PETROLOGY OF THE HOPEWELL SERIES IN THE OJO CALIENTE DISTRICT OF NEW MEXICO

Thesis by

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Contents

Illustrations

Abstract

The Hopewell series is a group of pre-Cambrian metamorphic rocks exposed in the Picuris, Petaca, and Ojo Caliente districts of northern New Mexico. In the Ojo Caliente district these and other pre-Cambrian rocks are exposed in an elongate inlier in the surrounding Tertiary strata. This inlier represents a low mountain or monadnock on an early Tertiary erosion surface.

The Hopewell series has been divided into two phases, the Picuris basalt and a series of metasedimentary rocks. Both general rock types show a well defined sequence of metamorphic degree, but the variation of metamorphic degree is roughly bedding controled. The highest degree of metamorphism noted in the area is correlative with the sillimanite zone.

In type, the metamorphic processes involved could be classed as normal regional metamorphism, which includes a certain amount of metasomatism. From the evidence in the Ojo Caliente district it seems probable that the processes of normal regional metamorphism were carried out in large part under the influence of hydrothermal solutions.

INTRODUCTION

Purpose of the investigation

Some of the oldest known mica mines in the United States are located in the Petaca district of northern New Mexico, where sheet mica was mined by hand as early as the seventeenth century. The Ojo Caliente district, which is the area under consideration in this report, is essentially a southerly extension of the Petaca district. It contains numerous pegmatite deposits, the largest of which, the Joseph, was prospected and opened about forty years ago.

Despite the fact that the mines of the Petaca district have been worked during so long a period, little systematic study of the area was made until very recently. Holmes[1] briefly examined and described the pegmatite mines in 1899, and Lindgren[2] discussed the hot-spring deposits at Ojo Caliente in 1910. The general geology of the Petaca and Ojo Caliente districts as well as some of the mines were described by Just[3] in 1937. Jahns[4] mapped most of the pegmatite mines of the districts in detail in 1946.

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1 Holmes, J. A., Mica deposits in the United States: U. S. Geol. Survey, 20th Ann. Rept., pp. 706-707, 1899.

2 Lindgren, Waldemar, Graton, L. C., and Gordon, C. H., The Ore deposits of New Mexico: U. S. Geol. Survey Prof. Paper 68, pp. 72-74, 1910.

3 Just, Evan, Geology and economic features of the pegmatites of Taos and Rio Arriba counties, New Mexico: N. Mex. School of Mines, State Bur. Mines and Min. Res. Bull. 13, 1937.

In addition, the Tertiary formations of the area were studied by Smith[5] and described in 1938.

Little is known in detail about the petrography of the pre-Cambrian rocks of northern New Mexico; hence it is hoped that this report will furnish a start in the study of this great series of rocks, and that it will be helpful in an understanding of the relations of the economically important pegmatites, which have been intruded into them. Perhaps it will also be helpful in pointing to evidence concerning the principles of metamorphism.

Method of investigation and acknowledgements

The field mapping of the Ojo Caliente district was done jointly by R. H. Jahns, W. R. Muehlberger, C. T. Smith, and the writer during September, 1947. A topographic base map, with a 100-foot contour interval, was prepared on a scale of 1/12000 by laying out a planimetric drainage plan, transferred by means of a grid from a corrected aerial photograph mosaic. Contours were plotted during the course of geologic mapping, with vertical control obtained by means of barometer, hand level, and brunton compass.

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4 Jahns, R. H., Mica deposits of the Petaca district, Rio Arriba county, New Mexico: N. Mex. Scholl of Mines, State Bur. Mines and Min. Res. Bull. 25, 1946.

5 Smith, H. T. U., Tertiary geology of the Abiquiu quadrangle, New Mexico: Jour. Geol., vol. 46, pp. 933-965, 1938.

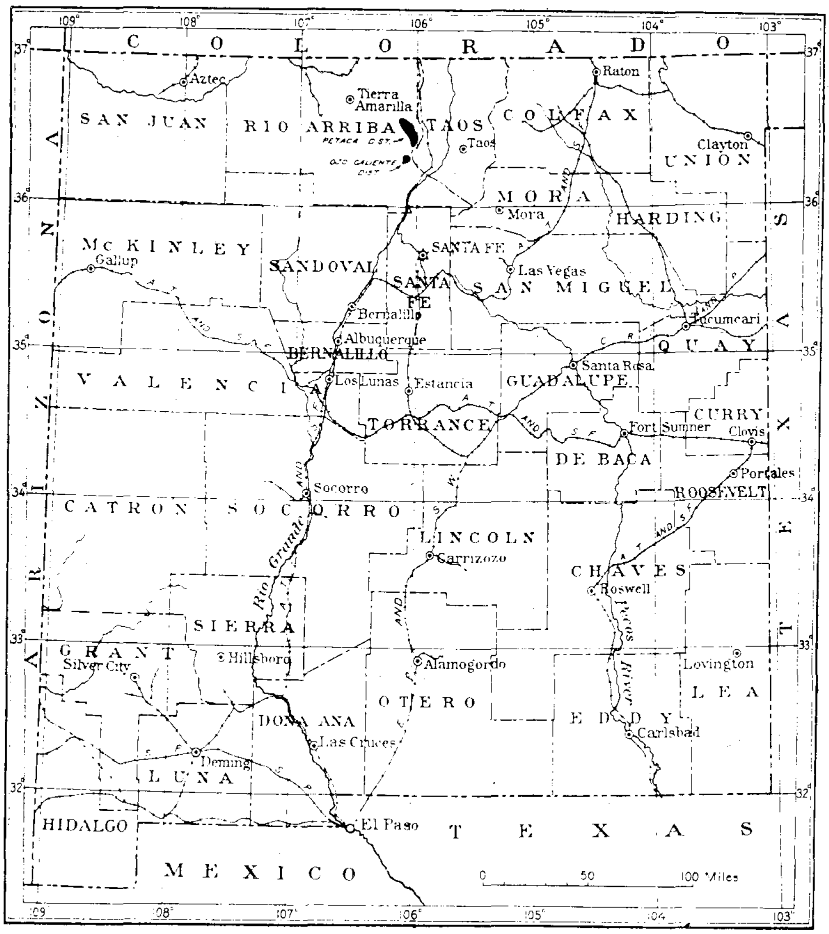
Numerous thin-sections were cut from the hand specimens obtained in the field, and the writer examined 23 of these under the petrographic microscope.

Sincere thanks are due to Professor R. H. Jahns, under whose instructive leadership this project was carried out, and to Professor C. T. Smith and W. R. Muehlberger, with whom much of the field mapping was done. The writer also wishes to thank Professor Ian Campbell, who has been most kind in offering helpful criticism and suggestions.

Physical features of the Ojo Caliente district

The Ojo Caliente district is in Rio Arriba County, northern New Mexico (Plate I). It lies immediately west and north of the little town of Ojo Caliente, which is seven miles south of La Madera. It is on the west side of the Caliente River, which flows southward into the Chama, a tributary of the Rio Grande. The mapped area, which includes some of the region surrounding the main mining district, lies between the altitudes of 5700 and 7400 feet, and includes Ojo Caliente Mountain on the west side, and a part of La Madera Mountain on the northeast side. That part of the area considered in this report occupies about nine square miles in T.24N.

Plate I



Index map of New Mexico showing locations of Petaca and Ojo Caliente districts.

and T.25N., R.8E., and is directly accessible by means of U. S. Highway 285.

As the climate is fairly arid and the vegetation consequently rather scant, the slopes in the area are moderately steep and the rock exposures very good, so that detailed mapping was feasible.

General geology of the Ojo Caliente district

Stratigraphy

Pre-Cambrian rocks

Hopewell series.-- The oldest rocks in the Ojo Caliente district constitute the Hopewell series, a metamorphosed group of interlayered basalts, basaltic tuffs, and fine-grained silty and sandy sedimentary rocks. Just[6] has correlated these rocks with those in the type area of the Hopewell series on Jawbone Mountain and around the town of Hopewell, after which he named the group. He also has designated the basalts separately as the Picuris basalts because of the persistence of basaltic igneous activity well into a period later than the deposition of the Hopewell sediments.[7] The Hopewell series is exposed across the center of the area in a broad band bounded on the west and north by faults, and on the east and south by overlapping Tertiary formations and pre-Cambrian intrusions of rhyolite.

Ortega quartzite.-- Separated from the Hopewell series by a major fault is a thick section of sillimanite-bearing quartzite that underlies La Madera Mountain. This quartzite has been shown by Just[8] to be conformably above the Hopewell series in areas to the north and east, and he has termed

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6 Just, Evan, op. cit., p. 42.
7 Just, Evan, op. cit., p. 44.
8 Just, Evan, op. cit., p. 43.

it the Ortega quartzite, after the Ortega Mountains in which they are well exposed. One large inclusion of this quartzite of which may be measured in scores of feet, occurs in the large intrusive mass of metarhyolite near the border of the Hopewell series on the south.

Most of the quartzite is massive, medium grained, and rather pure and vitreous except for scattered bundles of radiating fibrolite (sillimanite). Some facies appear to be feldspathic, and others contain a very high proportion of sillimanite. This mineral is partly altered to muscovite, which imparts a somewhat schistose character to the rock. A vague bedding which can be discerned by bedding controlled joint planes and by compositional stratification, makes it possible to plot structure in quartzite.

Vallecitos rhyolites.-- The Vallecitos rhyolites, named by Just[10] fortheir good exposures along the Rio Vallecitos, display considerable lithologic variation, from massive coarsely porphyritic phases to fine quartzitic types or schistose, highly sericitic varieties. All types have been recrystallized by metamorphism; the sericitic types have been mineralogically altered, and traces of tourmaline in some of the phases suggest that pneumatolysis has taken place to a certain extent.

10 Just, Evan, op. cit., p. 44.

The Vallecitos rhyolites have been intruded into the rocks of the Hopewell series, and apparently also into the Ortega quartzite, as can be seen from the inclusion of quartzite. The intrusive nature of these rocks is clearly demonstrated on the north flank of Ojo Caliente mountain, which is underlain by a large, dome shaped mass of metarhyolite. Here the contact between the igneous rock and the overlying Hopewell schists is broadly concordant, but the metarhyolite transects the bedding of the schists in many places, and invades the schists in a lit-par-lit and feldspathizing fashion. The large inclusion of quartzite is also evidence of the intrusive nature of the metarhyolite. In many places the metarhyolite is interlayered with the metabasalts and metasediments of the Hopewell series, where it also probably was intruded as a series of sills. Certainly the lack of any structures of extrusive flows preserved in the metarhyolites and the improbability of basalts and rhyolites being interlayered corroborates this hypothesis. Furthermore it is unlikely that two lithologically identical rhyolites should occur in the same area but have different structural relationships. Thus doubt is cast on Just's[9] interpretation that most of the Vallecitos rhyolites are extrusive, at least in the case of the Ojo Caliente district.

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9 Just, Evan, op. cit., p. 44.

<u>Pegmatites and other pre-Cambrian intrusive rocks</u>.-- Both the rocks of the Hopewell series and the Vallecitos metarhyolites have been intruded by numerous pegmatite and quartz dikes. The pegmatites have been investigated and described by Sterrett[11], Talmage and Wootton[12], Just[13], and by Jahns[14], who has investigated in detail all of the deposits which have been worked. Jahns states[15], "The pegmatites, most of which occur in the amphibole schist and associated metamorphic rocks, are tabular bodies 25 to 750 feet long and 3 to 65 feet in maximum outcrop breadth. Their ratio of length to thickness is distinctly greater than that of the Petaca pegmatites. Many of these bodies are sill-like. Their general trend is N. 70°E., with steep northerly dips. Zonal structure is characteristic." The chief zonal constituents are massive quartz, blocky microcline, and finer-grained microcline and albite. Large books of muscovite occur locally in the cores of the pegmatites. The accessory minerals comprise spessartite, fluorite, beryl, columbite, monazite, samarskite,

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11 Sterrett, D. B., Mica deposits of the United States: U. S. Geol. Survey Bull. 740, pp. 163-164, 1923, and Mica in Rio Arriba County, New Mexico: U. S. Geol. Survey Bull. 530, p. 388, 1913.

12 Talmage, S. B., and Wootton, T. P., the non-metallic mineral resources of New Mexico and their economic features: N. Mex. School of Mines, State Bur. Mines and Min. Res. Bull. 12, pp. 116-117, 1937.

13 Just, Evan, op. cit., p. 65. (quotation from Sterrett).

14 Jahns, R. H., op. cit., pp. 367-274.

15 Jahns, R. H., op. cit., p. 267.

bismutite, and some sulfides. A few of the pegmatites grade along the strike into vein-like masses of quartz, but most of these quartz "veins" occur separately.

One small dike of a hypersthene-biotite-quartz gabbro was observed south of Ojo Caliente Mountain. It is grouped here with the pre-Cambrian rocks, but it may possibly be much younger.

Age of the pre-Cambrian rocks.-- No evidence for the pre-Cambrian age of the pegmatites and the older rocks which they intrude is present in or immediately around the Ojo Caliente district, but must be taken from areas to the south or to the north in Colorado, where similar metamorphic rocks and pegmatites are found. There the pegmatites are unconformably overlain by relatively unmetamorphosed Paleozoic formations. Known Paleozoic pegmatites are much smaller and simpler in structure and mineralogy than those of the Ojo Caliente and Petaca districts, according to Jahns[16].

