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CONTACT METAMORPHISM OF THE ROCKS IN THE PEND OREILLE DISTRICT, NORTHERN IDAHO

BY

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CONTACT METAMORPHISM OF THE ROCKS IN THE PEND OREILLE DISTRICT, NORTHERN IDAHO

By JOSEPH L. GILLSON

ABSTRACT

In the Pend Oreille district, Idaho, a section of sediments, part belonging to the Belt series, of Algonkian age, and part to the Cambrian system, was intruded and intensely metamorphosed by granodiorites of late Mesozoic or early Tertiary age. This metamorphism proceeded in three overlapping stages. During the intrusion of the igneous rocks a general recrystallization of the sediments took place, the siliceous rocks changing to adinoles near the contacts and to plagioclase-bearing rocks at greater distances and the limestones turning to marbles. Later, during the crystallization of the granodiorites, emanations carrying the so-called mineralizers were given off in quantity and formed high-temperature silicates in the sediments. Still later, after the igneous rocks had solidified and the temperature of the masses had become lower, sericite, chlorite, serpentine, magnetite, and sulphides were formed by replacement of the earlier minerals. Although no rare minerals were found in the contact zones, more than 50 minerals common to such zones were identified.

LOCATION AND GENERAL GEOLOGY

The Pend Oreille silver-mining district lies in Bonner County, in the panhandle of Idaho, and is adjacent to the south arm of Pend Oreille Lake, a large body of water lying in a tremendous glacier-cut trough. (See fig. 16.) An area about 15 miles wide and 20 miles long was studied by a party of the United States Geological Survey under Edward Sampson in the summers of 1921, 1922, and 1924, and in the support of this study the Idaho State Bureau of Mines and Geology kindly cooperated.[1]

The district is underlain by sediments of Algonkian age (the Belt series) and Cambrian age intruded by igneous rocks, the largest masses of which, at least, are of late Mesozoic or early Tertiary age. These igneous rocks, which crop out over about one-fifth of the land area, have already been described by the writer.[2]

The surface character of a part of the district and some of the geologic features are shown in Figure 17.

THE PROBLEM

The intrusion of the igneous rocks was accompanied by metamorphism so intense that in few places are the sediments free from its effects. The study of the rocks of the district has shown that the process of igneous metamorphism was long continued, and

FIGURE 16.—Map of the Pend Oreille area, Bonner County, Idaho. Stippling indicates zones of intense contact metamorphism

that conditions progressively changed during the crystallization of the magma. Three periods or stages in the metamorphism can be recognized, and the chief purposes of this paper are to prove that these stages occurred and to describe them. The calcareous rocks were changed in a different manner from the non-

[1] Sampson, Edward, Geology and silver-ore deposits of the Pend Oreille district, Idaho: Idaho Bur. Mines and Geology Pamph. 31, 1928.

[2] Gillson, J. L., Granodiorites in the Pend Oreille district of northern Idaho: Jour. Geology, vol. 35, pp. 1-31, 1927.

calcareous rocks, and the difference indicates that the primary character of the sediments was an important factor in the metamorphism. Furthermore, considerable material was introduced during all three stages of the metamorphism.

THE ROCKS PRIOR TO METAMORPHISM

The section of Belt rocks in the Pend Oreille district is similar to that in the near-by Coeur d'Alene district, described by Ransome and Calkins.[3] The Pend Oreille section differs principally from that in the Coeur d'Alene district in that the rocks at the horizons of the Revett and St. Regis formations—that is, the rocks underlying the Wallace formation and overlying the Burke formation—are more siliceous, and a new name, Blacktail formation, has been given to them. The Belt rocks are chiefly argillites and quartzites of great thickness, and the strata differ only in color and in the proportions of argillaceous and siliceous material. They are affected by load metamorphism, and where not contact-metamorphosed they consist almost entirely of quartz and white mica. Under the microscope the quartz grains appear detrital and each is surrounded by a film of finely divided mica. In the more argillaceous beds the mica flakes are very abundant and tend toward a general orientation with their flat sides parallel to the bedding. The rocks are almost everywhere devoid of flow cleavage and preserve such sedimentary features as ripple marks, cross-bedding, mud cracks, clay galls, and rarely casts of salt crystals. The Wallace formation, which overlies the Blacktail, differs from the rest of the series in that it contains almost throughout a considerable amount of calcite, which is present in very peculiar structures, considered to be of algal origin. The Striped Peak, the uppermost formation of the series, is also locally calcareous.

