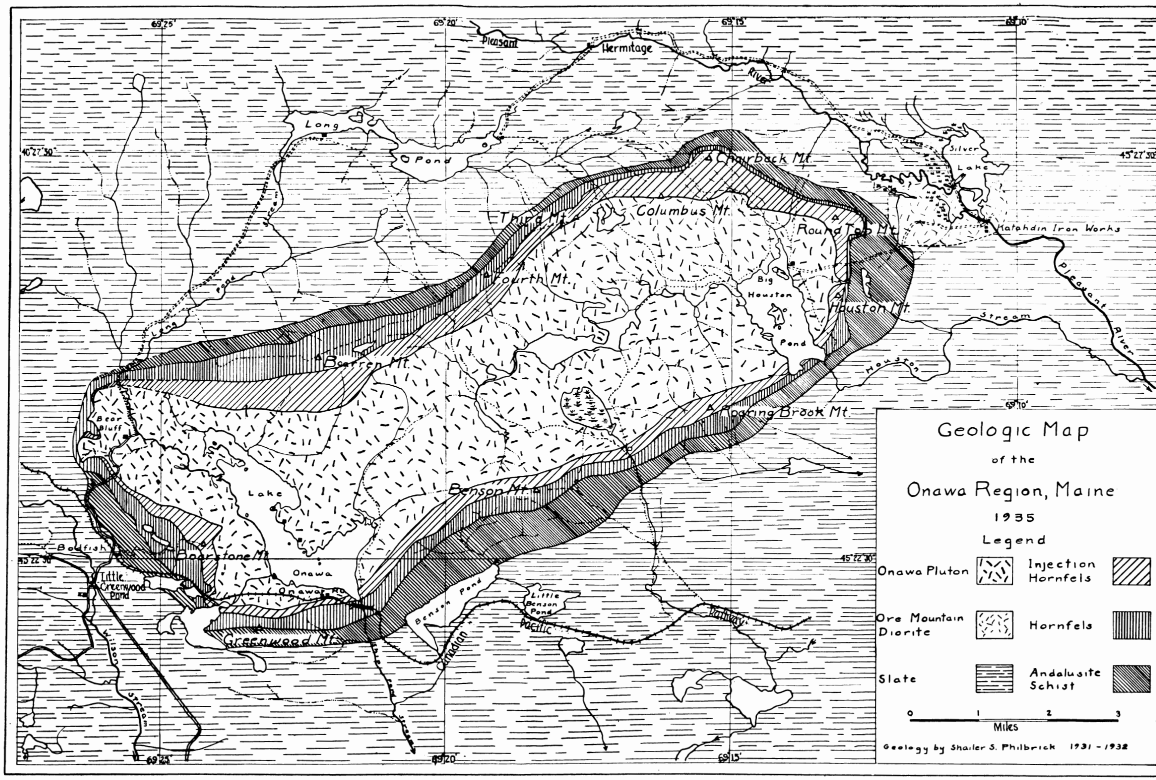

Geologic Map
of the
Onawa Region, Maine
1935
Legend
Onawa Pluton
Injection Hornfels
Ore Mountain Diorite
Hornfels
Slate
Andalusite Schist
Miles
Geology by Shailer S. Philbrick 1931 - 1932
Chairback Mt.
Columbus Mt.
Third Mt.
Fourth Mt.
Round Top Mt.
Houston Mt.
Barren Mt.
Roaring Brook Mt.
Benson Mt.
Boarstone Mt.
Greenwood Mt.
Big Houston Pond
Lake
Onawa
Long Pond
Silver Lake
Katahdin Iron Works
Pleasant River
Hermitage
Little Greenwood Pond
Benson Pond
Little Benson Pond
Canadian Pacific Railway
Houston Stream
Bear Bluff
Bodfish
Wilson Stream

Fig. 1.

road, traversed on the western and southern sides by the Canadian Pacific Railway and served on the east by motor truck haulage over the rails of the discontinued branch of the Bangor and Aroostook Railroad from Brownville Junction to Katahdin Iron Works and crossed on the north by the recently completed Appalachian Trail. It is an area easy of access but less easy to cross; there is no thoroughfare for canoe travel. There are two lake basins cut in the rock of the pluton and walled by ridges of the resistant metamorphic rocks of the aureole. These basins are structurally members of a larger one, coinciding in location with the pluton, and are separated from each other, physiographically, by a low divide formed by the junction of spurs from the mountains on opposite sides of the intrusive. This coincidence of position of the igneous rock with the basins, and the metamorphics with the ridges is of significance because by this relationship the metamorphics are well exposed. The lowland basins covered by many ponds, swamps, and a great thickness of glacial drift did not afford a good opportunity to study the pluton.

The region was entirely without reliable base maps and the writer, with the capable assistance of Carl Broedel, Charles Cohen, and Lewis Danziger, in 1931, and Hobart E. Stocking, in 1932, constructed a topographic map on a scale of 1:48,000 with a 50-foot contour interval. The area had been controlled in part by the triangulation and transit traverse of the U. S. Geological Survey and by the leveling of the U. S. Coast and Geodetic Survey. Late in the summer of 1931 it was photographed by the U. S. Army Air Corps and a base map was compiled by the writer from these photographs under the direction of Mr. C. H. Davey, of the section of photo mapping of the U. S. Geological Survey. This photogrammetric base provided the final base on which the topography and geology were mapped.

The writer wishes to thank the U. S. Geological Survey for the loan of instruments and assistance throughout the study. To Professor E. R. Smith of DePauw University he is indebted for the loan of a plane table stadia outfit. Professor E. B. Mathews aided the writer greatly with his advice and criticism throughout the entire project, and suggested the Onawa region among others as a possible dissertation subject. Professor C. H. Behre placed the facilities of the Department of Geology of Northwestern University at the writer's disposal during the preparation of this paper.

GEOLOGY OF THE ONAWA REGION.

In presenting the results of this study the writer has chosen to describe first the character of the country rock slate and the nature of the Onawa pluton to develop the setting for the second phase of the description, which is concerned with the metamorphic products resulting from the interaction of the pluton and the slate.

Slate.

The slate series, which carries the commercial slate quarried at Brownville, Williamsburg, Barnard, Monson, and Blanchard, and which forms the country rock of the Onawa region, consists of interbedded clay slates, graywackes, sandstones, quartzites, and quartzitic slates. The ratio of slate to sandy beds and the thickness of individual beds vary locally, but over the entire extent of the formation these characteristics seem to be nearly uniform. In the Onawa region the rock typical of the slate series is of two kinds, generally interbedded: quartzite and clay slate.

The quartzite occurs in beds ranging from less than an inch to over a foot. It is light to dark gray in color and generally is lighter when weathered. The fracture is irregular to conchoidal and, locally, blocky. Minor cross-lamination is not uncommon.

The clay slate is more abundant than the quartzite and is fissile, thin bedded, and commonly schistose, breaking with a hackly fracture. It forms thin partings up to four inches thick between the beds of quartzite. It is gray to dark bluish gray or black and is generally lighter when weathered. Ripple marks have been observed along its bedding planes in a cut along the Canadian Pacific Railway near Little Benson Pond. Locally it carries small angular holes, possibly the result of weathering out of a mineral, andalusite (?). Fissile slate without visible, interbedded quartzite occurs in the eastern part of the area on the northern slope of Chairback Mountain from East Chairback Pond down to Pleasant River in the vicinity of the Hermitage; about a quarter of a mile south of Bodfish on the Canadian Pacific Railway; and on the ridge northwest of Bodfish School. Elsewhere the slate formation is the normal interbedded clay slate and quartzite.

The slate series is not a resistant formation and does not commonly form cliffs or strong outcrops. The lowlands bordering the outer slopes of the mountains are underlain by the slate series and only where the outer contact of the metamorphic aureole occurs on the higher slopes, which are themselves supported by the strongly resistant metamorphics, does slate occur above the general level of the lowlands. Bear Pond Ledges and the ridge trending northwest from Bodfish School seem to be contrary to this generalization, but they are the southern border of what Perkins has called the Moosehead Plateau[2] and belong to another physiographic unit with which they are consistent in relief. The outcrops of this series are generally inconspicuous and infrequent, occurring commonly as low strike ridges. A few streams have cut through the mantle of glacial material to expose the bedrock, slate. Two of them have cut narrow box canyons: the Gulf of Pleasant River and the canyon of the Little Wilson Stream. Along the Canadian Pacific Railway cuts have exposed the slate and, with the exception of the two canyons, these form the best exposures.

The age of the slate series has not been exactly determined, since no diagnostic fossils have yet been collected from it and since the stratigraphy of the region is known too little to permit correlation on the basis of lithology and sequence alone. Keith[3] has mapped these slates as Silurian, which age is accepted by the writer. However, on Keith's map is shown a narrow band of Cambro-Ordovician rock partially encircling the Onawa pluton, but pinching out along its northern border, which practically coincides with the aureole as described in this paper. The writer found no evidence in the field on which to separate the metamorphosed rocks of the aureole as Cambro-Ordovician from the country rock slate mapped by Keith as Silurian. The writer holds no brief for one age as opposed to the other, since he has found no paleontologic evidence either way; but the structural and petrographic evidence, derived from his field work, points to a common age for both, rather than to separate ages.

The commercial slates of the Brownville-Monson series have been studied in detail by Dale who describes the petrography of the slate from each of several quarries. In comparing these slates it appears that, although they vary slightly in the rela-

[2] Perkins, E. H.: "Contributions to the Geology of Maine, No. 2, pt. 1. The Moose River Sandstone and its Associated Formations. This Journal, 5th Ser. 10, p. 371, 1925.

[3] Keith, Arthur: Preliminary Geologic Map of Maine, State of Maine Geological Survey, 1933.

tive amounts of their mineral constituents, they are much alike and are classed as mica slates. The following table, in which the localities are listed from east to west, reading downward, gives the chief mineral constituents and is taken directly from Dale.[4]

Mineral Constituents of Commercial Slates of Maine. After Dale.