Just[17] has classed all of the pre-Cambrian rocks in the area as Proterozoic on the basis of analogies drawn between an inferred history of geosynclinal deposition

16 Jahns, R. H., op. cit., p. 25.
17 Just, Evan, op. cit., pp. 11-14.

and subsequent acute deformation, for these rocks, and the similar pre-Cambrian trends recorded in Colorado[18] and in the Proterozoic rocks of the Great Lakes region. But he also comments on the lithologic similarities of the Picuris basalts and the Vishnu schists, which, by stratigraphic position beneath the Grand Canyon series, have been classified as Archean.

The pegmatites of the Ojo Caliente district are unmetamorphosed, and therefore the minimum amount of time that must have elapsed between the deposition of the metasediments and the intrusion of the pre-Cambrian pegmatites is equal to the time required to deform and highly metamorphose a series of stratified rocks. Admittedly this sequence of events could easily have occurred entirely within the Proterozoic era but from a purely statistical point of view such a sequence would probably cover as great or greater a span of time than is represented by the Proterozoic era. Therefore, it seems reasonable to assume that the metamorphic rocks are just as likely to be of Archean age as they are to be Proterozoic in age.

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18 Stark, J. T., and Barnes, F. F., The structure of the Sawatch Range: Am. Jour. Sci., 5th ser., vol. 24, pp. 471-480, 1932.

Owing to lack of definite evidence, it seems best to refer to the metamorphic series as pre-Cambrian.

Cenozoic rocks

Above the pre-Cambrian rocks lie the Tertiary basalts and stream deposits, which overlap on the early Tertiary monadnocks now exposed as Ojo Caliente and La Madera Mountains.

Caliente conglomerate.-- Some of the earliest of the stream deposits occur as isolated patches, rarely more than 30 to 40 feet in thickness. These fill some of the ravines on the mountain sides of the old Tertiary erosion surface, which is now being exhumed in the present cycle of erosion. The deposits are composed of materials derived from the underlying pre-Cambrian rocks, mostly quartz and amphibolite, from which they apparently acquired their olive-brown color. They are poorly sorted, unstratified, poorly consolidated, and consist of angular and subangular cobbles in a matrix of fine sand and silt. Although these deposits occur as isolated patches, it seems fairly safe to correlate them all on the basis of lithologic similarity. The name Caliente conglomerate is proposed for them, after the Caliente River, near which they are best exposed, in the narrows between Ojo Caliente and La Madera Mountains. The Caliente conglomerate is overlain unconformably by the Abiquiu tuff, classified by Smith[19] as Upper Miocene. Thus the Caliente conglomerate is at least pre-Upper Miocene in age and perhaps even as old as Eocene. Indeed, it bears certain lithologic similarities to the Eocene Huerfano formation of southern Colorado. Possibly it is correlative with the Carson conglomerate, which covers extensive areas in the Petaca district, and which Just[20] considers to be the equivalent of the Raton formation farther to the east and of the early Tertiary deposits of the San Juan basin.

El Rito(?) formation.-- Another early Tertiary formation, very similar in lithology to the Caliente conglomerate, is exposed on the south flank of La Madera Mountain. Like the Caliente, it fills the gulleys of the early Tertiary surface. It is distinguished from the Caliente conglomerate by a distinctive brick red color, and by this color and its other lithologic characteristics, described below, it is tentatively identified with the El Rito formation. Smith[21], who described the El Rito formation, considers the red color to be of special paleoclimatic significance. Owing to the patchy distribution of both the El Rito and Caliente formations, their age relationships are indeterminate. It is possible that they are contemporaneous,

19 Smith, H. T. U., op. cit., p. 958.
20 Just, Evan, op. cit., p. 49.
21 Smith, H. T. U., op. cit., pp. 940-944.

although Smith[22] suggests that the Caliente conglomerate may be the younger of the two.

The El Rito (?) formation in the Ojo Caliente area is an unstratified, angular, moderately consolidated, unsorted, breccia. It consists of pre-Cambrian cobbles, mainly Ortega quartzite. The deposit differs from the El Rito formation of the only type locality in a lesser degree of consolidation and in depth; its maximum thickness is 50 feet. Locally it seems to have been bleached by calcareous solutions issuing from nearby hot springs.

<u>Abiquiu tuff</u>.-- The Abiquiu tuff named and described by Smith[23], is exposed in a broad belt on the north, east, and south side of the Ojo Caliente Mountain. On the west side it has been completely covered by the Santa Fe formation. Its maximum thickness was not accurately determined but is of the order of a few hundreds of feet. The entire formation is well stratified and is locally channeled and cross-bedded. It is clearly of fluviatile origin.

Individual beds are massive and moderately sorted, and vary from very fine to very coarse sand. The coarser beds are rich in angular to subangular granules and pebbles of andesite, which impart a lavender tint to the

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22 Smith, H. T. U., personal letter to R. H. Jahns, 1947.
23 Smith, H. T. U., Tertiary geology of the Abiquiu Quadrangle, New Mexico, pp. 944-952.

rock. Finer, orange to buff colored beds are composed of angular medium-grained quartz sand. Local stringers of reddish silt, or volcanic and metamorphic pebbles, and a few thin stringers of white, extremely fine, slightly altered tuff are scattered throughout the section. In general, the formation is poorly consolidated, but locally it is cemented by caliche, which evidently was deposited by fault-controlled springs.

The Abiquiu tuff overlies the pre-Cambrian rocks and the older Tertiary formations with a distinct unconformity. The contact is highly irregular in plan because of the steepness of the slopes of Ojo Caliente and La Madera Mountains, against which the tuff overlapped during Tertiary time. The contact between the Abiquiu tuff and the overlying Santa Fe formation is gradational, and the two formations are distinguished on the basis of general lithology. Smith[24] dates the apparently unfossiliferous tuff as Upper Miocene on the basis of its stratigraphic position below the better known Santa Fe formation, and on the basis of lithologic correlation with the Conejos tuff of Miocene age.

A series of amygdaloidal augite and olivine basalts overlies a part of the Abiquiu tuff on the east flank of Ojo Caliente Mountain and along the low cliffs on the

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24 Smith, H. T. U., op. cit., p. 958.

west side of the Caliente River, two miles north of Ojo Caliente. In most places these remnants of simple flows, but in one locality, near the Joseph mine, very coarse flow breccia is present. It would be impossible to determine by the field relations of these basalts, within the limited area under consideration, how much younger than the Abiquiu tuff they might be. Directly south of Ojo Caliente Mountain, however, lithologically identical basalts are interlayered with the Abiquiu tuff. The feeder dikes of these flows transect the older tuff beds. Smith[25] includes all of them with the Abiquiu tuff, and their age is Upper Miocene, as they are interlayered and contemporaneous with the Upper Miocene tuff.

Santa Fe formation.-- The Abiquiu tuff grades upward into the typical fluviatile sands and gravels of the Santa Fe formation. These differ from the underlying tuff principally in composition, containing a much lower proportion of andesitic fragments, or total lacking them. The Santa Fe formation is also somewhat coarser than the Abiquiu tuff. It is exposed along the extreme western edge of the Ojo Caliente area, where it is down-faulted against the Abiquiu tuff and pre-Cambrian rocks. It also appears east of the Caliente River and South of La Madera Mountain, where it conformably overlies the tuff. Its

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25 Smith, H. T. U., op. cit., p. 947.

maximum thickness probably is of the order of hundreds of feet on the western side of the area. Evidence from vertebrate fossils, collected from this formation, in other areas, indicate an age ranging from Upper Miocene to Lower Pliocene[26]. Probably only the lower, or Upper Miocene part of the Santa Fe formation is present in the Ojo Caliente area.

Owl Cliff tufa.-- The Owl Cliff tufa comprises a series of hot-spring deposits that overlies the Abiquiu tuff. It also lies above some of the terrace gravels west of the Caliente River, north of Ojo Caliente Mountain, and on the west flank of La Madera Mountain. There the tufa forms the capping of the steep Owl Cliffs. Its distribution is controlled by the major faults along which lime-charged solutions have flowed.

Many parts of the tufa are highly vesicular, and the presence of life in the hot springs during the time of deposition is indicated by hollow tubes, left by reeds, and by tiny shells of fresh-water gastropods and pelecepods. Other facies are more solid and massive, and contain isolated pockets of pebbles, which give a suggestion of bedding.

The tufa is composed chiefly of microcrystalline calcite with minor quantities of detrital quartz and seams

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26 Osborn, H. F., Cenozoic mamalian horizons of Western North America, U. S. Geol. Survey Bull. 361, p. 65, 1909, and Equidea of Oligocene, Miocene, and Pliocene of North America, Iconographic Type Revision, Mem. Amer. Mus. Nat. Hist. (N.S.), Vol. II, Part I, pp. 34, 98-99, 1918.

of travertine. Its overall color is a light creamy buff. The maximum thickness of the deposits is about 50 feet at the Owl Cliffs, where deposition is continuing at the present time.

Lindgren[27], who studied the spring deposits at Ojo Caliente itself, believed that the formation of some of calcite and fluorite veins there must have extended back into Tertiary time. Because of the terrace-like position of the Owl Cliff tufa, however, most of the tufa there is probably not older than Quaternary.

Terrace gravels.-- The Caliente River and its larger tributaries are flanked by a series of terrace deposits, which overlie the pre-Cambrian rocks, as well as the Tertiary sedimentary and volcanic rocks. These deposits are composed of crudely stratified and poorly sorted gravels with pebbles of quartz and volcanic and pre-Cambrian rocks. Locally they are cemented with caliche or interbedded with the Owl Cliff tufa. Their overall color is brownish grey. The thickest terrace deposits observed overlie the Santa Fe formation east of the Caliente River and south of La Madera mountain. There the gravels are 30 feet thick.

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27 Lindgren, Waldemar, Graton, L.C., and Gordon, C. H., op. cit., p. 72.

Plate II

Stratigraphic table for the rocks

of the Ojo Caliente district.

<table>
<tr><td rowspan="6">Cenozoic</td><td colspan="2" rowspan="2">Quaternary</td><td colspan="2">Terrace gravels and alluvium</td></tr>
<tr><td colspan="2">Owl Cliff tufa</td></tr>
<tr><td rowspan="4">Tertiary</td><td>Lower Pliocene
to
Upper Miocene</td><td colspan="2">Santa Fe formation</td></tr>
<tr><td>Upper Miocene</td><td colspan="2">Abiquiu tuff with interlayered basalts</td></tr>
<tr><td rowspan="2">Eocene(?)</td><td colspan="2">Caliente conglomerate</td></tr>
<tr><td colspan="2">El Rito(?) formation</td></tr>
<tr><td colspan="3" rowspan="5">Pre-Cambrian</td><td colspan="2">Pegmatites, quartz veins, and rare hypersthene gabbro</td></tr>
<tr><td colspan="2">Vallecitos rhyolites</td></tr>
<tr><td colspan="2">Ortega quartzite</td></tr>
<tr><td rowspan="2">Hopewell series</td><td>Picuris basalts</td></tr>
<tr><td>Metasedimentary schists</td></tr>
</table>

Structure

Folds

The Tertiary formations have very gentle dips, except where dragged along the larger faults. In contrast, all the pre-Cambrian formations dip steeply, except on Ojo Caliente Mountain. The intrusive metaryrolite of Ojo Caliente Mountain forms a dome-shaped structure, and a minor side dome is located on the northeast side of the mountain just west of the Joseph mine. North of Ojo Caliente mountain the pre-Cambrian strata dip to the north, up to a large fault which transects the structure. This definitely implies that the metasedimentary and metavolcanic strata are right-side-up (youngest to the north and oldest next to the intrusive body under Ojo Caliente Mountain) unless the whole dome of metarhyolite were inverted. Nearly all of the pre-Cambrian strata, except those beneath Ojo Caliente Mountain, strike west to west-northwest with only minor variations.

North of the above-mentioned fault the strata dip south, and it is difficult to determine whether or not the section is overturned on the basis of evidence within the area mapped. This section does not match up with any strata around Ojo Caliente Mountain. On La

Madera Mountain, believed to be separated from the western part of the area most by another large fault, most of the pre-Cambrian beds dip within five or ten degrees of the vertical. Certainly the evidence in the area mapped gives no basis for Just's[28] interpretation of isoclinal folding, as there is no repetition of stratigraphic sequence. The irregularities of areal distribution of the rocks, upon which Just evidently based part of his conclusions, seems to be chiefly the result of faulting.

As a whole, the strata are unusually free of distortion, considering their geologic antiquity and the degree of metamorphism to which they have been subjected. Furthermore, the schistosity is nearly everywhere parallel to the bedding, as seen in the field, in hand specimens, and in thin section. This seems to imply that the direction of schistosity has been largely controlled by the original bedding of the rocks.