Belt sediments.—The beds of the lowest formation, the Prichard, consist of dark-colored argillite and grayish quartzite. Some beds of the quartzite are fairly coarse grained. Many of the beds are closely laminated, owing to frequent alternations of sand and mud in deposition. The argillaceous layers are thin, black, and in many places very closely spaced.

The Burke formation, which overlies the Prichard, consists of thin layers of medium-gray fine-grained light-weathering quartzite interbedded with dark-gray siliceous argillite, the bedding surfaces of which are micaceous, are either green or nearly black, and exhibit conspicuous mud cracks. Some of the quartzite has a distinctly bluish tint on fresh fracture. Some beds are laminated; others are not. Some thick masses of heavy-bedded light-colored quartzite also occur.

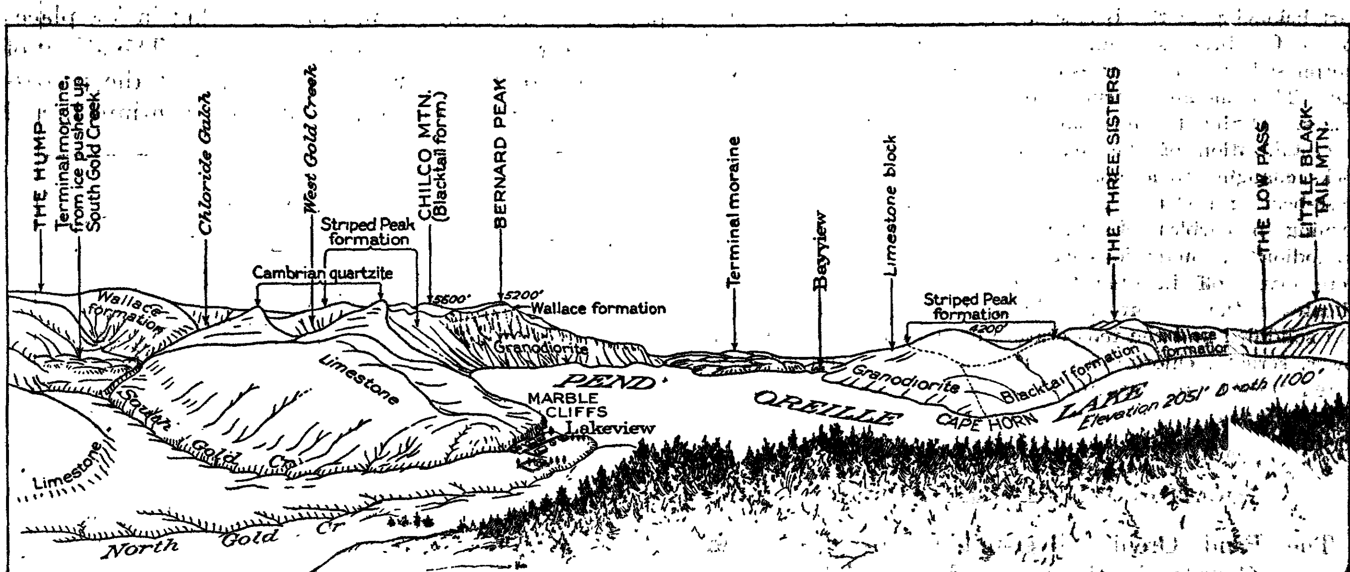

FIGURE 17.—Sketch from photographs taken from hill north of Lakeview, Idaho, looking west and south

The lower part of the Blacktail formation, which overlies the Burke, is dominantly a very massive bluish-gray quartzite that weathers nearly black and breaks into large rectangular blocks. On exposed faces across the bedding discontinuous grayish or purplish bands occur, abundant in some beds, rare or absent in others. The bedding surfaces are thin shaly partings, purple or maroon, lustrous and conspicuously mud cracked and ripple marked. The upper part of the formation is more argillaceous, and the purple shaly partings are closely spaced. Many layers of the upper part are green but do not differ otherwise from the rest.