Locality and Quarry	Chief Mineral Constituents in Order of Decreasing Abundance
Merrill Quarry, Brownville	Muscovite, quartz, magnetite, pyrite
Monson Pond Quarry, Monson	Muscovite, quartz, chlorite, biotite
Portland-Monson Quarry, Monson	Muscovite, quartz, chlorite, magnetite, biotite
Maine Slate Co., Monson	Muscovite, quartz, biotite, chlorite
West Monson	Muscovite, quartz, chlorite, pyrite
North Blanchard	Muscovite, chlorite, quartz, pyrite

Igneous Rocks.

The igneous rocks of the Onawa region occur as two units: the Onawa pluton and its associated dikes and aplitic veinlets, and the Ore Mountain diorite. The Onawa pluton will be described in some detail in order to show the characteristics of the magma that produced the contact metamorphism. The Ore Mountain intrusive is a small mass of which no careful study was possible in the field because of the lack of exposures. It is mentioned only briefly since it is apparently not connected genetically with the contact metamorphism.

The Onawa Pluton.

The Onawa pluton is an intrusive body 11 miles long and 3 miles wide in its greatest dimensions, with an area of about 27 square miles. On the geologic map the pluton resembles a boot with the upper part trending northeastward and the heel at the southwestern end. The term "batholith"[5] has been applied to this intrusive, but it seems more correct to designate it a "pluton" because of lack of evidence necessary to determine its exact type. Perkins,[6] correlating it with that of the

[4] Dale, T. N., et al: Slate in the United States. U. S. Geol. Survey, Bull. 586, plate opp. p. 188, 1914.
[5] Philbrick, S. S.: "Contact Metamorphism of the Onawa Batholith, Piscataquis County, Maine," abst. Am. Min., vol. 18, p. 116, 1933.
[6] Perkins, E. H.: Personal communication, 1931.

Dedham granodiorite in Massachusetts, has suggested that it was intruded in the late Devonian.

Although the pluton is apparently fairly homogeneous lithologically, it contains nine rock types of the quartz-rich sub-alkaline group, ranging from granite through intermediate types to gabbro. They occur in a rather poorly defined series of zones with the acid rocks in the center and the basic ones along the border of the intrusive. The center is composed of granite, surrounding which is quartz monzonite and granodiorite. The basic border is composed of quartz diorite with some diorite, orthoclase-bearing gabbro, quartz norite, quartz gabbro, and gabbro. The zones become less distinct in the border, so that it is not uncommon to find quartz diorite at the contact of the pluton and gabbro a few feet inside the mass. Granodiorite occurs near the contact locally, so that the Onawa pluton affords an opportunity of comparing the effects of acidic and basic portions of the same magma on the same country rock.

The injection of two apophyses of mappable size into the country rock and their consequent petrographic characteristics and subsequent metamorphic effects present further evidence of the influence of rate of heat dissipation and heat content of igneous rock on the process of metamorphism of country rock. The larger of these two apophyses, the Bear Bluff apophysis at the northwestern end of the pluton, is a quarter of a mile in length and somewhat less in width. The rock is a quartz diorite, not uncommon in the pluton, but here distinguished for its texture which is porphyritic with a microfelsitic groundmass carrying spherulites. The Houston apophysis, a thin finger less than 800 feet long and 300 feet wide on the eastern side of the pluton, is composed of a porphyritic, medium grained, holocrystalline orthoclase-bearing gabbro.

The rocks of the pluton are characterized by the presence of biotite, quartz, and potash feldspar in practically all of the members of the series. They are commonly medium grained, lacking any definite megascopic structure, but in the eastern part of the intrusive a well-defined flow structure is present locally. Unoriented inclusions are not uncommon and are profusely present in the eastern half. Zoned plagioclase crystals in which the general progression in acidity from core to periphery of grain is not infrequently broken by slight zonal increases in basicity are common in this series of rocks. Aside from these slight variations, the series is very similar to a typical subalkaline suite of igneous rocks.

The pluton outcrops in the low lake and swamp-filled basins in which exposures are scarce except near the contact, which commonly occurs on the slopes of the adjacent ridges. The contact is sharp, but is crossed by occasional dikes; locally it dips outward at angles up to the vertical but no general attitude could be determined either from closely spaced direct observations or from detailed mapping.

Dikes and Quartz Veins.

The dikes associated with the Onawa pluton are of two types, acidic and intermediate, and occur in two areas, the acidic in the eastern part of the region and the intermediate in the western part. They occur as isolated outcrops and could not be traced; five were found of which two are probably exposures of the same dike. In thickness the dikes range from two inches to over ten feet. They are of interest because of their assimilation of country rock, which is represented by small xenoliths or by aluminous minerals. The dikes were not all intruded at the same time, for aplitic veinlets occur in profusion in a dike of tonalite porphyry on Boarstone Mountain and are cut by another dike of alaskite aplite near the summit of Columbus Mountain.

The petrographic evidence afforded by three of the dikes points very strongly to assimilation of country rock during, or prior to, their injection. In a microgranodiorite from Boarstone Mountain small inclusions of rock, which is approximately biotite schist, are evidence of minor stoping and reaction with the magma of the dike. The tonalite porphyry from the same mountain megascopically looks more like a hornfels with medium-grained feldspar porphyroblasts than a dike. The biotite in these two dikes is the small, palely pleochroic, shredded type which is characteristic of the hornfels of the aureole. Microscopically they are like the hornfels except for the presence of strongly zoned and commonly sericitized, plagioclase phenocrysts, which are characteristic of the Onawa intrusive. The tourmaline-andalusite microgranite dike on the northeastern slope of Roaring Brook Mountain is composed of quartz, orthoclase, a small amount of oligoclase, andalusite, and alferrics. The andalusite with its alumina suggests an excess of alumina in the dike. This is further shown by a chemical analysis calculated from a Rosiwal analysis, which gives the percentage of alumina as 16.68 and silica as 71.33.

The consideration of these three dikes leads to the conclusion that there has been some contamination of the magmas that crystallized to form them. In the microgranodiorite the reaction between the magma and the inclusions went so far as to develop biotite schist from the original country rock slate. In the tonalite porphyry the reaction seems to have gone farther and produced a rock that is somewhat similar to the hornfels of the injection zone. In the tourmaline microgranite the reaction seems to have been complete and the inclusions have disappeared. The included siliceous and aluminous material appears as andalusite and much quartz. The processes of assimilation and subsequent crystallization that would produce andalusite in an igneous rock, especially one so thin as a one-foot dike, are not known to the writer. The question arises as to the place of assimilation. If high temperature and continued heat are necessary, then it would seem that the material was assimilated locally by the pluton. This displacement of the assimilation to the mass of the pluton accords with the occurrence of xenoliths, only partly assimilated, in the two dikes previously mentioned. This partial assimilation leads to the conclusion that these dikes, microgranodiorite and tonalite porphyry, did not have the ability to assimilate their inclusions, and since they are thicker and more basic, carrying more heat and at a higher temperature than the tourmaline-andalusite microgranite, it does not seem probable that the andalusite-bearing dike could have done what the others failed to do.

Narrow quartz veins up to two inches thick carrying euhedral black tourmaline less than an inch long occur frequently throughout the aureole and probably represent the pegmatitic stage of the igneous activity of the Onawa pluton.

The Ore Mountain Diorite.

Between Katahdin Iron Works and Big Houston Pond outcrops a poorly exposed body of mineralized igneous rock, determined from one thin section to be diorite. The location of this body is well shown by the rusty soil produced by the weathering of the sulphides. It was formerly mined for iron[7] but has been idle for some time. More recently it has been extensively prospected by one of the larger chemical companies as a possible source of sulphur. The size of this mass is con-

[7] Bastin, E. S.: Eng. and Min. Jour., vol. 104, pp. 758-759, 1917.

jectural as its exposures are rare and as it is apparently overlapped on the northern side by the glacial gravels of the Pleasant River valley. It is the writer's belief that the Ore Mountain diorite is older than the Onawa intrusive, since there is no change in the andalusite schist in the vicinity of the diorite. It is possible that the Onawa intrusive and the Ore Mountain diorite are related genetically to the same magma, but the highly mineralized, non-metamorphosing character of the latter does not strongly support this view.

The Metamorphic Aureole.

The Onawa pluton is surrounded by a zone of contact metamorphosed rocks called the metamorphic aureole, the shape of which is roughly that of the boundary of the pluton. Its width ranges from 150 feet at the western end of the Bear Bluff apophysis to over 7000 feet on Boarstone, Barren, and Benson Mountains, but is about 3500 feet on the average.

The rocks of the aureole have been divided into three units which were found to persist around the entire border of the intrusive except where a salband, such as the Bear Bluff apophysis or the Houston apophysis, is present; there it is narrower and some of the units, or zones, are missing. In a traverse from the country slate toward the pluton the following zones are encountered in this order: andalusite (chiastolite) schist, hornfels, and injection hornfels carrying many narrow, aplitic veinlets. On Boarstone Mountain, in the southwestern part of the aureole, they are distinctly and fairly easily separable rock types and, although to the eastward they vary somewhat from the Boarstone types, they have a fairly persistent character throughout the aureole. This is shown by the fact that the writer on beginning the second season of this investigation at the eastern end of the aureole was able to pick out the three zones without having to trace them eastward from the western part of the aureole.

One of the common characteristics of these rocks is fineness of grain. None of the minerals exceeds 3 or 4 mm. in length and the average grain size is less than 1.0 mm.

The outer zone of the aureole is composed of andalusite or chiastolite schist and is called the schist zone. The rock is dark bluish gray to black and carries small prisms of andalusite or chiastolite. The width of outcrop of the zone ranges from nothing near the Bear Bluff apophysis, where it pinches out completely, to 4800 feet at the eastern side of the aureole. The average width is probably between 1500 and 2000 feet. Petrographically it is a sericite-quartz schist with porphyroblastic grains of andalusite or chiastolite. The andalusite crystals commonly weather in relief.

The middle zone is the hornfels zone. The rock is brownish black, fine-grained, and micaceous with well-preserved sedimentary features, such as bedding, minor cross-bedding, ripple marks (Fig. 2), and large mud cracks. These features are

Fig. 2. Ripple marks in Hornfels.

well shown in the cuts along the Canadian Pacific Railway near Little Greenwood Pond. The width of the hornfels zone ranges from 200 feet, where it is cut out at the Houston apophysis, to 3000 feet on Barren Mountain. The average width is probably about 1000 feet.