Faults

Caliente fault.-- Although the Caliente fault is almost unexposed, its existence can hardly be denied. The one

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28 Just, Evan, op. cit., Plate III

place where it is exposed is on the tip of a blunt eastward protuberance of the west bank of the Caliente River. Elsewhere it is buried under El Rito(?) beds, the Abiquiu tuff and Santa Fe formation, basalts, Owl Cliff tufa, terrace gravels, and valley-bottom alluvium. This burial is the result of localization of fluviatile deposits in the weak and topographically low fault zone. In addition, the trace of the fault is well marked by a series of hot springs, which have formed tufa deposits that also tend to conceal the fault. Probably the hot springs at Ojo Caliente are a continuation of this series and have formed along the same fault zone. As the fault is nearly completely buried not much can be determined concerning the nature of its dip, direction of displacement, or breadth of zone. It trends northerly, and appears to be somewhat sinuous, with a trace that is convex to the east. Apparently there has been no recent movement along the fault such as to offset the overlying beds. Therefore it must be at least of pre-El Rito(?) age and probably is much older, considering the seeming effect it has had in determining the relations of even the Tertiary topography.

El Rito fault.-- In contrast to the Caliente fault, the El Rito fault is well exposed where it bounds the west side of Ojo Caliente Mountain and farther north, where it branches. The northern branch lies near the El Rito road (after which the fault is names) for a distance, north of which it trends to the northeast, and the southern branch trends about east northeast and lies somewhat less than a mile south of the El Rito road. Farther to the south the fault curves sharply and trends more nearly south. To the south the El Rito fault is fairly complicated, and comprises a fault zone with many subsidiary fractures. Here it separates the pre-Cambrian rocks on the east side from the Santa Fe formation on the west. To the north one branch lies entirely within the crystalline rocks, separating two areas of oppositely dipping strata. Farther to the east it is covered by terrace deposits and Abiquiu tuff, which it apparently has not displaced. The northermost branch, on the other hand, has displaced the Santa Fe formation, separating the Santa Fe gravels from the Abiquiu tuff, but it has not disturbed the terrace gravels which cover it in places. Faulting, then, has occurred along the main part of the fault and the northern branch in post-Santa Fe-pre-Terrace time, or somewhere in late Pliocene or early Pleistocene time. Evidently both branches join, or at least intersect the Caliente fault under the alluvium and Santa Fe beds to the east. Smith[29] has mapped a continuation of the El Rito fault, offset by smaller cross faults, farther to the south.

Judging from its trace, the El Rito fault is very steep and the apparent direction of displacement has been down on the west and up on the east. It is not possible to determine the true displacement, however, as at no place, can beds be matched across the fault. Therefore the actual direction of movement and total amount of displacement remains problematical. As in the case of the Caliente fault, the northern branch of the El Rito fault has been responsible for the location of tufa deposits precipitated from solutions rising along the fault zone. Lindgren[30] thinks that these hot solutions are of the type connected with the dying stages of igneous activity, and perhaps they are genetically related with the Quaternary basalts found in the surrounding regions.

<u>Minor faults</u>.-- Many smaller faults occur in the area. They generally strike north-northeast or more or less northwesterly. Some of them cut and offset Tertiary deposits, whereas others are overlain by such

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29 Smith, H. T. U., op. cit., p. 937 and 947.

30 Lindgren, Waldemar, Graton, L. C., and Gordon, C. H., op. cit., p. 74.

beds and do not seem to have disturbed them at all. Where obserable, the apparent displacement is everywhere normal. These smaller faults seem to form a pattern that suggests a north-south shearing stress in the block bounded by the Caliente and El Rito faults, but this is purely suggestive as the smaller faults are of distinctly different ages.

Smith[31] states that the faulting observed in the Abiquiu quadrangle (which includes the Ojo Caliente district) is characteristically of normal nature. Certainly this is in accord with the evidence observable in the Ojo Caliente district. At least two distinct periods of faulting are recorded, one pre-El Rito(?), and the other post-Santa Fe-pre-Terrace in age.

31 Smith, H. T. U., op. cit., pp. 961-962

PETROGRAPHY OF THE HOPEWELL SERIES

Picuris basalts

The Picuris basalts consist of a series of epidote and plagioclase amphibolites and feldspathic hornblende schists, which represent basalts and andosites in various stages of metamorphism.

Plagioclase amphibolite

The plagioclase amphibolites constitute the largest portion of the Picuris basalts. These amphibolites are composed, on the average, of 50 percent hornblende, with varying amounts of generally subordinate quartz and moderately calcic plagioclase. Epidote occurs in minor amounts, and biotite, which is, in the main, absent, in places constitutes as much as 20 percent of the amphibolite. Magnetite is the dominant accessory mineral, but apatite and sphene, which normally occur only in traces, are less commonly present in amounts of 1 and 2 percent. Hydrothermal minerals such as sericite and chlorite are found in traces, and exceptionally the plagioclase component of the amphibolite may be largely converted to sericite. Some calcite has been introduced into the rocks along fractures, in many instances, and is finely disseminated.

As the major component, the hornblende occurs, as a rule, as medium-grained, extremely poikiloblastic and ragged, prismatic metacrysts. These are set, for the most part, in an apparently unorganized or felty fashion in a much finer grained, granoblastic groundmass of quartz and plagioclase. Coarse grains of quartz are commonly concentrated in phacoidal structures that are clearly palimpset amygdules and quartz filled fractures. Scattered throughout the rock, the epidote is present either as early formed grains, about as coarse as the plagioclase-quartz groundmass, or as anhedral, late replacement, very fine grains. In extreme cases a replaced hornblende metacryst has given rise to very coarse epidote. The accessory minerals are mostly rather fine grained, but magnetite normally forms coarser irregular or platy grains, especially where it has replaced biotite. In many places it occurs in stringers of fine prisms which show a marked schistosity. In other instances the magnetite has recrystallized to form equant euhedrons. Apatite is generally euhedral, but sphene is more commonly anhedral and associated with the magnetite as a surrounding coat. Chlorite preserves the form of the replaced biotite, which is platy and somewhat coarser than the groundmass.

Except for the palimpset amygdaloidal structures and quartz seams the coarser plagioclase amphibolites are essentially massive, but the finer-grained facies possess a crude schistosity formed by the alignment of the hornblende needles and any biotite, or pseudomorphs of or magnetite after biotite that may be present.

Feldspathic hornblende schist

The feldspathic hornblende schists differ mainly from the plagioclase amphibolites in that they contain less hornblende and more plagioclase; plagioclase forms the dominant constituent. Otherwise their composition is very similar to that of the amphibolites as epidote is more or less a major component, depending on the degree of metamorphism, and a considerable amount of biotite is present in some instances. Minor amounts of the accessories minerals, magnetite, sphene, and apatite are scattered throughout the rocks in every case. One of the feldspathic hornblende schists contains, in addition, a small percentage of microcline and traces of zircon and olivine. A detailed comparison of the composition of the Picuris basalts is given in Plate IV.

In the finer grained hornblende schists the bulk of hornblende forms small rosettes of slender prisms one to two milimeters in diameter, set in a finer granoblastic groundmass of plagioclase and quartz, but in the coarser facies these are replaced by larger ragged laths oriented haphazardly. The rosettes are concentrated in vague alternate bands, with the somewhat longer dimension of the rosette parallel to the banding; the component crystals are generally highly poikiloblastic, with inclusions of all the other constituents of the rock, and they contain, in some places, vermiform cavities. Other, coarser and more ragged grains of hornblende are scattered throughout.

Early formed epidote is generally subhedral, about the same grain size as the groundmass (approximately

Plate IV Composition of the Picuris basalts.

Minerals	Epidote amphibol.	Plagioclase amphibolites*					Feldspathic hornblende schists*			
Hornblende	30%	65%	35%	55%	50%	30%	25%	3%	35%	35%
Plagioclase	Olig. 10%	And. 10%	And. 25%	And. 25%	And. 20%	And. 50%	Olig. 40%	And. 40%	And. 35%	Lab. 35%
Quartz	10%	--	15%	15%	25%	10%	15%	40%	20%	15%
Epidote	50%	3%	5%	1%	trace(?)	3%	5%	0.5%	1%	10%
Biotite	--	20%	--	--	trace	trace	--	15%	3%	trace
Magnetite	trace	3%	1%	2%	3%	4%	3%	1%	3%	trace
Sphene	0.5%	trace	1%	0.5%	--	--	trace	--	1%	0.5%
Apatite	--	trace	trace	2%	trace	trace	trace	trace(?)	2%	0.5%
Chlorite	--	--	--	trace	--	0.5%	--	--	trace	trace
Sericite	--	--	15%	trace	--	0.5%	--	trace	trace	trace
Others	--	--	--	--	bleached h'blende 0.5%	--	micro-cline-3%; zircon & olivine - traces	zircon - trace	--	kaolin-trace

Percentages estimated visually.

*Samples arranged in approximate order of increasing degree of metamorphism.

0.1 milimeters), and commonly contains vermiform cavities or inclusions, whereas late forming epidote is anhedral and normally fine grained, but in some places, where it has replaced a hornblende metacryst in toto, a much coarser grain may be formed. Biotite, when present, is platy; magnetite is very fine grained and generally anhedral but in some places, is recrystallized as tiny prismatic euhedrons. Most of the magnetite is concentrated in stringers in the more feldspathic and quartz-rich bands, and the whole structure gives a strong impression of palimpset bedding. Sphene and apatite are generally fine grained and may be either subhedral or anhedral.

In most of the feldspathic hornblende schists the only structure, if it has not been obliterated by metamorphism, is the palimpset bedding. However, where biotite is present, a distinct schistosity results from the orientation of both the biotite and the hornblende. This orientation is approximately parallel with the traces of bedding.

Epidote amphibolite

Rarest among the Picuris basalt group are the highly epidotic amphibolites or epidote-hornblende schists, which consist of 50 percent or more epidote, with subordinate hornblende and minor quantities of interstitial quartz and oligoclase. In addition they contain traces of magnetite and less than half a percent sphene.

Generally they are fine grained but inequigranular, and average about 0.05 milimeter in grain size. The epidote is anhedral and equidimensional, and occurs mostly in very fine grains, but in some instances as slightly poikiloblastic metacrysts 0.2 and 0.3 milimeter in maximum dimension. The pale actinolitic hornblende, on the other hand, displays a complete gradation of size of the slender prismatic grains from very minute crystals to lengths of 0.5 milimeter. Anhedral quartz and oligoclase constitute a fine-grained groundmass for the ferromagnesian minerals, and coarser, anhedral grains of sphene, commonly with a nucleus of magnetite, are scattered throughout the rock.

Structurally, the epidote-amphiblites are nearly massive, as the hornblende laths have a slight preferential orientation which is visible only in the hand specimen.

Metamorphism of the Picuris basalts

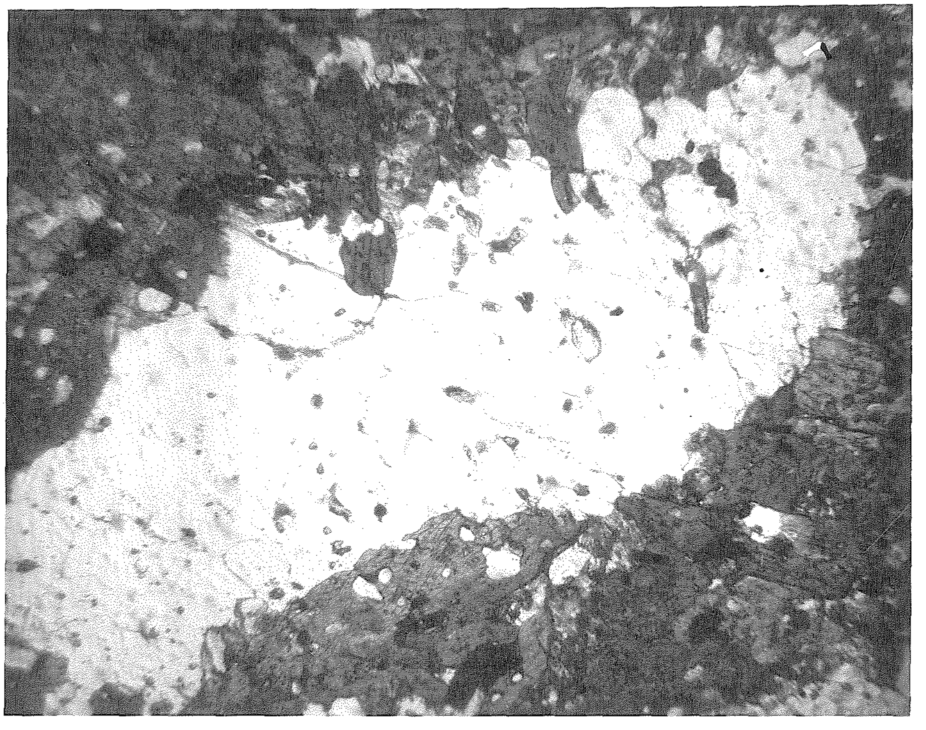
Original constitution of the basic metamorphic rocks

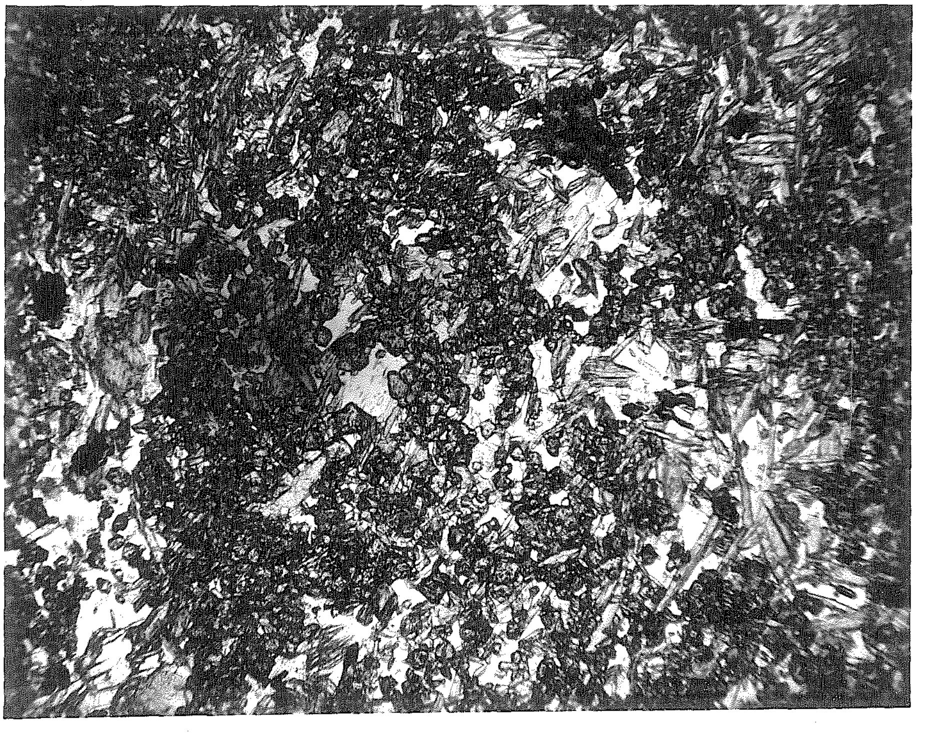
Owing to the basic composition of the epidote and plagioclase amphibolites, rare types of marly and ferromagnesian sedimentary rocks and basic igneous and pyroclastic rocks are the only types that could have given rise to these metamorphic rocks. Both the far greater preponderance of igneous rocks and the preservation of such indicative structures as amygdules (Figure 1) point to the fact that these amphibolites were once effusive, basic rocks -- basic andesites and basalts. As the amphibolites are fine grained and have probably become much coarser during the process of metamorphism, it is all the more likely that they were originally extrusive rocks.

Similarly the feldspathic hornblende schists are most readily explained by ascribing to them an igneous or pyroclastic origin. The nearly identical sequence of metamorphism in the amphibolites and hornblende schists, which will be demonstrated later, the presence of such a mineral as olivine, which is usually destroyed in the normal course of sedimentation, and the fact that the amphibolites and hornblende schists are intimately associated gives strong support to this hypothesis. However, the higher percentage of felsic minerals (occurring together with olivine) the traces of zircon, the distinct suggestion of original bedding, and the absence of any remnants of the structures of extrusive rocks all imply a pyroclastic derivation for this group of rocks. Therefore it seems reasonably safe to conclude that the epidote and plagioclase amphobolites and the feldspathic hornblende schists represent metamorphosed basic andesites and basalts and andesite and basaltic tuffs.

Figure 1. Palimpset quartz amygdule in a plagioclase amphibolite. (plain light, X42)

Figure 2. Epidote amphibolite with fine grained epidote and slender needles of actinolitic hornblende. Note the sphene with magnetite (lower center). (plain light, X54)





Sequence of metamorphism in the amphibolites

The lowest grade metamorphic rocks present in the Ojo Caliente region of the amphibolites are the epidote amphibolites . At this stage of metamorphism coarse and fine grained epidote is in preponderance but slender prisms of pale actinolitic hornblende have developed (Figure 2). The plagioclase is near oligoclase. Rounded, anhedral masses of sphene are present and usually contain fine nuclei of anhedral magnetite.

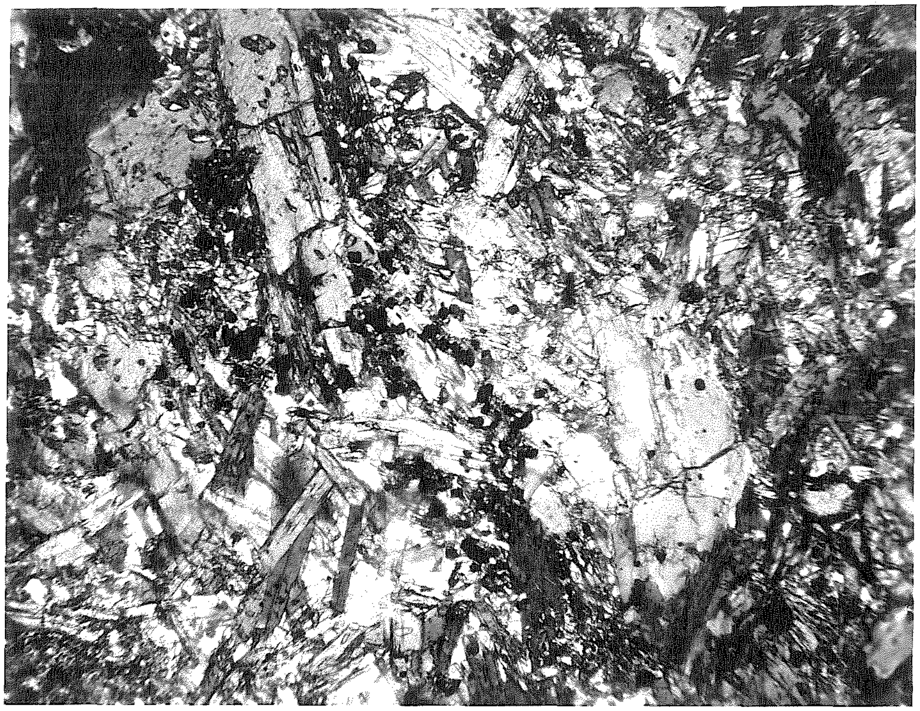
The next stage is marked by the presence of a large amount of biotite. Considerable increase of grain size of the hornblende can be noted, but its growth was not rapid as to make the hornblende metacrysts highly poikiloblastic (Figure 3). Both the biotite and the hornblende grains are considerably coarser (1 to 2 milimeters in length), although the interstitial groundmass of quartz and plagioclase remains fine, and minute hornblende crystals are present. There is an increase in the amount of sphene, which is subhedral and poikiloblastic, and the amount of fine-grained magnetite is increased also. The plagioclase at this stage is somewhat more calcic, and lies in the andesine range. Another distinctive feature of this stage is the decided, but by no means perfect orientation of the hornblende and biotite grains.

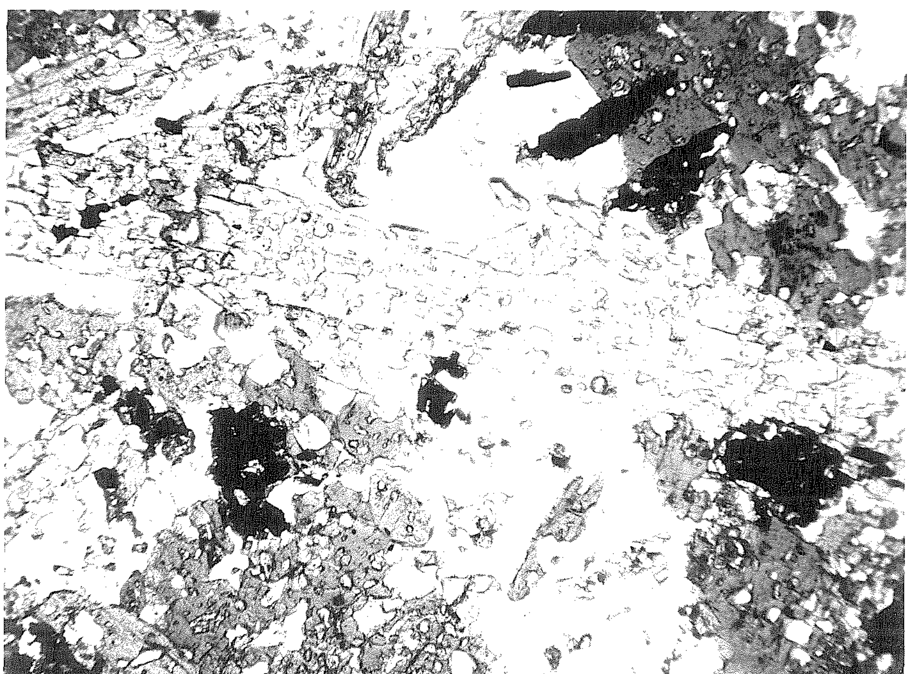
Most distinctive, however, is the great reduction of epidote, which, for the most part, has formed hornblende.

The highest grade of metamorphism in the amphibolites in the area is characterized by an increased grain-size of the hornblende and the more or less complete alteration of biotite to hornblende, both of which result in the destruction of the previously developed schistosity. The hornblende prisms are as much as 5 milimeters in length and are highly poikiloblastic and ragged (Figure 4). Some of the biotite is replaced by magnetite, the salic components of the biotite possibly contributing to the groundmass feldspar. Reduction of sphene and an increase of magnetite over previous stages can be seen, and the magnetite is partially recrystallized into equant euhedrons. Some ilmenite may also be present. The plagioclase, at this stage, is calcic andesine or sodic labradorite. Most of the epidote has disappeared, but traces of previously formed epidote may survive in some facies of the more highly metamorphosed amphibolites. Despite the extensive mineralogical changes and more or less complete recrystallization of the constituents that have taken place at this stage, the palimpset amygdules and quartz seems have undergone little obliteration and are still readily recognizable, even in the hand specimen.

Figure 3. Intermediate metamorphic stage of the plagioclase amphiboloites with both coarse and fine grained hornblende and scattered crystals of biotite. (plain light, X54)

Figure 4. Poikiloblastic, prismatic metacrysts of hornblende in a high metamorphic grade of plagioclase amphibolites. Note also the tabular pseudomorphs of magnetite after biotite and the magnetite armored with sphene. (plain light, X54)





The effects of various degrees of retrogressive metamophism degree are commonly visible in many of the more highly metamorphosed amphibolites. The first change is an attack of the hornblende metacrysts by plagioclase (Figure 3). Possibly with a contemporaneous formation of magnetite. Then sericitization of the plagioclase sets in, along with the development of generally very fine grained anhedral epidote in both the plagioclase and the hornblende. In some cases this reaction may go to the extent that the hornblende metacrysts are nearly or completely replaced by epidote. Then the epidote is recrystallized into coarse pseudomorphs, and the plagioclase is largely converted to sericite. Finally, any biotite present is chloritized. Possibly some chloritization takes place in the hornblende, or the hornblende is bleached. This latter effect is very likely a surface weathering effect instead.

Sequence of metamorphism in the feldspathic hornblende schists

Despite the difference of composition between the amphibolites and the hornblende schists, the metamorphism of both types has followed nearly identical lines of mineralogical and textural transformation.

In the lowest stage of metamorphism observed in the hornblende schists, epidote is present in only minor amounts, and a trace of olivine has been preserved. The epidote is equant and seriate; the larger grains are highly poikiloblastic, and the olivine is largely replaced directly by hornblende. Most of the hornblende occurs as rather fine, slender, euhedral prisms in radial rosettes (Figure 6), with small vermiform inclusions reminiscent of those in the coarser epidote. Coarser, ragged, anhedral hornblende also occurs scattered throughout the rock. The plagioclase of this stage is near oligoclase. Some of the sphene seems detrital, whereas other grains of this mineral appear to be more definitely secondary. Palimpset bedding is fairly well defined. Quartz and microcline-rich layers, with stringers of fine magnetite, alternate with more femic bands containing epidote and hornblende. However, there is no apparent schistosity.