Petrographically it is a hornfels of varying character, being either a true, apparently completely recrystallized rock with the typical hornfels minerals; or not a true hornfels, in the sense of the European petrographers, especially Tilley and Goldschmidt, with some low or medium grade mineral that does not appear in the accepted mineral assemblages of the katazone hornfelses. This requires a brief comment on the subject of the definition of hornfels as used in this paper. "True hornfels" is the term here used to designate a rock that occurs in one of the two inner zones and which by its katazone mineral assemblage and texture gives evidence of more or less complete recrystallization. Sericite-quartz hornfels and sericite hornfels are terms used to designate the character of a sericite-bearing, usually sericite-rich rock which occurs in one or the other of the two inner zones, the hornfels zone or the injection hornfels zone. Thus hornfels has a double connotation: first, it refers to the position of the rock in the aureole, and, second, it refers to the mineral assemblage denoting rocks which carry a theoretical katazone mineral assemblage.

The inner zone of the metamorphic aureole surrounding the Onawa pluton is the injection hornfels zone. It completely encloses the pluton except near the Houston and Bear Bluff apophyses. In two places on the northern slope of Chairback Mountain small areas of injection hornfels surrounded by narrow bands of normal hornfels outcrop within the andalusite schist zone. The injection zone varies in width of outcrop from a maximum of 3800 feet on Chairback Mountain to nothing at Bear Bluff where it pinches out completely. The average width is about 1500 feet. The rock of the injection zone is dark gray to black on the fresh surface, generally weathering to a lighter gray which may be tinged with brown. It is dense, fine grained, and micaceous. The aplitic veinlets, which are the determining criterion of this zone are thin, light-colored veins which cut the rock at random, or in parallel planes to produce an injection gneiss, or wind through the rock in contorted ptygmatic folds. Usually these aplitic veinlets weather in relief and the rock presents a rough surface. The rocks of the hornfels zone are very similar in appearance to those of the injection zone except for the presence of the veinlets in the latter.

The outcrops of the metamorphic aureole occur on a series of ridge-like mountains that surround the topographic basins underlain by the Onawa pluton, since the rocks of the aureole are more resistant than the country slate and stand up in sharp contrast to the generally even level of the low ridges of the adjacent region. The separate zones of the aureole show differences in resistance to erosion. The schist zone, most like the slate in lithology, is the weakest member of the aureole, occurring usually on the lower parts of the outer slopes of the mountains. The hornfels, or middle zone, forms the mountain crests of Greenwood, Barren, Fourth, and the eastern spur of Benson; on the other mountains it forms the upper part of the outer slopes. The most resistant zone of the aureole as suggested by boldness of topographic features is the injection, or inner zone; it forms the crests of all the mountains not capped by the hornfels zone and on those it occurs on the upper parts of the inner or basin slopes. The sharp cliffs and peaks of Boarstone Mountain are cut in the rock of the injection zone.

Despite the cover of glacial material, outcrops are frequent within the aureole except where it is crossed by a major valley like that of Long Pond Stream or Houston Stream. Of the three zones the schist is the least exposed. The rocks are usually fresh with possibly a thin veneer of weathered material. The chief result of weathering seems to be to raise the andalusite crystals into relief, in the schist zone, and the aplitic veinlets into relief in the injection zone, and emphasize the bedding by differential weathering in the rocks of the hornfels zone.

The contact of the aureole with the pluton is definite and not infrequently crossed by small apophyses of igneous rock, not more than a few feet in length. The contact of the aureole and the country rock slate is not so definite and is usually characterized by a transition zone one or two hundred feet wide, in which the slate is spotted but is not typical andalusite schist. In some places, as at the eastern end of the aureole, this transition zone is much wider, approaching a maximum width of 4000 feet. The contact between the schist zone and the hornfels zone is likewise a transition in which the rock has some of the characteristics of both zones. In some places this contact is characterized by the occurrence of interbedded andalusite schist and hornfels, probably the result of differences in the character of the original rock which caused different types to be produced under the same metamorphic conditions. The contact is placed at the point where there are equal amounts of the characteristics of both zones. In other words, the contact is drawn at that point where the rock looks just as much like schist as hornfels, or where, in an interbedded series, there are equal amounts of schist and hornfels. The contact between the hornfels and injection hornfels zones is placed at the outer limit (away from the pluton) of the occurrence of aplitic veinlets. None of these contacts is straight or regular on a single outcrop.

Petrography of the Andalusite Schist Zone

Petrographic study shows that the schist zone in the Onawa aureole is similar to previously described occurrences such as the Steiger Schiefer.[8] The chief difference is the absence of a persistent *Knotenschiefer* member in the schist zone at Onawa.

A typical example of the rock of the schist zone is a specimen collected on the Canadian Pacific Railway near the head of Little Greenwood Pond. The rock is very fine grained with a porphyroblastic texture. The constituents in order of decreasing abundance are: quartz, chlorite, chiastolite, biotite, sericite (white mica), graphite (?), and magnetite. Of these minerals only chiastolite and chlorite attain a size of more than 0.1 mm. The quartz, in small, anhedral grains with weakly undulose extinction, with the two micas and the fine-grained chlorite form the groundmass (grundgewebe). Somewhat larger chlorite flakes which attain a maximum size of 0.6 mm. are usually associated with one of the spots of light-colored minerals. These spots are the small knots that appear in the spotted schist in the transition zone between the schist and the slate. They are composed of a poikiloblastic light-colored mineral with an index slightly above Canada balsam. The figure obtained is biaxial with large optic angle and consistently gives a negative sign. It could not be determined to be the acute or obtuse bisectrix. If the negative bisectrix is obtuse, then the mineral is cordierite. The most conspicuous mineral of the rock is the non-pleochroic chiastolite, which attains a maximum size of 1.4 mm. x 2.0 mm. The characteristic crosses are shown in almost every grain by the two trains of very fine flakes of sericite (white mica) which intersect at the center of the crystal. Some of the grains have not developed terminal faces and salient masses of the groundmass are partially surrounded by the chiastolite. The graphite (?) is localized along the outer sides of the crystal.

A specimen from the northeastern slope of Barren Mountain at the contact of the schist and the hornfels shows the interbedded rock types. (Fig. 3.) The schist is like that described above, except that it has no graphite and shows a schistose structure in the groundmass. The contact of the hornfels and schist is sharp and there is no transition in petrographic character between them. The hornfels is a muscovite-biotite-quartz hornfels composed of a fine-grained mass of quartz and biotite with a small amount of muscovite, and the texture is typically hornfelsic. A poorly developed schistose

[8] Rosenbusch, H.: "Die Steiger Schiefer und ihre Contactzone," Abh. Geol. Spezialkarte Elsass Lothr., vol. 1, pp. 80-393, 1877.

structure forms an acute angle to the bedding. This interlamination of metamorphic types has been noted by Grout[9] in certain contact schists from Minnesota where differing schists occur in neighboring laminae. He does not mention schists associated with hornfels in this manner. A similar interdigitating association of different metamorphic rocks is

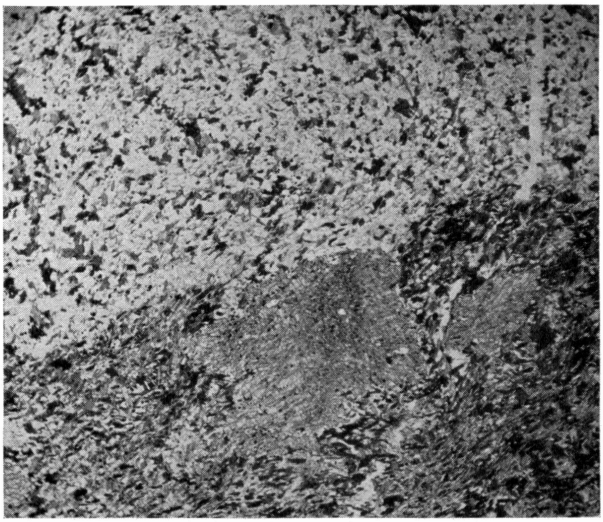


Fig. 3. Photomicrograph of contact of andalusite schist and muscovite-biotite-quartz hornfels. x 27.

reported by Tilley[10] from the Comrie area in Perthshire, where a layer of cordierite hornfels rich in spinel occurs in "sandstone hornfels." Rastall[11] describes another example of this kind of association in the aureole surrounding the Skiddaw granite. Numerous other examples could be cited to show that the amount of diffusion of materials between adjacent strata is extremely minute, if not negligible, in argillaceous and arenaceous sediments under the several grades of thermal metamorphism ranging from low, as in the Skiddaw aureole, to high, as in the Comrie area.

[9] Grout, F. F.: "Contact Metamorphism of the Slates of Minnesota by Granite and by Gabbro Magmas," Bull. Geol. Soc. Am., vol. 44, pp. 1003-1004, 1933.

[10] Tilley, C. E.: "Contact Metamorphism in the Comrie Area," Quart. Journ. Geol. Soc., vol. 80, p. 40, 1924.

[11] Rastall, R. H.: "The Skiddaw Granite and its Metamorphism," Quart. Journ. Geol. Soc., vol. 66, pp. 116-141, 1910.

Petrography of the Hornfels Zone.

The rocks of this zone are separable into two major groups: the true hornfelses and the sericite hornfelses. Examples of each will be described.

A specimen collected on the Canadian Pacific Railway near Little Greenwood Pond is taken as a representative of the true hornfelses. It is an andalusite hornfels that approaches in mineral composition Goldschmidt's[12] lime-free, clay slate hornfelses and also the hornfelses of Grubenmann's[13] field 1. However, it does not fit into either classification because of the apparently low content of lime. The rock is fine grained with a poikiloblastic texture. The constituent minerals in order of decreasing abundance are: quartz, biotite, andalusite, muscovite, perthitic orthoclase, magnetite, and apatite. The andalusite occurs in ragged poikiloblastic prisms up to 4.0 mm. in length, which show marked but spotty pleochroism with X = pale pink, and Y and Z colorless. Inclusions of magnetite, biotite, and quartz are common. The small rounded quartz grains of an average diameter of 0.4 mm. included in the andalusite are probably original detrital grains; but the larger similarly oriented masses of quartz which have a maximum size of 0.6 mm. were probably developed during the metamorphism.