The next higher stage is marked, as in the amphibolites, by the presence of biotite, and by the schistose arrangement of both the biotite and the hornblende (Figure 7). Hornblende has increased at the expense of epidote, and the rosettes are well developed, and somewhat elongate in the direction of schistosity. Traces of epidote persist however. The plagioclase at this stage is near andesine, and the hornblende is darker, and apparently richer in soda and alumina. Magnetite

Figure 5. A large poikiloblastic metacryst of hornblende, which has been partially altered to plagioclase and epidote in a plagioclase amphibolite. (plain light, X54)

Figure 6. A rosetts of hornblende crystals surrounded by fine grained epidote in a feldspathic hornblende schist. (plain light, X54)

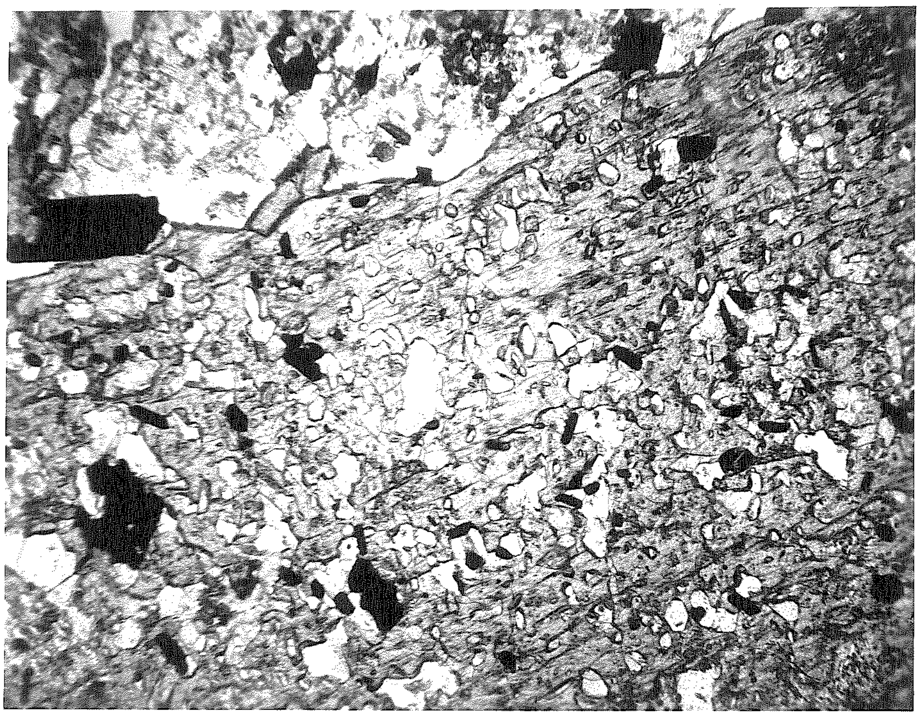
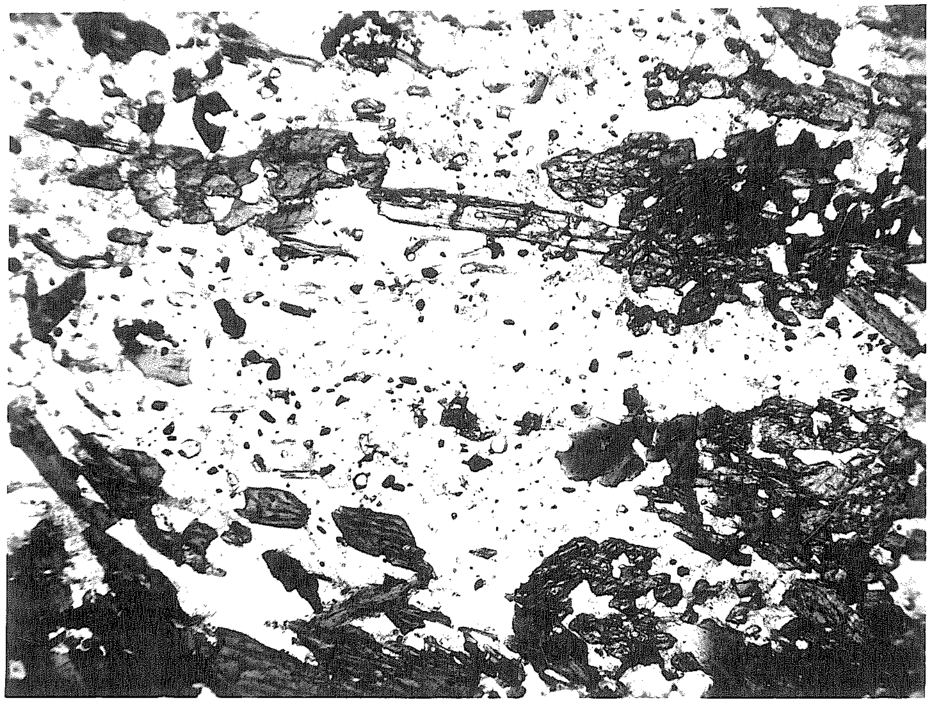


Figure 7. Intermediate metamorphic grade feldspathic hornblende schist with schistose hornblende and biotite in a groundmass of quartz and plagioclase. (plain light, X54)

Figure 8. Feldspathic hornblende schist with hornblende in large part replaced by fine grained epidote. (plain light, X54)



is in stringers of fine anhedral grains marking the trace or original bedding, and the sphene is subhedral.

In the highest stages of metamorphism observed in the hornblende schists, the hornblende is much coarser, as large as 3 and 4 milimeters in grain size, and more poikiloblastic, ragged, and anhedral. The plagioclase is still more clacic and is in the labradorite range. The accessories have been mostly recrystallized; magnetite forms euhedral prisms and apatite is much coarser. A trace of biotite remains, but any schistosity that may have been present has been more or less completely destroyed.

Retrogressive effects in the hornblende schists are identical to those in the amphibolites. Hornblende is attacked first by plagioclase and then by epidote, and in some places is almost completely replaced pseudomorphously by coarse-grained epidote. Plagioclase is broken down into sericite and epidote, and the traces of biotite are mostly chloritized.

Hopewell schists

The metasedimentary rocks of the Hopewell series form a group of rather fine-grained schists, ranging from low-rank metamorphic types of quartz-muscovite schists to high-rank types exemplified by knotty sillimanite schists.

Quartz-muscovite schist

Among the sequence of metasedimentary rocks the rarest types are the quartz-muscovite schists. These are dominantly quartz with subordinant amounts of various types of muscovite, and in some cases a small amount of chlorite. They contain, in addition, minor amounts of plagioclase, in some instances, and traces of magnetite, apatite, tourmaline, and zircon.

As a rule, the quartz-muscovite schists are fine grained, averaging a fraction of a milimeter in grain size, but certain facies contain augen, or coarser grains, of quartz, as large as 2 and 3 milimeters in diameter. The augen are either composed of a single grain or an aggregate of coarse grains and are generally surrounded by a mortar of finer quartz grains. Together with plagioclase, if it is present, the rest of quartz forms a granoblastic groundmass transcected by bands of slightly coarser, platy, muscovite, shistose in the direction of banding. If augen are present the folia of muscovite wrap around the augen to some degree. In those facies with chlorite the chlorite flakes are either parallel to the schistosity or the chlorite occurs in typical lenticular grains, lying parallel to the schistosity. In these grains the direction of cleavage of the mineral is perpendicular to the schistosity.

The very fine-grained accessory minerals are mostly auhedral and are scattered throughout the rock.

Quartz-feldspar-mica schist

The quartz-feldspar-mica schists, which constitute a major part of the metasedimentary series, are characterized by a moderate content of quartz, varying amounts of both potash feldspar and plagioclase, and the presence of both light and dark mica, with biotite normally dominant over muscovite. The feldspars combined generally make up half of the schists, whereas the total quantity of mica rarely exceeds 10 percent. Magnetite and apatite are nearly everywhere present in very minor amounts, although one specimen containing about 4 percent magnetite was observed, and in a few instances sphene is present in small traces. Some of the apparently more highly metamorphosed schists contain, in addition, traces of garnet. Late-forming minerals, such as sericite, chlorite, and zoisite, occur in varying amounts in about half of the schists, and a trace of kaolin was observed in all of the rocks of this type.

Texturally, the quartz-feldspar-mica schists show considerable variation, but all are fine grained, and they are characterized both by a well developed orientation of the micas, with little or no tendency towards crenulation, and by the lack of any outstandingly coarse metacrysts. Some types are very fine grained, averaging about 0.2 milimeters grain size, and more or less equigranular, whereas others are somewhat coarser and seriate or slightly porphyroblastic. In all cases the quartz and feldspars, excluding microcline, form a fine granoblastic groundmass, and, in the inequigranular types, some of the quartz forms coarser grains or the microcline or plagioclase forms anhedral, irregular, and highly poikiloblastic metacrysts. With the exception of one bedof quartz-feldspar-mica schist that occurs next to an intrusion of rhyolite, and which is believed to have been somewhat feldspathized by the intrusive material, the microcline, where present, is coarser than the groundmass, highly poikiloblastic, and accompanied by small myrmekitic intergorwths of quartz and feldspar. Some of the plagioclase, in a few instances, shows the same poikiloblastic development.

As a rule the micas are somewhat coarser than the groundmass and platy, showing a well developed schistiosity. Magnetite is fine grained and equidimensional, in some places anhedral and in other instances fairly well recrystallized. Similarly, apatite is fine grained and generally subhedral and equant. Garnet, where present, is coarser than the groundmass, subhedral, equant, poikiloblastic, and crowded with inclusions of quartz.

Structurally the quartz-feldspar-mica schists present considerable variation also. Apart from the schistosity of the micas some of the schists are essentially homogeneous, showing no tendency toward a layering of the constituents. On the other hand, other quartz-feldspar-mica schists have a well developed textural and compositional banding or layering. Generally mica-magnetite-garnet rich bands alternate with coarse quartz bands or fine quartz-feldspar bands. The width of the banding is, for the most part, several times the diameter of the average grain. This together with the stringer-type distribution of the magnetite strongly suggests that the banding represents palimpset bedding and not gneissic segregation. Such an interpretation seems especially likely since the banding occurs, as will be shown later, most prominantly in the lower grade metamorphic rock types. However, in all cases, the schistosity is essentially parallel with the banding.

"Knoten schist"

The coarser schists display a much greater variety of composition than do any of the other well defined groups of rocks in Hopewell series. This is probably due both to differences in original composition between the members of this group and to differences in degree and type of metamorphism, which, in this area seem to be highly dependent on the original constitution of the rocks. All of the coarser schists are grouped together as "knoten schist" because they possess certain textural and structural features in common, and because they grade into one another. In all the "knoten schists" quartz is the dominant constituent, and a certain amount of plagioclase is present. Orthoclase may or may not be present. Biotite is a distinctive but minor component, and in places muscovite constitutes as much as 25 percent of the rock. Magnetite and apatite are present in amounts similar to those in all the other schists, but sphene is conspicuously absent. Traces of zircon and tourmaline were also observed in some facies. Most characteristic of the "knoten" schists, however, are the coarse metacrysts of such typical metamorphic minerals as garnet, kyanite, sillimanite, and rarely staurolite. Sillimanite in some places constitutes as much as 25 percent of the rock. Late-forming minerals and weathering products, such as chlorite and kaolin, are also present in traces. A comparison of the details of composition of all of the metasedimentary types is given in Plate V.

The "knoten schists" display so much variation in texture that it is difficult, if not impossible, to make a true generalized statement about the texture of the group taken as a whole. Quartz, in all instances is anhedral, in some places forming a rather fine grained granoblastic groundmass with orthoclase or some of the plagioclase, and in other cases is merely interstitial

Plate V Composition of the Hopewell metasedimentary schists.

Minerals	Quartz-muscovite schists		Quartz-feldspar-mica schists						"Knoten" schists		
Quartz	70%	85%	15%	35%	35%	45%	40%	45%	35%	60%	50%
Plagioclase	Olig. 20%	--	And. 25%	And. 30%	And. 5%	And. 30%	Olig. 15%	--	And. 30%	Olig. 15%	Olig. 10%
Orthoclase Microcline	-- --	-- --	15% 40%	10% 15%	10% 35%(#)	10% --	35% --	35% --	-- --	15% --	-- --
Biotite	--	--	3%	7%	10%	3%	2%	2%	3%	3%	5%
Muscovite	7%	15%	0.5%	1%	2%	3%	1%	2%	25%	0.5%	10%
Magnetite	1%	trace	3%	1%	0.5%	trace	2%	4%	2%	0.5%	2%
Apatite	0.5%	trace	0.5%	1%	0.5%	trace	trace	trace	0.5%	trace	0.5%
Garnet	--	--	--	--	--	--	trace	trace	2%	--	0.5%
Chlorite	2%	--	--	trace	--	--	0.5%	--	--	0.5%	trace
Sericite	trace	--	trace	trace	--	--	0.5%	--	--	--	--
Others	zoisite trace, tourmaline trace	zircon trace, tourmaline trace	kaolin trace, zoisite trace ?	kaolin trace	hematite t, kaolin trace, zircon trace ?	kaolin trace, zoisite trace ?	kaolin trace	kaolin trace, zoisite trace?, Fe sulfates t	kaolin trace, hematite t, tourmaline 5%	kyanite trace, fibrolite 3%, zircon trace	epidote trace, zoisite trace, fibrolite 25%

Percentages estimated visually.
Samples arranged in approximate order of increasing degree of metamorphism.
(#) Microcline introduced from intrusive rhyolite.

between folia of mica and knots of sillimanite. The groundmass of all the knoten schists is coarser than that of the other metamedimentary rocks, as it averages about 0.5 milimeter in grain size. Plagioclase in the "knoten schists", in many instances, forms metacrysts 1 to 2 milimeters in diameter. These are anhedral and extremely poikiloblastic, and the inclusions, chiefly mica and quartz, in places, are well oriented. The micas are coarser than the groundmass, platy, and highly schistose, but the planes of schistosity are in many instances crenulated in one centimeter waves or wrap around the dense metacrysts and knots of the coarser constituents. In places coarse muscovite itself may form some of the knots around which the folia wrap. Magnetite is generally coarser than the groundmass, euhedral, and equant, and apatite and tourmaline are usually fine grained, euhedral, and equant or slightly prismatic.

The minerals of the "knoten" are of special interest, particularly because they are all indicators of the higher grades of metamorphism. Garnet is commonly found in the "knoten schists", but not usually in such coarse grains as to give a knotty appearance to the rocks. Kyanite occurs in very coarse, long, bladed crystals, which mark a very distinct facies of the schists. The crystals generally are very ragged and poikiloblastic. In places the kyanite has altered to coarse muscovite, or in other instances it has given place to a felted mass of the fibrolite variety of sillimantite. Fibrolite also forms coarse "knoten" by itself, or in some places contains nuclei of coarse and fine garnets. Very coarse staurolite metacrysts were observed in the field, but not in any of the thin-sections.

In addition to the schistosity, some gneissic banding has developed in a few of the "knoten schists", notably the kyanite types. The wavy schistosity, curved gneissic banding and twisted knots of sillimanite give an impression of turbulent flow in some facies.

One other structure, observed in the kyanite schists, deserves mention at this point. In one specimen tiny feathers of inclusions with delicate labyrinthine patterns were developed in fracture planes and twin planes within the grains of quartz and feldspar, and on the surfaces between the grains. As these minute structures definitely lack angular boundaries they are most likely liquid or gaseous inclusions. The specimen in which they occur is highly weathered, and it is possible that they have been produced by weathering processes.

Metamorphism of the Hopewell schists

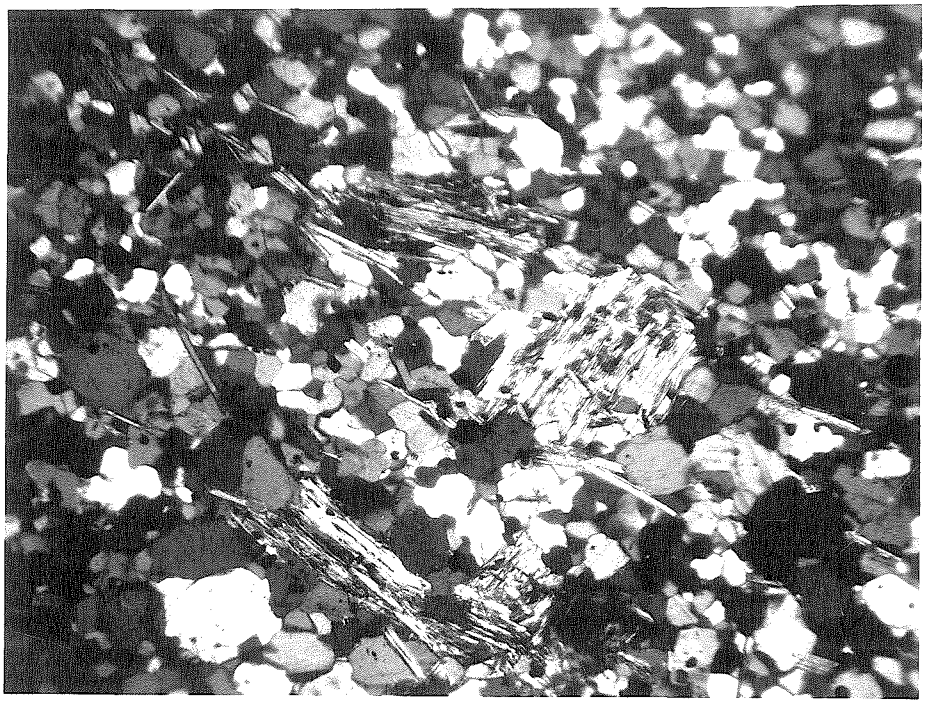
Doubtless much of the difference between the various members of the Hopewell series is due to differences of the original constitution of the rocks, but through the group as a whole a certain sequence of metamorphism is manifest. Furthermore, low-grade metamorphic rocks such as the quartz-muscovite schists occur in the same vicinity as high grade metamorphic types like the "knoten schists". Therefore it is probable that some of the original properties of the rocks, for instance bulk composition and permeability, have played a large part in determining the grade of metamorphism developed.

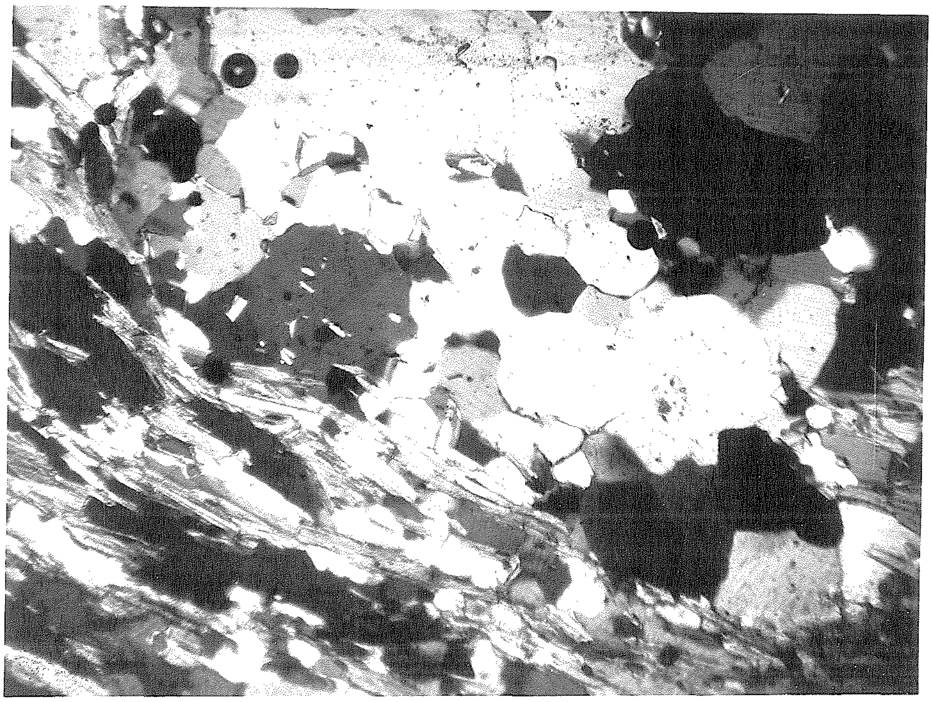
Sequence of metamorphism in the metasedimentary schists

The lowest grade of metamorphism observed in the area is represented by the chloritic quartz-muscovite schists. These, as can be determined from their bulk composition must have been silty or argillaceous sandstones. Quartz and tourmaline are completely recrystallized, and some of the original argillaceous component has been converted to a calcic oligoclase or sodic andesine. The lime content of the plagioclase possibly was derived from a trace of calcareous material in the original sediment. Some chlorite is present (Figure 9) but most of it has been replaced by muscovite. The magnetite grains are fine, subhedral and equant; possibly they

Figure 9. Chloritic quartz-muscovite schist with the typical grains of chlorite in which the cleavage is perpendicular to the schistosity and the long dimensions of the grains are parallel to the schistosity. Note also the fine euherons of magnetite. (crossed nicols, X54)

Figure 10. A portion of an auge with the muscovite folia wrapping around it in a quartz-muscovite schist. (crossed nicols, X54)





were recrystallized before metamorphism took place, or perhaps they are in their detrital form. Original bedding is well defined by folia rich in chlorite, muscovite, magnetite, and apatite, and by layers of somewhat coarser quartz. The well developed schistosity is parallel to the bedding.

A slightly higher stage of metamorphism is represented by the somewhat coarser quartz-muscovite augen schist. Because of a higher percentage of quartz and an originally coarser texture, this schist must have been a somewhat purer type of sandstone than were the chloritic schists. Quartz and tourmaline are recrystallized, and the muscovite, folia of which clearly define original argillaceous laminae, is considerably coarser than the muscovite in the chloritic types. There is no trace of chlorite; it either has been completely altered to muscovite or was never present to begin with. Most distinctive of this stage, however, are the small augen structures (Figure 10) where originally coarser grains of quartz were being broken down in the course of metamorphism. The folia of mica wrap around the augen.

Higher grades of metamorphism are represented by the quartz-feldspar-mica schists, which show a considerable range of metamorphic degree among themselves. As they contain less than 50 percent quartz and large amounts of alumina, which has been incorporated into the feldspars and micas, these schists must have been argillaceous and consequently fine grained sediments to begin with. They probably lay mostly within the range of siltstones. Varieties rich in microcline contain a much higher percentage of potash than is normally present in silty sediments, and this fact, together with the porphyroblastic, poikiloblastic occurrence of the microcline (Figure 11) and the concurrent presence of myrmekites, implies as introduction of certain amounts of potash by solutions involved in the metamorphic processes. Similar poikiloblastic development of some of the plagioclase, in a few cases, suggests some introduction of soda also. As a group, the quartz-feldspar-mica schists are set apart as an advanced stage over the quartz-muscovite schists by the consistent presence of biotite, which has probably formed at the expense of muscovite.

Traces bedding are marked by bands of coarser quartz. In the lowest grade of quartz-feldspar-mica schist observed, which incidentally contains about 40 percent coarse poikiloblastic microcline the plagioclase is andesine, and biotite constitutes about 85 percent of the mica present. A large amount of anhedral and mostly fine grained magnetite is present. Schistosity of the mica is only moerately well developed.

In a somewhat higher stage more of the muscovite has been converted to biotite, and the magnetite is much coarser and subhedral. Potash has been introduced to form coarse microcline, and, in this instance, some of the andesine seems to have been hydrothermally enriched also. The rock has a prominent fissility due to a higher percentage of very schistose mica, and a faint suggestion of bedding is still present.

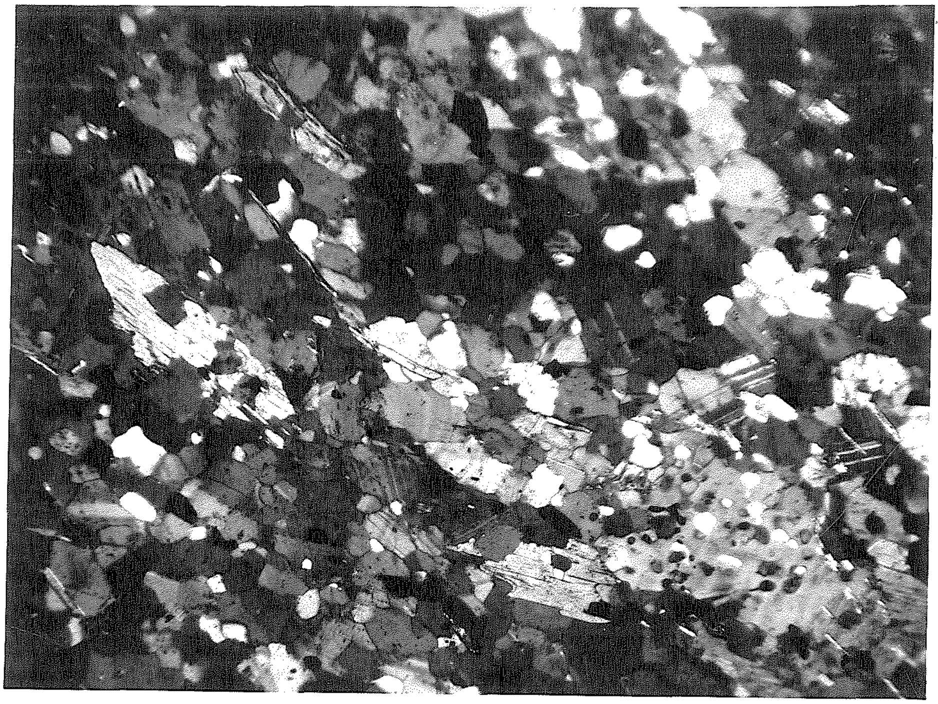
A quartz-feldspar-mica schist of a seemingly still higher metamorphic grade contains poikioblastic metacrysts of both andesine and orthoclase. The orthoclase has probably recrystallized from previously formed metacrysts of microcline. Biotite and muscovite are present in equal quantities, but there is very little magnetite, so that further conversion of muscovite to biotite has probably been prevented by the lack of iron. What magnetite is present is euhedral. Some of the quartz seems to have become coarser by recrystallization, and there is a suggestion of the beginning of gneissic banding. Schistosity is well developed in the micas.