A specimen of tourmaline-bearing andalusite-sericite hornfels from the eastern end of the crest of Barren Mountain is described as an example of sericite hornfels. It has no counterpart in the classifications proposed by Goldschmidt and Grubenmann, owing to the presence of sericite which is not considered by them to be a katazone mineral. Its occurrence, appearance, and constituents, except sericite, define it as a hornfels. The structure of this rock is similar to that of the schists found in the aureole, but the character of its andalusite and its lithology is that of a hornfels. On this basis these somewhat doubtful rocks are classified as hornfels. The rock is fine-grained poikiloblastic with a lepidoblastic groundmass. The minerals in order of decreasing abundance are: sericite, quartz, andalusite, biotite, magnetite, zircon, and tourmaline. The most prominent is andalusite occurring as poikiloblastic grains carrying quartz and biotite and attaining a maximum size of 1.0 mm. x 2.3 mm. The groundmass of the rock is

[12] Goldschmidt, V. M.: "Die Kontaktmetamorphose im Kristianiagebiet," Vidensk. Skr. Bd. 1, pp. 130-154, 1911.

[13] Grubenmann-Niggli: "Die Gesteinsmetamorphose," p. 389, 1924.

formed by the shredded sericite and biotite which envelop the andalusite. Quartz in small grains is not uniformly present but is concentrated locally. Tourmaline occurs sparsely in yellow prismatic grains and is considered to have been introduced in the later stages of metamorphism. A few very small grains of magnetite and zircon are present.

Aberrant types of hornfels appear near Bear Bluff. At the western end of the pluton an apophysis of fine-grained, allotriomorphic, porphyritic granodiorite extends westward into the aureole. Surrounding it except on the northern side is the poorly exposed hornfels zone. The rock here is not typical of the remainder of the hornfels zone, being finer grained, more schistose and yet, megascopically, is not the common schist of the andalusite schist zone. It was mapped as hornfels and placed in the hornfels zone on the basis of its closer resemblance to the hornfels than to the andalusite schist. This deviation from the characteristic lithology of the hornfels zone was considered during the field work and, although later petrographic investigation has shown that it is more schistose than the common hornfels, it seems wiser to consider it part of that zone. Outcrops are infrequent and further field examination would probably yield no more definite information. The rock at the igneous contact is fine grained, possibly somewhat finer grained and more schistose than the typical hornfels, but very similar. At a distance of 100 feet from the contact the rock is fine grained with recognizable crystals of andalusite and with characteristics of both the hornfels and schist zone. At 150 feet from the contact the rock looks like the country rock slate of that vicinity, being blocky, with closely spaced planes of cleavage and occasional, minute, glassy crystals.

Petrographic study shows that this narrow zone at the western end of the Bear Bluff apophysis contains representatives of the hornfels, the andalusite schist and the spotted schist member of the andalusite schist zone, in the order named proceeding outward from the igneous contact. The metamorphic aureole is restricted in extent to 150 feet, but only one member, the injection hornfels, is missing. The metamorphic rock at the igneous contact is a biotite-quartz-sericite schist of lepidoblastic texture and an average grain size of less than 0.03 mm. The constituent minerals in order of decreasing abundance are: sericite (white mica), biotite, and quartz, with some magnetite. Very fine-grained andalusite schist of lepidoblastic texture and an average grain size of less than

0.01 mm. occurs 100 feet from the contact. The constituent minerals in order of decreasing abundance are: biotite, sericite, quartz, andalusite, chlorite, and magnetite. The poikiloblastic grains of andalusite are more readily recognizable under crossed nicols. At the outer margin of the aureole, 150 feet from the igneous contact, the rock is an andalusite schist, with lepidoblastic texture and average grain size of less than 0.07 mm. Its chief distinction from the rock just mentioned is the weaker appearance of the few grains of andalusite which are not readily seen except under crossed nicols and which carry many more inclusions of the groundmass. These andalusite grains are much less developed than those in the common rock of the schist zone. The constituent minerals in order of decreasing abundance are: sericite, quartz, biotite, andalusite, chlorite, and magnetite.

Petrography of the Hornfelses of the Injection Zone.

The rocks of the injection zone are named and described without reference to or consideration of the aplitic veinlets, which are described later. The rocks are named on the basis of their constituent minerals excluding those occurring in, or probably produced by, the aplitic veinlets. Thus a rock composed of andalusite, biotite, quartz, and acid feldspar cut along the bedding planes by quartz-microcline veinlets is not called an andalusite injection gneiss but is called an andalusite hornfels, the discussion of the veinlets being deferred to the general description of the aplitic veinlets.

The several petrographic varieties of hornfels within the injection zone have been grouped into two types and classified first, on the basis of the presence or absence of sericite and second, on the character of the most prominent mineral or minerals. This continues the classification used in discussing the rocks of the normal hornfels zone. There is no definite system in the distribution of these several types, either radially from the contact, or laterally around the pluton. The normal, non-sericitic hornfels is the characteristic rock of this zone.

The True or Non-Sericitic Hornfels.

The true hornfelses are characterized by four minerals: quartz, potash feldspar, biotite, and muscovite, which are almost always present in the rock. Of the eighteen specimens examined potash feldspar and biotite occur in all; quartz is lacking in four, and muscovite in only one. The accessory minerals are: magnetite, which occurs in all the specimens; apatite, in six; and zircon, in three. Besides these essential minerals there occur in varying amounts and combinations five other minerals which, by their presence singly or in combination, determine the name of the rock. These minerals in order of decreasing number of occurrences are: andalusite, tourmaline, cordierite, acid plagioclase, and sillimanite (variety fibrolite).

Types of true hornfels.

1. Andalusite hornfels.
   a. Sillimanitic tourmaline-bearing andalusite hornfels.
   b. Tourmaline-bearing andalusite hornfels.
2. Cordierite-andalusite hornfels.
   a. Sillimanite-bearing cordierite-andalusite hornfels.
   b. Tourmaline-bearing cordierite-andalusite hornfels.
3. Tourmaline-bearing cordierite-quartz hornfels.
4. Biotite-potash feldspar hornfels.
5. Orthoclase-quartz hornfels.
   a. Tourmaline-bearing orthoclase-quartz hornfels.

The groups of true hornfelses contain representatives of some of the classes described by Goldschmidt from the Kristianiagebiet. The classes represented are all characterized by high alumina and low lime. They belong either to the silica-rich lime-free "Tonschieferhornfelse" or to classes 1 and 2 of the "Tonschiefer-Mergelschiefer-Hornfelse."[14] These hornfelses fall in field 1 in the triangular diagram of Grubenmann,[15] in which the three end members are sillimanite or andalusite, orthaugite, and wollastonite. The presence of tourmaline in several types may be sufficient to exclude them from these classifications if it is considered to be the result of the recrystallization of the original sedimentary constituents. If, however, the tourmaline was developed as a result of pneumatolytic action following the recrystallization, then all of the true or non-sericitic hornfelses fall in field 1. This latter seems to be more in keeping with the usual occurrences of tourmaline and, hence it will be considered that the true hornfelses of the injection zone of the Onawa aureole fall in field 1.

[14] Goldschmidt, V. M.: op. cit., pp. 133-154.
[15] Grubenmann-Niggli: op. cit., p. 389.

1. Andalusite Hornfels. This type of hornfels is one of the "border types" of Grubenmann's field 1.[16] It corresponds to a cordierite-free member of Goldschmidt's[17] silica-rich lime-free "Tonschieferhornfelse." The chief mineral constituents in order of decreasing abundance are: quartz, potash feldspar (microcline, perthitic orthoclase, and orthoclase), biotite, andalusite, and muscovite with accessory magnetite and apatite. In some slides biotite is more abundant than potash feldspar and muscovite more than andalusite. The rocks are fine grained with an average grain size of about 0.1 mm. The hornfels texture is not present in all the specimens, some of them showing lepidoblastic or inequigranular granoblastic textures. The biotite is common as ragged flakes of a maximum size of 0.6 mm., richly pleochroic in straw to reddish brown colors, and containing many minute inclusions surrounded by pleochroic halos. Andalusite is sparse as prismatic grains, less than 0.3 mm. in size, which show only faint pleochroism.

1. a. Sillimanitic Tourmaline-bearing Andalusite Hornfels. This type of hornfels is represented by two specimens in the injection zone. It is not a true hornfels type in the sense used by Goldschmidt or Grubenmann or any of the other writers on the hornfels classes, but is rather a transition rock between the andalusite hornfels and the sillimanite hornfels. The presence of the tourmaline is probably the result of pneumatolytic action and hence does not seriously affect the assignment of the rock to the hornfels series. However, it does not seem wise to try to warp this type into one of the classes suggested by Goldschmidt except to suggest that it would fall in the general group of the andalusite hornfelses were it not for the presence of sillimanite. The rock is fine grained with the typical hornfels texture and carries several poikiloblastic grains of andalusite. The minerals in order of decreasing abundance are: quartz, microcline, orthoclase, biotite, andalusite, muscovite, tourmaline, and magnetite. All minerals except the andalusite have the usual characteristics common to these rocks. The andalusite is generally rimmed by a thin bundle of fibers of sillimanite which extend into the neighboring quartz grains and tend to give added relief to the andalusite grains. The tourmaline is ragged and dichroic with "E" colorless and "O" slightly greenish golden yellow.

[16] Op. cit., p. 389.
[17] Op. cit., p. 133.

1. b. Tourmaline-bearing Andalusite Hornfels. The rocks of this type differ from andalusite hornfels only in the presence of a few grains of tourmaline, without which the rock would be a true andalusite hornfels. They are fine grained with a typical hornfels texture, and contain in order of decreasing abundance: quartz, biotite, potash feldspar (orthoclase, perthitic orthoclase, and microcline), andalusite, muscovite, tourmaline, magnetite, acid plagioclase, and zircon. The average grain size is less than 0.4 mm. Andalusite in poikiloblastic prisms is the most prominent mineral, attaining a maximum size of 3.0 mm. The tourmaline commonly occurs as ragged to round grains occasionally over 2.0 mm. in size.