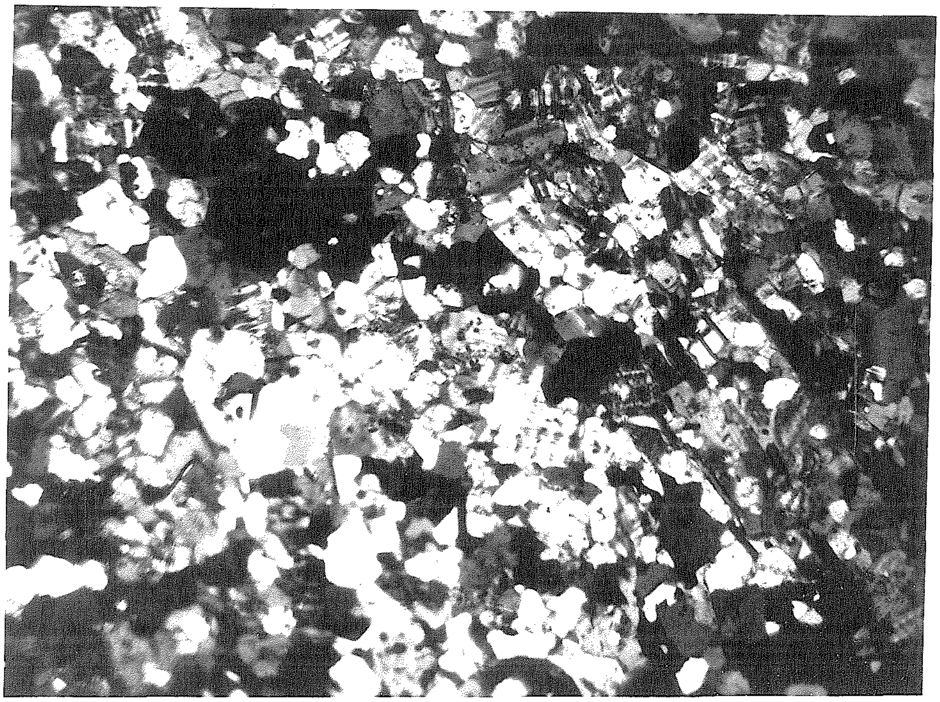
In view of its general texture, the quartz-feldspar-mica schist adjacent to the large rhyolite intrusion probably lies somewhere in this range of metamorphic grade. Here, however, the microcline content probably has a different origin than that in the other schistsof the same general type. The microcline together with quartz forms a fine granoblastic groundmass (Figure 12), but the plagioclase displays a poikiloblastic texture. This suggests that the microcline from the intrusive rhyolite was introduced, before general metamorphism set in, and that the plagioclase was hydrothermally enriched as in the cases discussed before. Biotite occurs in considerable predominance over muscovite, and the magnetite is completely recrystallized into small equant euhedrons. The rock is fairly fine grained, averaging about 0.2 milimeter in grain size, and coarser grains and stringers of quartz mark palimpset bedding.

The highest metamorphic grades of quartz-feldspar-mica schists are distinguished by the presence of garnet. There is also a dissappearance of microcline and a decided increase in orthoclase at this stage. The orthoclase in some facies is poikilitic, and it is logical to suppose that what might have been originally microcline has been converted to orthoclase. Then the temperature point of inversion from microcline to orthoclase approximately coincides with the temperature point of formation of garnet, in this instance. Texturally the schists remain about the same with this advance in metamorphism, as the garnets are as fine grained as the

Figure 11. Quartz-feldspar-mica schist with poikiloblastic metacrysts of microcline (lower right). (Crossed nicols, X54)

Figure 12. "Feldspathized" quartz-feldspar-mica schist with fine granoblastic groundmass of quartz and microcline. (Crossed nicols, X54)



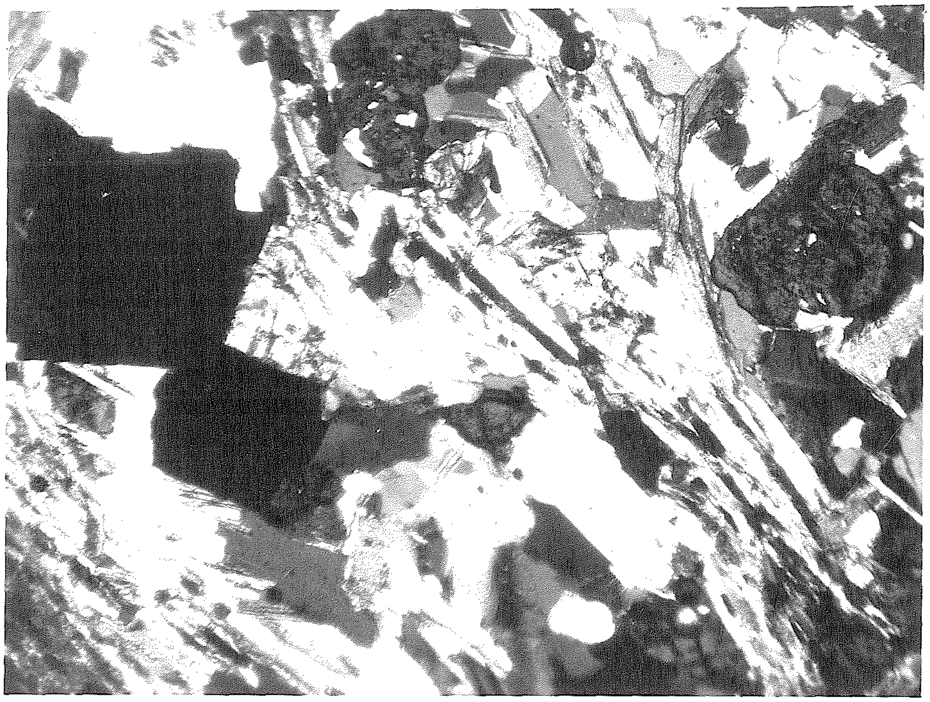


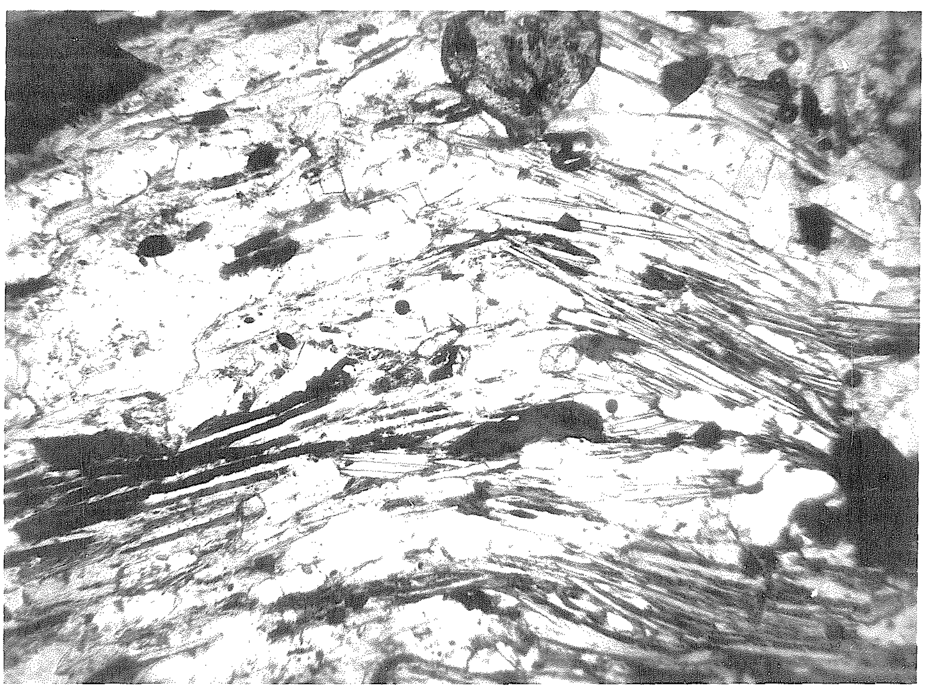
fine grained as the groundmass. Traces of bedding, even in this stage, are perfectly preserved, outlined by quartzose layers alternating with feldspathic and mica-garnet-magnetite layers. It is noteworthy that with advancing metamorphism muscovite has considerable stability, even in the presence of a large excess of magnetite.

Although there appears to be a continuous gradation between "knoten" schists and the finer quartz-feldspar-mica schists, both in spatial relationship and in rock type, the finer "knoten schists" (Figure 13) seem to mark a distinct advance in metamorphism. They still belong in the garnet stage, but the garnets have become much more numerous, scattered throughout the rocks as fine to medium, subhedral, equant, poikiloblastic grains. Magnetite is present as medium grained equant euhedrons. Metacrysts of andesine two to three milimeters in diameter are anhedral and polilloblastic, and their inclusions in many places show a well developed shistosity. Even the finer-grained "knoten schists" are, as a whole, much coarser than the quartz-feldspar-mica schists, and average about a milimeter in grain size. The original structures are completely obliterated. Schistosity is very pronounced, particularly because of the high proportion of muscovite (about 25 percent), and the planes of schistosity are crenulated in waves about a centimeter

Figure 13. Fine grained "knoten schist" with poikiloblastic garnets, equant euhedrons of magnetite and strongly schistose muscovite. (crossed nicols, X54)

Figure 14, Fine grained "knoten schist" showing crenulation of muscovite folia. (plain light, X42)





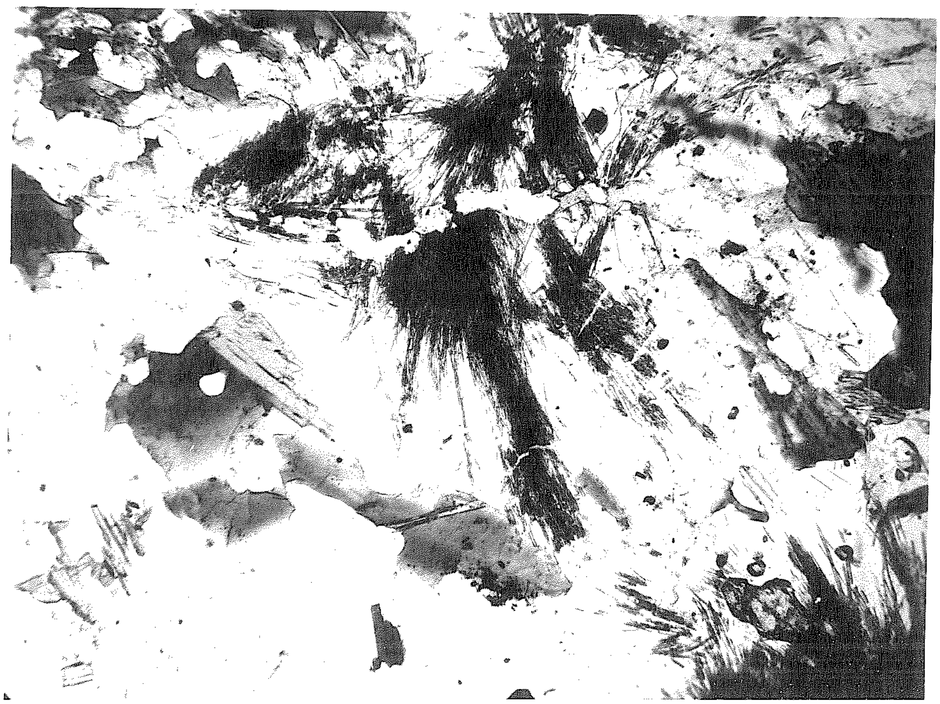
in length (Figure 14). This high proportion of muscovite is probably merely indicative of a high proportion of argillaceous materials in the original sediment. The presence of somewhat less than 0.5 percent of tourmaline is possibly indicative of some pneumatolitic introduction of borates, but the tourmaline is just as likely of detrital origin.

Further metamorphism results in the development of coarse elongate, ragged, extremely poikiloblastic metacrysts of kyanite several centimeters in length in some instances, (Figure 15). If the bulk composition is just right, metacrysts of staurolite are present instead. With little further increase in the degree of metamorphism, "knoten" of fibrous sillimanite begin to develop (Figure 16) starting as small radiating clusters of minute prismatic crystals. The grain size at this stage is still coarser than in the previous stages, and a distinct gneissic banding is observable in the hand specimens. In the kyanite schists all of the muscovite seems to be secondarily produced after kyanite, and it is possible that all of the muscovite present in the highest grade metamorphic type schists is the result of retrogressive metamorphism.

In the most highly metamorphosed sedimentary rocks observed in the area, large knots of sillimanite, a centimeter or larger, are developed, which commonly

Figure 15. "Knoten schist" with extremely ragged metacryst of kyanite associated with fairly coarse muscovite. (plain light, X54)

Figure 16. "Knoten schist" with both minute and well developed radial clusters of sillimanite. Note also the garnet and coarse biotite. (plain light, X42)

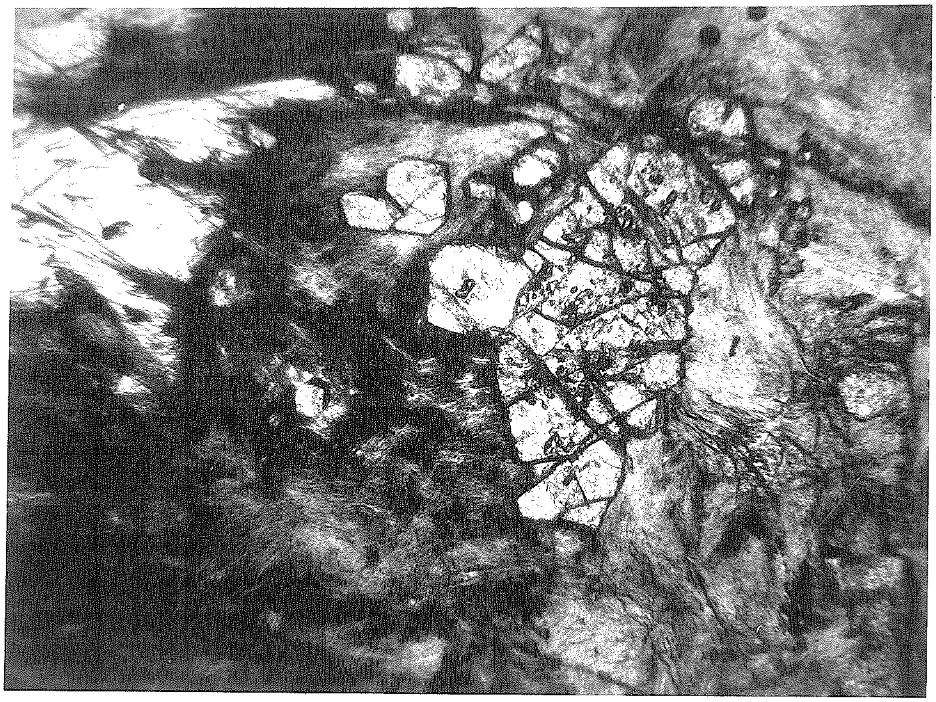


contain nuclei of garnets (Figure 17). Minute clusters of sillimanite needles also occur, indicating that the knots do not represent pseudomorphs of sillimanite after kyanite or some other mineral. Instead, judging from the association of the garnets, the sillimanite was probably formed at the expense of the biotite scattered throughout the rock. Smaller metacrysts of highly poikiloblastic oligoclase, and coarse aggregates of muscovite are also present. The muscovite "knoten" are very likely pseudomorphous, retrogressive alterations of kyanite (Figure 18). The high grade "knoten schists" are much coarser than any of the other schists, averaging about 3 milimeters in grain size, and schistosity of the micas is very well developed, the mica folia wrapping around the metacrysts and the "knoten". Both the fibrous sillimanite masses and the warped mica folia give the impression of turbulent flow within the rock.

The effects of retrogressive metamorphic alteration are absbservable in both the knoten schists and the quartz-feldspar-mica schists. Biotite and garnet revert to chlorite and all types of feldspars may be moderately sericitized. The kyanite of the knoten schists is commonly nearly entirely replaced by coarse muscovite.

Figure 17. A sillimanite knot, with garnet nuclei, in the coarse "knoten" schist. (plain light, X42)

Figure 18. A muscovite knot, with muscovite folia wrapping around it, in the coarse "knoten schist". (crossed nicols, X42)



CONCLUSIONS AND GEOLOGIC HISTORY

Formation and metamorphism of the Hopewell series

Conditions of deposition of the Hopewell sediments

As the Hopewell series has undergone a more or less high degree of metamorphism, all information about the original constitution of these rocks must necessarily be inferential. However, the composition of the schists gives certain clues to some of the original lithologic characters, and, in the instance of the low metamorphic grade muscovite schist, the small augen furnish further evidence concerning the original texture of that rock.

The high content of quartz in the quartz-muscovite schists indicates fairly clearly that they represent metamorphosed sandstones, and the augen structures demonstrate that at least some of these sandstones were fairly coarse grained. Furthermore, the chlorite and muscovite present suggest that these sandstones were more or less impure or argillaceous, although a certain percentage of the mica may be attributable to the introduction of mica forming materials, principally potash and water, by metasomatic processes.

The quartz-feldspar-mica schists were undoubtably of a more argillaceous composition to begin with than were the quartz-muscovite schists, although, here again, metasomatic processes have possibly introduced more potash and soda than was originally present in the rocks. The natural corollary of more argillaceous composition is finer grain size, and therefore it seems most likely that the quartz-feldspar-mica schists were siltstones, some facies with more quartz, perhaps more sandy, and others probably even grained. As the higher grade metamorphic types, the "knoten schists", contain a somewhat higher percentage of quartz than do the quartz-feldspar-mica schists they probably represent coarser siltstones or very fine argillaceous sandstones.

These sediments, as has been shown, were interbedded with flows of basalt and tuff beds, the pyroclastic materials of the tuff being intermixed in some places with a certain amount of normal sedimentary material. Later the strata were intruded by sill-like bodies of rhyolite. The metarhyolites, which represent a separate unit in the time sequence of the pre-Cambrian history of the area, should remain under a separate classification as the Vallecitos rhyolites.

However, the metabasalts since they are interstratified with the metasedimentary rocks would be more properly referred to the particular metasedimentary series with which they are correlative. Thus, the metabasalts should be called the Picuris basalt phase of the Hopewell series, and the basalts interstratified with the Ortega quartzite should be given a new name.

The series of sediments outlined above is typical of shallow marine, offshore deposits. Continental conditions of deposition for these sediments is not as likely because of the lack of rock types that might be interpreted as originally coarse or conglomeratic sedimentary rocks. This, however, is by no means conclusive. Just's[32] interpretation of geosynclinal deposition certainly seems reasonable in light of the evidence present in the Ojo Caliente district.

Degree and type of metamorphism

The degree of metamorphism attained in the area, as has been shown by the fairly well defined sequence of metamorphism that can be demonstrated, is highly variant from one stratum to the next. Considering the high degree of schistosity developed in many of the rock types, and the presence of typical stress minerals such as kyanite and staurolite, the type of metamorphism that has been operative can be broadly classed as regional metamorphism. But the general constancy of metamorphic degree, or the zoning of metamorphic degree that has been described from other areas seems to be lacking. In fact, a bed of chloritic quartz-muscovite schist is adjacent to a stratum of

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32 Just, Evan, Op. cit., p. 12.

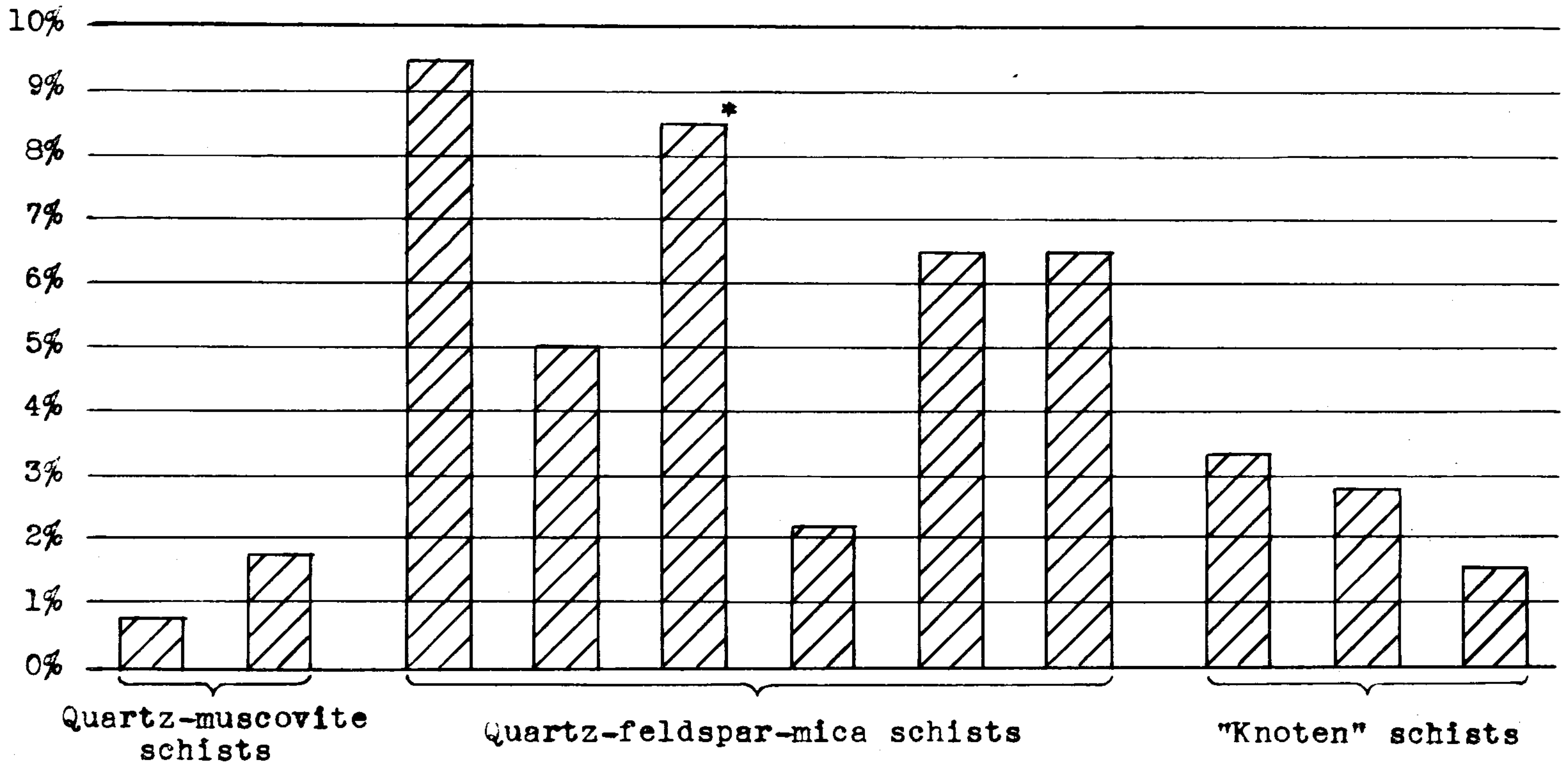
kyanite-sillimanite knoten schist. In other words, the lowest grade metamorphic types are adjacent to the highest grade metamorphic types observed in the area, which means some rock types do not reach equilibrium at the greatest intensity of metamorphism. This definitely implies that the grade of metamorphism developed is in a large part controlled by the original nature of the rocks upon which the metamorphic processes are operative. Therefore, variation of metamorphic effect observed is roughly controlled by the bedding. The maximum degree of metamorphism imposed upon the rocks is indicated by the "knoten schists", which, by the zoning scheme, can be referred to the sillimanite zone. However, the Metamorphism was not so intense as to destroy the well developed schistosity in these rocks, to increase the grain size to a very large extent, or to develop any pronounced gneissic banding.

Superimposed upon the effects of a simple combination of thermal and dynamic metamorphism may be seen the fairly well defined effects of metasomatism or hydrothermal action. It is extremely improbable that most of the original sediments should contain the large amount of potash which many of the metasedimentary rocks now possess. Potash is a very soluble constituent of rocks and is nearly always carried off in solution in the processes of weathering and erosion, not to be precipitated again with clastic and suspended sediments. The variation in potash content of the metasediments is tabulated in Plate VI. The anhedral, poikiloblastic, porphyroblastic occurence of much of the potash feldspar with associated myrmekites further corroborates the interpretation of metasomatic introduction of potash. Certain similar occurrences of plagioclase suggest a concomitant metasomatic introduction of soda also.

Here, then, seems to be good evidence that the processes of metamorphism are carried out by solutions, not only in water indigenous to the rocks, but also by hydrothermal solutions, introduced perhaps from some magmatic source such as must frequently if not always be responsible for most of the rise of thermal gradient involved in regional metamorphism. The grade of metamorphism, under the conditions of infiltration of hydrothermal waters, would then be partly a function of the permeability of the rocks and their reactions to these solutions. Therefore, since such properties as permeability vary with different beds, the metamorphic grade should, to some extent, be bedding controlled, and this, as is demonstrated, is exactly the case in the Ojo Caliente district.

Finally, the relation between the deformation observed in the rocks and the processes of regional

Plate VI **Potash** content of the Hopewell metasedimentary schists.



Samples arranged in approximate order of increasing degree of metamorphism.

Percentages calculated from estimated mineralogical compositions given in Plate V.

* In this sample a large part of the potash content was introduced in microcline from an intrusion of rhyolite.

metamorphism that have taken place should be considered. Normal regional metamorphism usually involves acute shearing stress, and this generally results in considerable deformation such as overthrusting or tight folding. The beds in the Ojo Caliente district are dipping steeply, and, undoubtably, some of their deformation must logically be attributed to the metamorphic stresses that have been operative. However, the dome shape of the large intrusive body of metarhyolite suggests that much of the deformation resulting in the dome was associated with the intrusion of the rhyolite prior to metamorphism. Furthermore, in the long span of geologic time since the pre-Cambrian, many tectonic forces could have acted on this region since the metamorphism took place. Therefore, it is not safe to correlate all of the present structures in the pre-Cambrian rocks of the area with the dynamic forces that were involved in the processes of metamorphism.

Sequence of geologic events

The probable sequence of geologic events recorded in the rocks of the Ojo Caliente district is as follows:

1) Deposition of the Hopewell sediments and concomitant extrusion of the Picuris basalt phase during pre-Cambrian time.

2) Subsequent intrusion of Vallecitos rhyolites with a certain amount of deformation associated with the

intrusion. Also, additional deposition of rock burying the Hopewell series deeply.

3) Transformation of the Hopewell series and Vallecitos rhyolites, involving dynamic, thermal, and metasomatic metamorphism.

4) Intrusion of pegmatites, and perhaps hypersthene gabbro, later in pre-Cambrian time.

5) A great unrecorded period including the Paleozoic and Mesozoic eras, represented by the angular unconformity between the pre-Cambrian and Tertiary rocks.

6) Displacement along the Caliente, El Rito, and some minor faults in pre-El Rito time.

7) Deposition of the El Rito (?) conglomerate in the early Tertiary.

8) Deposition of the Caliente conglomerate, probably later in the early Tertiary.

9) Erosion before deposition of late Tertiary beds.

10) Deposition of the Abiquiu tuff and concomitant extrusion of basalts during the upper Miocene.

11) Deposition of the Santa Fe formation lasting probably until the Middle Pliocene.

12) Displacement along the El Rito and some minor faults in late Pliocene or early Pleistocene time.

13) Formation of the Owl Cliff tufa and the terrace deposits during the Pliestocene, the deposition of tufa continuing on to the present.

14) Continued erosion, developing the landscape to the mature stage at the present time, and the formation of recent alluvium.