2. Cordierite-Andalusite Hornfels. Only one specimen of this type of hornfels was found in the injection zone. It has all of the properties and characteristics of the andalusite hornfels but differs in the addition of cordierite. It belongs to class 1 of Goldschmidt's "Tonschiefer-Mergelschiefer-Hornfelse"[18] of the Kristianiagebiet. It is the general type of Grubenmann's field 1.[19] In one specimen a thin rim of sillimanite in the form of fibrolite surrounds some grains of andalusite. This is the only distinction between sillimanite-bearing cordierite-andalusite hornfels and cordierite-andalusite hornfels. Since there is no recognized chemical difference in composition, the sillimanite-bearing variety is included with the true cordierite-andalusite hornfels. It does not, however, fit into any class of the well-known systems of the European writers. The tourmaline-bearing variety differs only in the presence of subhedral poikiloblastic tourmaline which is considered to be the result of later pneumatolytic action and this type is therefore grouped with the cordierite-andalusite hornfelses, although it has had no place in the standard classifications.

Lacroix[20] describes a leptynolite from the vicinity of Fontrabiouse in the Pyrenees which is mineralogically similar to the cordierite-andalusite hornfels of the Onawa region but carries both sillimanite and tourmaline. Bosworth[21] reports a similar rock, but lacking tourmaline, near the contact of the Ross of Mull granite. Both of these rocks are considerably coarser in grain and are characterized primarily by large

[18] Goldschmidt, V. M.: op. cit., p. 140.

[19] Grubenmann-Niggli: op. cit., p. 389.

[20] Lacroix, A.: "Le Granite des Pyrenees et ses Phenomenes de Contact," Bull. Serv. Carte Geol. France, 71, p. 5, 1900.

[21] Bosworth, T. O.: "Metamorphism around the Ross of Mull Granite," Quart. Jour. Geol. Soc. 66, pp. 380-385, 1910.

prisms of sillimanite, up to several centimeters long, instead of minute needles of fibrolite such as occur in the Onawa rocks.

The rock from Onawa aureole is fine grained and has the typical hornfels texture. The constituents in order of decreasing abundance are: quartz, potash feldspar, cordierite, biotite, andalusite, muscovite, acid plagioclase, and magnetite. Cyclic twinning is common in the cordierite and both the biotite and faintly pleochroic andalusite reach a size of over 2.5 mm.

3. Tourmaline-bearing Cordierite-Quartz Hornfels. This type of hornfels was found in the injection zone at only one locality, about 600 feet northwest of the summit of Third Mountain. It does not fit into any of the accepted classes of hornfels. The presence of tourmaline is one cause, but the association of cordierite and orthoclase without either plagioclase or andalusite throw it out of Grubenmann's field 1 and, also, eliminate it from any of Goldschmidt's classes. Tilley,[22] however, has described a hornfels from the Comrie area, Perthshire, which is similar to this but lacks muscovite and apatite, as well as tourmaline, and carries pyrite. He places it in "class 1, Mg. 1: (a)" as a biotite-rich type.

This rock is fine grained with the typical hornfels texture. The constituent minerals in order of decreasing abundance are: cordierite, orthoclase, biotite, muscovite, tourmaline, and accessory magnetite and apatite. Cordierite occurs as small cyclic twins with anhedral outline and attains a maximum size of less than 0.3 mm. The orthoclase, which is commonly perthitic, is slightly larger, occurring up to 0.4 mm. in size. These two minerals form the major part of the rock. Biotite occurs in ragged flakes up to 0.3 mm. in size, carrying many, small grains of magnetite, and is spotted with pleochroic halos about very minute inclusions. The muscovite is generally in larger flakes of a maximum size of about 0.4 mm. A few small poikilitic grains of tourmaline, dichroic from colorless to greenish yellow, are also present. The chief accessory mineral is magnetite in very small grains. Apatite is subhedral.

4. Biotite-Potash Feldspar Hornfels. This type of hornfels is represented by only one specimen, which occurs at an elevation of 2000 feet on the eastern face of the southern spur of Barren Mountain. The rock is similar in appearance to the other types of hornfels, but mineralogically it is different in that it lacks both cordierite and andalusite. It does not corre-

[22] Tilley, C. E.: "Contact Metamorphism in the Comrie Area," Quart. Jour. Geol. Soc., vol. 80, p. 36, 1924.

spond mineralogically to the plagioclase-biotite hornfels of Goldschmidt's class 3 due to the low content of plagioclase and the high content of orthoclase and microcline. Similarly, because of the lack of andalusite and cordierite, it does not fall in field 1 of Grubenmann nor in any of the other fields of his triangle.

The rock is fine-grained granoblastic. The constituent minerals in order of decreasing abundance are: microcline, biotite, orthoclase, quartz, plagioclase, and muscovite. Subhedral microcline grains, cut at random by flakes of biotite, carry inclusions of small rounded quartz grains and shreds of muscovite. The average size is about 0.4 mm., but one Carlsbad twin showing indistinct microcline twinning attains a size of 2.6 mm. x 4.6 mm. A few small masses of myrmekite are located along the boundaries of the microcline grains. The ragged flakes of strongly pleochroic biotite containing a few pleochroic halos have an average size of about 0.5 mm. Andesine occurs in small albite-twinned individuals.

5. Orthoclase-Quartz Hornfels. The quartz hornfelses are characterized by abundant quartz and a lack of cordierite and andalusite. They differ from the sericite-quartz hornfelses in lacking sericite and having muscovite as the colorless mica. The rock may carry tourmaline. The texture is fine-grained granoblastic. The constituent minerals in the average order of decreasing abundance are: quartz, orthoclase, biotite, acid plagioclase, muscovite, tourmaline, magnetite, apatite, spinel (?), and zircon. Quartz and orthoclase form the greater part of the rock, occurring as small, anhedral grains. The other minerals require no description, occurring in the character common to this suite of metamorphic rocks. The tourmaline in one specimen is probably the result of pneumatolytic action and is not due to an original chemical difference in the sediment.

Sericitic Hornfelses.

The presence of sericite in these rocks would seem to be somewhat inconsistent with the usual constituents of a hornfels and would also suggest that the rock is not a hornfels. The occurrence and appearance, however, of these rocks are those of hornfels. Of the four specimens of this group, three were collected within 15 feet of the contact of the pluton and the fourth at a distance of about 100 feet. All were well within the injection zone and some distance from the hornfels zone. In only two specimens do the typical minerals of the injection zone occur, and with them is associated sericite.

1. Sericite-Quartz Hornfels. The sericite hornfelses are divided into two groups, sericite-quartz hornfels and sericite hornfels. In the first group the notable lack of the metamorphic minerals that characterize the hornfelses of the injection zone may be due to various factors. They may have been produced by the metamorphism of sediments that were richer in silica and lower in alumina than the average sediments of the zone. They may represent a lower degree of metamorphism in which sericite was stable. The latter explanation seems unlikely, since all the specimens were collected close to the intrusive. One, in particular, collected 2 feet from the igneous contact on Benson Mountain, is associated with adjacent bands of cordierite-biotite-sericite hornfels and sericite-quartz hornfels. This shows that the metamorphic conditions were intense enough to produce cordierite and, hence, it seems more likely that these sericite-quartz hornfelses owe their present mineral composition to the original chemical content of the sediments from which they are derived. These rocks do not have a mineral assemblage that corresponds to any found in either of the classifications proposed by Goldschmidt or Grubenmann.

A specimen of sericite-quartz hornfels was collected at the igneous contact on the small hill northeast of Greenwood Mountain. It is fine grained with a granoblastic texture. The constituent minerals in order of decreasing abundance are: quartz, muscovite (sericite), biotite, plagioclase, and accessory magnetite, apatite, and zircon. The quartz grains are round and irregular in shape, showing slightly undulose extinction. Throughout this rock are very fibrous and ragged masses of sericite with an average diameter of about 0.3 mm. Some of these seem to be original muscovite of larger flakes, but most of them consist of common sericite. Some are similarly oriented and give a negative figure over an eye, but most of them are fibrous with random orientation. Biotite, in flakes about 0.3 mm. in size, shows transitions into sericite aggregates and, also, local and subordinate alteration into chlorite. Very fine magnetite grains are commonly included in the biotite. Plagioclase, oligoclase (?), is occasionally twinned on the albite-Carsbad law and is not uncommonly zoned.

A specimen from near the summit of Benson Mountain differs from the rock just described in having a few grains of cyclic twinned cordierite and small occasionally Carlsbad twinned grains of perthitic orthoclase.

2. Sericite Hornfels. The second group of the sericitic hornfelses is represented by a specimen of sillimanite-bearing andalusite-chlorite-sericite hornfels from the southern spur of Barren Mountain about 100 feet above the igneous contact. In this case the stability of sericite at high temperatures is clearly demonstrated, since it is co-existent with sillimanite. It would seem, therefore, that the absence of the common suite metamorphic minerals in its full development and the presence of chlorite and sericite in this rock were the result of the inherent pre-metamorphic chemical characteristics, and not the result of local variations in the metamorphic conditions. The rock is fine-grained porphyroblastic with a lepidoblastic groundmass. The constituent minerals in order of decreasing abundance are: chlorite, quartz, sericite, andalusite, apatite, magnetite, and sillimanite (fibrolite). It is composed mainly of chlorite and sericite with porphyroblastic grains of nonpleochroic andalusite. These attain a maximum size of 0.6 mm. and are surrounded partially by a thin rim of fine fibers of sillimanite which penetrate the adjacent quartz. The chlorite has been derived in part from biotite.

Aplitic Veinlets.

The aplitic veinlets of the injection zone constitute one of the dominant characteristics of the Onawa aureole. Their prevalence throughout this zone and their conspicuousness stamp them as the diagnostic features of the inner zone. These veinlets occur in different modes with respect to the pre-metamorphic characteristics of the rock and with different petrographic compositions.

Types of Occurrence of the Aplitic Veinlets.

The following classification is proposed in an effort to simplify the discussion of the aplitic veinlets. It is a geometrical classification from which a genetic classification will be drawn.

I. Lit-par-lit.
   a. Single injection.
   b. Multiple injection.
      1. Without modification of form of earlier unit.
      2. With ptygmatic folding of earlier unit.
      3. Brecciated lit-par-lit injection hornfels in aplitic matrix.

II. Random injection.

Lit-par-lit injection occurs at many places in the injection zone where its occurrence is controlled by the original character of the rock and by the degree and character of its metamorphism. If pre-injection planes of weakness, such as bedding, cleavage, or schistosity, were well preserved, then the aplitic veinlets entered along such planes. These planes of weakness, in some places, were not preserved during the metamorphism due to the extensive recrystallization of the rock. It is proposed to divide the lit-par-lit injections into two classes: single injection and multiple injection.

Single injection is defined as injection limited to one set of planes of weakness with no other associated injection or series of injections. This type is the limiting case of the group of systematic lit-par-lit injections. It is well shown at an elevation of about 1980 feet on the southern slope of the southern spur of Boarstone Mountain, where thin stringers of aplitic material follow the bedding planes in the injection hornfels.

Multiple injection is defined as that type of injection in which there are at least two series of geometrically different injections. It is far more common than single injection; furthermore, it is more varied, since there are three distinct varieties of multiple injection which are distinguished on the basis of the modification of the form of the first unit of the injection series.

The first variety is termed multiple injection without modification of form of the earlier unit. The earlier unit is not definitely determined as a lit-par-lit injection in all examples, but since the lit-par-lit unit can be shown definitely to be the earlier in many cases it is probably the earlier injection in all. Two subvarieties will be mentioned: the first and simplest is that in which the aplitic injections are not displaced at their intersection; and the second and more common is that in which the lit-par-lit unit is displaced at the intersection.

The first subvariety is nicely exposed at the "Ledges" at an elevation of 1250 feet on the trail from Big Houston Pond to East Chairback Pond. There are three sets of aplitic veinlets. The first of these is composed of thick branching dikes up to six inches thick which parallel the schistosity and, also, cut it to join other thinner dikelets or veinlets of the same generation. The second set differs from the first only in thickness and is composed of thin dikelets that parallel the schistosity as branches of the thicker dikes of the first set. The third set is composed of small cross joint veinlets which cut the branching veinlets of the first and second sets but not the thicker dikes of the first set.

The second subvariety, in which displacement of the earlier unit occurs, is exposed on the southern side of Boarstone Mountain where, due to differences in color between the several beds involved and the aplitic veinlets, the displacement is easily seen (Fig. 4). The aplitic veinlets are easily separable into

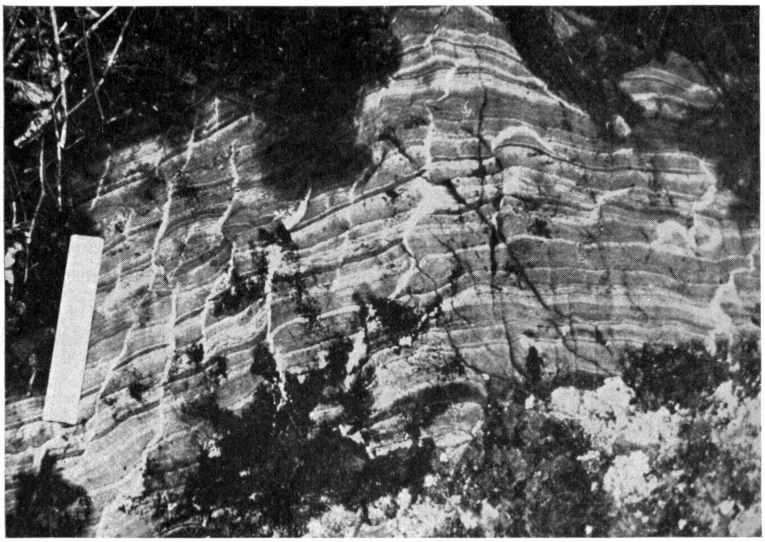


Fig. 4. Multiple injection: lit-par-lit veinlets offset by later aplitic veinlets. Scale is 7.35 inches long.

two sets: the first is the lit-par-lit set following the bedding which is apparently dipping to the left; the second set is localized in irregular lines that cross the first set. The thin dark beds enable one to recognize the displacement along the lines of the later veinlets. The veinlets are characteristically white in color. Another and slightly more complex example of this subvariety is well exposed at the cairn on Third Mountain about 600 feet northwest of the summit.

The second variety of multiple injection is termed multiple injection with ptygmatic folding of the earlier unit. The later unit in this case usually occupies a more or less simple fracture. The ptygmatically folded aplitic veinlets may or may not be offset along the lines of injection of the later unit. In some cases the folding of the earlier unit is so intense that it is impossible to determine whether there has been any displacement.

The best example of this variety of injection is exposed on the western peak of Boarstone Mountain (Fig. 5). The ptygmatic folds are small, intricate convolutions of the earlier, lit-par-lit (?) aplitic veinlets; the distance between crests of these

Fig. 5. Multiple injection with ptygmatically folded lit-par-lit veinlets. Scale is 7.35 inches long.

folds is of the order of half an inch or less. The later unit is represented by a more or less straight fracture along which displacements can be discerned occasionally. Another example of this variety of injection is found at the contact of the Onawa intrusive at the foot of the cliff on the eastern side of Boarstone Mountain. Here the aplitic veinlets of the earlier unit are so intensely contorted that it is impossible to recognize any offsetting along the cross-cutting veinlets.

The third variety is termed multiple injection: brecciated lit-par-lit injection hornfels in aplitic matrix. This variety consists of fragments of lit-par-lit injected rock, which are not similarly oriented with respect to the lit-par-lit veinlets, in a matrix of aplitic material. The injection hornfels of this character occurs on the western peak of Boarstone Mountain but its greatest development is on the face of the cliff on the eastern side. The simplest example (Fig. 6) occurs on the western peak. The fragments are almost all sub-parallelly oriented but a few cut the general trend of the lit-par-lit veinlets; the aplitic veinlets of the later unit branch and join but follow no definite system.

Fig. 6. Multiple injection: brecciated lit-par-lit injection hornfels in aplitic matric. Scale is 7.35 inches long.

Several more complex examples of this variety of injection are well shown on the cliff on the eastern side of Boarstone. The brecciation has been more intense, so that the rock gives the appearance of having been masticated. The matrix aplite is coarser and more resistant to weathering than the aplitic material of the lit-par-lit veinlets, or the remnants of the original country rock. The fragments, however, do not all weather in depression but some protrude above the general surface of the rock. This variety of injection occurs also near the crest of Chairback Mountain.

Random injection is that type of injection in which the aplitic veinlets show no system with respect to any discernable characteristic of the enclosing rock. Random injection is the most common mode of occurrence of the aplitic veinlets; it is the general case. This form of injection is limited to rock in which there was no remnant of pre-intrusive lines of weakness along which the aplitic material could be injected. The best examples of this type are on the summit of the eastern peak of Boarstone Mountain (Fig. 7). Thin, aplitic veinlets, generally less than a quarter of an inch thick, cut through the

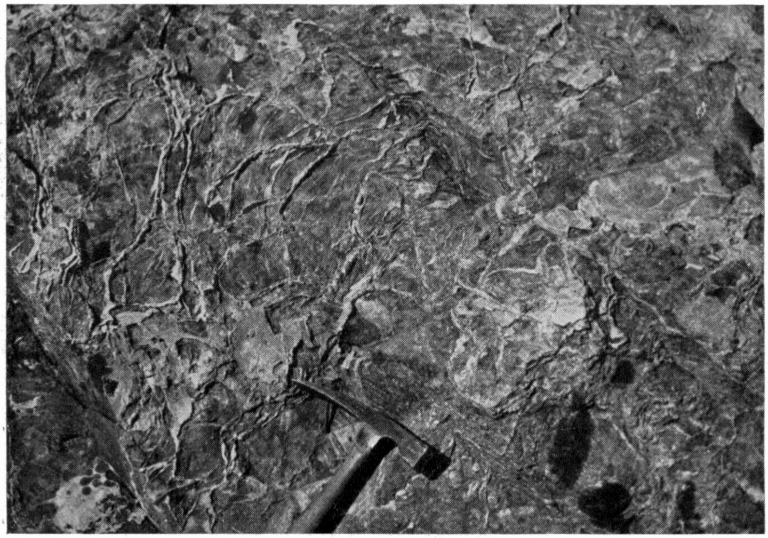


Fig. 7. Random injection.

rock, branching and joining and rebranching to give an intricate network of veining. Where the rock has exfoliated so as to reveal the plane of a veinlet, areas of white aplite appear, but this is comparatively rare.

Injection of aplitic veinlets by igneous masses in the process of contact metamorphism has been reported from many localities.[23] It is beyond the scope of this paper to review these occurrences except to mention briefly a few that are generally similar to the Onawa aureole.

[23] For a brief review of the geology of these occurrences the reader is referred to Grubenmann-Niggli, 'Die Gesteinsmetamorphose I," pp. 322-367, 1924.

The impregnation of pelitic gneisses by the Ross of Mull granite has been described by Bosworth[24] and subdivided into four classes according to the structural features that determined the course of the penetrating magma. He reports irregular veins and stringers: injections along bedding, injections along strain slips, and injection along foliation. The injection system in the Onawa aureole corresponds closely to this but has no member comparable to "injection along strain slips." All of the Ross of Mull features are of a larger scale and the injected rock is more granitic and less aplitic.

Lacroix reports a fairly well-developed zone of injection schists[25] in his description of the contact metamorphism of certain Paleozoic schists in the Pyrenees, in which is found single injection[26] of granite along the foliation of the schists. These aplitic veins differ somewhat mineralogically from those of the Onawa aureole in carrying small amounts of green amphibole and pyroxene.[27]

Brecciation of country rock near the contact of an intrusive has been described from numerous localities and in most places it seems to have been more intense than that which occurred in the Onawa region. However, the brecciated hornfels that Grout[28] reports near the contact of the Rove slate with the Duluth gabbro and a specimen of which the writer has seen is almost identical with that on Boarstone Mountain.

Petrography and Order of Injection of the Aplitic Veinlets.

The somewhat complex geometrical classification of the modes of occurrence of the aplitic veinlets is borne out in part by the petrographic differences between the types of veinlets. There are several types which in some cases are shown together in a single thin section; and from the relationships thus found or by comparison of thin sections of a megascopically determined, consecutive series of aplitic veinlets it has been possible to derive a tentative system of injection based on geologic and petrographic criteria.

[24] Bosworth, T. O.: op. cit., pp. 380-385.
[25] Lacroix, A.: "Le Granite des Pyrenees et ses Phenomenes de Contact," Bull. Serv. Carte Geol. France 64, p. 49, 1898.
[26] Lacroix, A.: op. cit., p. 9.
[27] Lacroix, A.: op. cit., pp. 31-32.
[28] Grout, Frank F.: op. cit., p. 1010.

Order of injection of aplitic veinlets.

1. Veinlets composed of quartz and perthitic orthoclase.
2. Veinlets composed of quartz, perthitic orthoclase, microcline, biotite, muscovite and accessories. With or without: andalusite, acid plagioclase, tourmaline.
3. Veinlets composed of quartz, biotite, perthitic orthoclase, sillimanite, and accessories. With or without: andalusite, tourmaline.
4. Unplaced veinlets.

1. Quartz and perthitic orthoclase veinlets. This type is represented by only one specimen, from the eastern side of Boarstone Mountain. The thin section shows veinlets of three types corresponding to three injections. The first injection, shown as such by the fact that the other injections cut it, is composed of quartz and perthitic orthoclase which form a fine-grained mosaic of an average grain size of less than 0.2 mm. It occurs in parallel bands interdigitating between bands of biotite, quartz, perthitic orthoclase, and andalusite, the remnants of the pre-injection metamorphosed sediment. This type of veinlet is lit-par-lit and occurs in the variety of multiple injection: brecciated lit-par-lit injection hornfels in aplitic matrix.

2. Veinlets composed of quartz, perthitic orthoclase, microcline, biotite, muscovite and accessories. With or without: andalusite, acid plagioclase, tourmaline. This is the most abundant petrographic type of the aplitic veinlets, being found in eleven thin sections. The texture is aplitic and the average grain size is about 0.3 mm. Quartz and potash feldspar are dominant, with varying amounts of other minerals and accessories such as magnetite, apatite, and, occasionally, zircon. This type is the common aplitic veinlet that occurs in all forms of injection except as the matrix in the brecciated variety of multiple injection.

3. Veinlets composed of quartz, biotite, perthitic orthoclase, sillimanite, and accessories. With or without: andalusite, tourmaline. The thin section which carried the single veinlets of petrographic type 1 contains also two other veinlets. Types 2 and 3 cut 1 but are parallel to each other. No cross-cutting relationships are possible between 2 and 3, but in type 2 occur thin lines and spots of a lemon-yellow color which the writer believes to be related in point of time to similar spots and lines which occur in type 3 and which seem to be genetically related

to type 3. This type of veinlet differs in microscopic appearance from either of the previously described types. The appearance is more that of a vein system filled with fibrous material, so fine as to be almost irresolvable with a magnification of 372 diameters. From these veins, fine fibers of sillimanite (fibrolite) (Fig. 8) extend into ellipsoidal grains of quartz and potash feldspar, usually orthoclase. Flakes of biotite occur within or at the edges of the vein systems. The

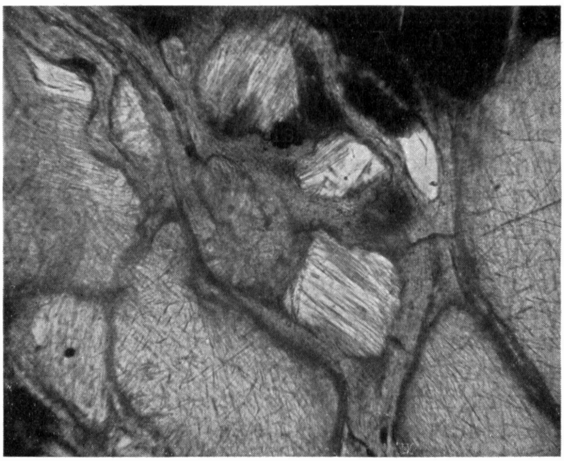


Fig. 8. Fibrolite needles penetrating quartz. x 170. Eastern cliff of Boarstone Mountain.

biotite is spotted and pleochroic in shades of orange; from it extend fibers of sillimanite. Tourmaline and andalusite occurring in these veins are similarly surrounded by sillimanite. The maximum thickness of veinlets of this type is about one inch. They form the matrix in the variety of multiple injection in which the earlier unit has been brecciated; and, also, occur as random injection veinlets.

4. Unplaced Veinlets. Some veinlets cannot be placed in the above system due to the lack of comparative data. In the unplaced veinlets there are two groups: those which are similar in texture and form to those classified above; and those which are characterized by the effect they have produced on the wall rock. The first type is composed of fine-grained sutured quartz and muscovite and occurs close to the igneous contact near the summit of Benson Mountain. The second type is

termed pseudo-aplitic, since megascopically it is like those previously described but microscopically its composition is seen to be distinctly different, being composed of an isotropic indeterminate substance which is probably an alteration product of some mineral of the country rock.

Two specimens of pseudo-aplitic veinlets were collected. The first occurs at the foot of the eastern cliff of Boarstone Mountain and cuts the ptygmatically folded veinlets of petrographic Type 2. It is shown in Fig. 8. The veinlet is composed of a yellow anisotropic substance with index of refraction less than 1.60. Associated with the veinlet is a lemon-yellow mineral with index between 1.58 and 1.59 and double refraction of less than 0.010. It is non-pleochroic and has optical anomalies. It is similar to antigorite but its index is too low and has a somewhat smaller, negative acute bisectrix.

The other veinlet occurs at the cairn 600 feet north of the summit of Third Mountain. It is composed of transverse fibers and in the center of the veinlet is an isotropic alteration (?) of biotite which is characterized by a decreased intensity of pleochroism and opening of the cleavage planes. There is, also, a brown ragged isotropic mineral with an index of refraction above that of the biotites. It is a granular aggregate, apparently related to the bleached biotite, adjoining and cut by the veinlet. Quartz forms part of the veinlet and extinguishes parallel with the bleached biotite.

Andalusite in the Aureole.

To determine more exactly the nature and, if possible, to make a quantitative determination of the degree of metamorphism of the three zones of the aureole, partial mineralogical analyses were made of over 40 specimens of rock from different localities. Andalusite was used as the key for this, since it is well distributed throughout the three zones. The results of this analysis are shown in the accompanying graphs (Figs. 9 and 10). Six suites of specimens were selected from those collected in the field to give six cross-sections of the aureole: one from each end and two from both the northern and southern sides. These suites are a series of rocks collected from the following mountains: Boarstone, Barren, Columbus, Houston, Roaring Brook, and Benson Mountains.

The specimens were crushed in a No. 1 Simplex Ore Crusher, manufactured by F. W. Braun of Los Angeles and San Francisco, to reduce as much of the specimen as possible to fine grain size. Further crushing was accomplished with an iron mortar and pestle. It was then sieved and the material passed by a No. 65 Taylor Standard sieve with an opening of 0.208 mm. and retained by a No. 120 U. S. Standard sieve with a nominal opening of 0.125 mm. was collected. As a result of the crushing and screening, the rock was reduced to a powder theoretically consisting of the several minerals in discrete grains, since the grain size of the powder was between

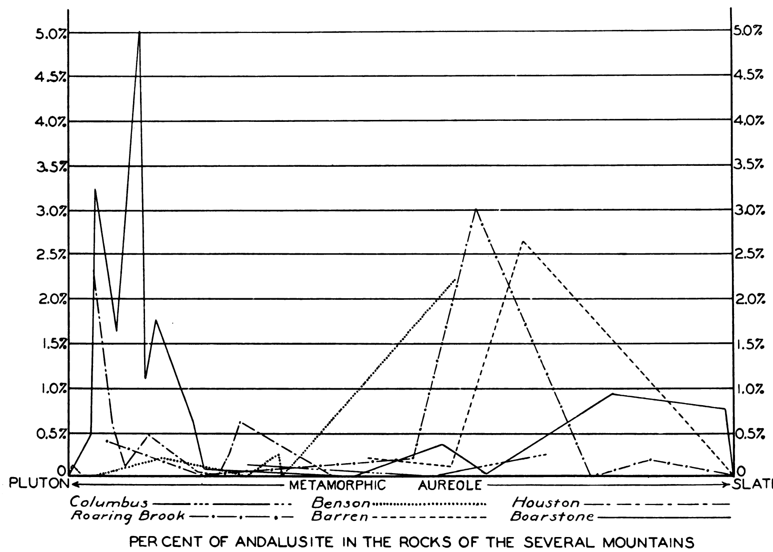
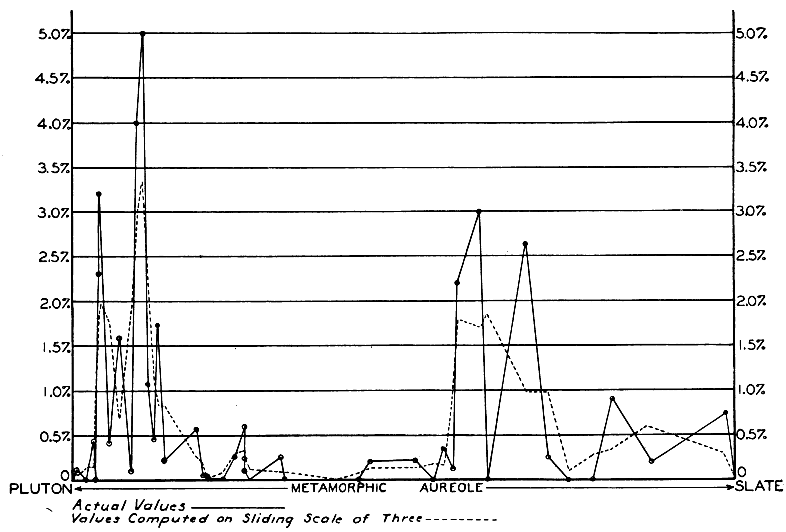


Fig. 9.

0.208 mm. and 0.125 mm., which is slightly smaller than the average grain size of these rocks as shown in the thin sections. The andalusite was then separated by means of bromoform having a gravity of 2.82. It was found that the gravity of the biotite was such that it sank in the liquid and masked the andalusite. To prevent this the specimens were treated before separation with concentrated sulphuric acid and heated for 24 hours, during which the biotite was decomposed and later was removed by washing. After separation, the andalusite was weighed and checked for impurities by petrographic examination. Separation was clean and no andalusite was ever found in the light residues.

To show the distribution of andalusite in the aureole, the samples were plotted on graphs (Fig. 9 and Fig. 10) in which the ordinate represents the percentage by weight of andalusite and the abscissa represents the relative distance of the place of occurrence of the sample from the boundaries of the aureole, the intrusive, and the slate. The distribution of andalusite in the individual mountains as determined by the analyses of samples from these mountains is shown by lines of different



COMPOSITE ANDALUSITE PERCENTAGE OF THE AUREOLE

Fig. 10.

character, as noted in the legend. Inspection of Fig. 9 shows that the largest amount of andalusite in the rocks of Columbus, Roaring Brook, Benson, and Barren Mountains occurs in the outer third of the aureole—in the andalusite schist zone near its contact with the hornfels zone. Boarstone Mountain shows almost one percent in this same zone, but Houston Mountain carries apparently none. In the middle of the aureole, in the hornfels zone, Houston is the only mountain to carry over one-half percent. But in the injection zone in the inner part of the aureole both Boarstone and Houston exceed two percent. In Fig. 10 all of the analyses have been plotted as in the preceding one, but they are considered together as if they were members of the same cross-section series. The dashed line derived from the actual values by means of a sliding scale of three intensifies the general character of the graph and shows two prominent maxima: one occurring in the andalusite schist zone in the outer third, and the other near the contact of the pluton in the injection zone. It shows also the very small amount of andalusite found anywhere in the hornfels zone. These two maxima correspond to the two generations of andalusite mentioned by Harker:[29] the low grade andalusite of the schist and the medium grade andalusite of the injection zone.

The individual series of analyses were plotted areally on the geologic map with the abscissa of each equal in scale to the width of the aureole at the location of the cross-section. Comparison of the structural trend lines with the positions of the individual maxima shows that there is no recognizable, direct common relationship between the several maxima, either individually or generally, and the geologic structure.

Structure.

Horizon markers and persistent stratigraphic units are as yet unrecognized in the slate series of central Maine. In the course of this investigation no bed or group of beds could be correlated from one part of the area to any other part; the maximum distance that any unit could be traced was less than a quarter of a mile. Under such conditions, and with little previous published work available, the writer was forced to use the attitudes of random, un-correlated exposures in studying the structure of the region.

The slate belt attains a width of outcrop of over 15 miles, throughout which the common dip is steep but not consistent in direction; the strike ranges from northeast to east and, in places, slightly north of west. No major faulting is evident but occasional minor cross faults striking generally north show that there has been some dislocation in the region. These few data suggest strongly that the slate formation is compressed into a series of tight folds, the axes of which trend generally eastward.

In the immediate vicinity of the Onawa pluton the structural lines are somewhat distorted and the usual tight folding is broken by more open structures. These trend lines, as

[29] Harker, A.: "Metamorphism," London, p. 56, 1932.

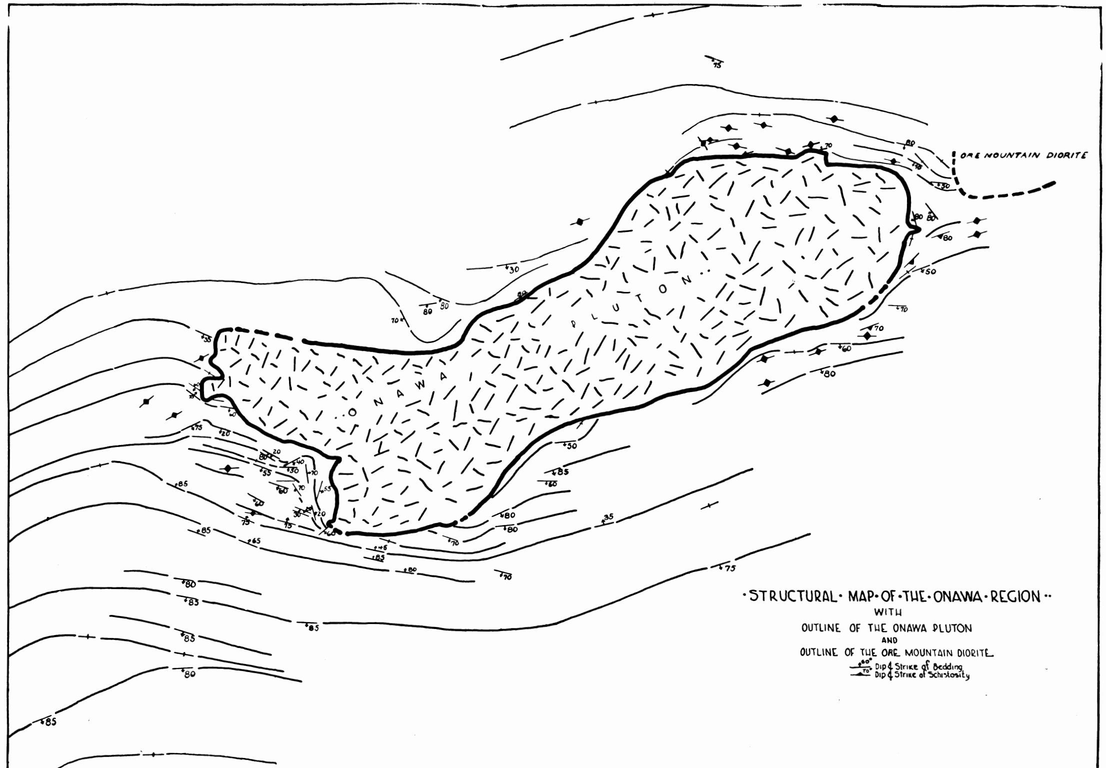

ORE MOUNTAIN DIORITE
ONAWA PLUTON
·STRUCTURAL· MAP·OF·THE·ONAWA·REGION··
WITH
OUTLINE OF THE ONAWA PLUTON
AND
OUTLINE OF THE ORE MOUNTAIN DIORITE
Dip & Strike of Bedding
Dip & Strike of Schistosity

Fig. 11.

shown in Fig. 11, tend to follow the outline of the pluton but locally, as at the northwestern end, abut against it. From this figure it can be seen that the pluton is essentially concordant to the structure of the country rock. The pluton is not exposed sufficiently to permit determination of its interior structure. However, in the eastern part there is vertical flow banding, striking east, accompanied by inclusions oriented vertically, but not horizontally. In the western part the rock shows sporadic inclusions but no flow structure. The relation of the Onawa pluton to the regional and local structure is much like that of a large, somewhat ellipsoidal eye of feldspar in a strongly foliated augen gneiss.

CONCLUSIONS.

1. The rocks of the Onawa region were folded sometime during the early Devonian.
2. The Onawa pluton was formed probably during the late Devonian by the intrusion of a quartz-rich subalkaline intermediate magma along a line of structural weakness parallel to the trend lines in the slate. There was minor concomitant folding at the ends of the pluton and subordinate stoping and assimilation. Differentiation occurred with production of a basic border.
3. Metamorphism of the slate series was begun during the intrusion of the pluton and continued throughout the associated igneous activities during which intermediate dikes were intruded into the sediments accompanied or followed by the injection of numerous aplitic veinlets of several compositions and in at least three stages.
4. Acid dikes with assimilated aluminous material were next intruded.
5. Quartz veins carrying black tourmaline are the last phase in the igneous history. Probably associated with them is the wide-spread but not intense development of tourmaline in the metamorphic aureole.
6. The degree and character of the metamorphism was independent of the type of equigranular holocrystalline igneous rock at the contact of the pluton but was much less intense in the vicinity of an apophysis of porphyritic microcrystalline igneous rock. Both intensity and character produced were governed by the conditions of crystallization of the igneous rock; this may be expressed in an analogy between the results

of storms in an open body of water as compared to those in a connected but sheltered estuary of that body.

7. The aplitic veinlets show in their modes of occurrence certain features that suggest that the rock reached a semi-molten condition. Ptygmatic folding of the veinlets occurs locally in the injection zone, but is not a wide-spread phenomenon. Following Sederholm,[30] the writer thinks that after the injection of the aplitic veinlets the rock reached a semi-molten condition during which time the somewhat fluidal motion of the rock was recorded in the folded veinlets. It does not seem valid to assume that the folding was produced by minor slippage along numerous closely spaced shear planes. The brecciation of the rock that occurs locally in the injection zone may be due to motions, possibly pulsating or undulose, of the magma of the pluton, during which the overlying injection zone was fractured and the fractures filled with aplitic material.

8. From this statement of conclusions one more inference can be drawn. It seems likely that the superheat of the Onawa pluton was large in quantity and slow in dissipation, as shown by the wide aureole and the extensive recrystallizations that have taken place. But the temperature was probably not very much above that of the country rock prior to and during the intrusion. This is shown in part by the lack of high-temperature minerals in the metamorphics. The highest degree of metamorphism recorded is not in the metamorphics along the contact but in a xenolith of plagioclase-cordierite-pleonaste-hypersthene hornfels, which belongs to the higher grade hornfelses. This xenolith offers evidence that chemically some part of the country rock was capable of assuming a mineral assemblage characteristic of the higher grade metamorphic conditions, but that the magma was not capable of producing those conditions except well within its interior.

[30] Sederholm, J. J.: "On Migmatites and Associated Pre-Cambrian Rocks of Southwestern Finland." Bull. Comm. Geol. de Finlande, 58, p. 85, 1923; and 77, p. 73, 1926.

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