The lithology of the succeeding Wallace formation is varied, but two features appear in so many of the beds that its identification was usually simple. The argillaceous partings of thin-bedded quartzite expose a bedding surface of lustrous black, on which are con-

[3] Ransome, F. L., and Calkins, F. C., Geology and ore deposits of the Coeur d'Alene district, Idaho: U. S. Geol. Survey Prof. Paper 62, pp. 29-44, 1908.

A BLOCK OF THE WALLACE FORMATION, 10 BY 18 BY 24 INCHES IN SIZE, FOUND ON THE BEACH OF PEND OREILLE LAKE NEAR TALACHE, IDAHO

Shows the peculiar contorted cavities caused by the more rapid solution of the calcite bodies than of the rest of the rock. These cavities are believed to be of algal origin.

spicuous mud cracks. Also, the peculiar structures of calcite above mentioned are especially diagnostic. The calcite masses are fine grained, and most of them are elongated in two directions at right angles. The vertical cross section is the most striking. It shows a peculiar wavy band from 0.5 to 4 millimeters wide and from 0.5 to 6 centimeters high. Some cross sections resemble a question mark into which a few extra crooks have been put. Owing to the more rapid solution of the calcite these structures are represented on weathered surfaces by cavities, and by them the formation was generally distinguished. (See pl. 15.) These calcite masses modified the metamorphism to a different type from that prevailing in the surrounding noncalcareous materials, and in intensely metamorphosed beds they were seen as pseudomorphs. Argillaceous beds of the Wallace are black on fresh fracture but weather buff. A flinty green argillite is found at the bottom of the formation, and at the top the beds are closely laminated, similarly to those in the Striped Peak formation.

The Striped Peak, the top formation in the Belt series in the Pend Oreille district, is a thin-bedded fissile dark-gray argillite with interbedded white quartzite. Brick-red is the predominant color on exposed surfaces. Mud cracks and ripple marks, few of which are more than a centimeter in width, are conspicuous on the beds. The intercalation of many thin argillite and quartzite layers, 15 or 20 to the inch, is a characteristic feature of the formation. A considerable thickness of the Striped Peak differs, however, from the main type and is an unlaminated olive-drab graywacke. At least at one horizon the upper part of the formation contains irregular masses of calcite similar to those in the Wallace.

Cambrian sediments.—The Cambrian rocks comprise a massive conglomeratic quartzite, a thin-bedded friable shale, locally fossiliferous, and a thick limestone with several facies, fossiliferous at some horizons. The quartzite probably corresponds to the Flathead quartzite of Montana; the shale contains a small fauna of Middle Cambrian age. The fossils of one stratum of the limestone correspond with those of the Langston limestone of the Blacksmith Fork section in Utah, and a shale in the limestone may be correlated with the Spence shale member of the Ute limestone of Utah.[4]

THE METAMORPHISM

GENERAL FEATURES

Each sedimentary formation was found to be profoundly metamorphosed somewhere in the district, and each was nearly everywhere slightly metamorphosed. The zones of intense metamorphism, in which complete recrystallization had taken place with an almost total elimination of sedimentary characters, are relatively small, few being more than 200 yards wide on the surface. Marmarization of the limestones, however, was more widespread, and at some places marbles occur without near-by exposures of igneous rock.

The metamorphism of the Prichard, the Burke, the Blacktail, the noncalcareous part of the Striped Peak, and the Cambrian quartzite is so similar as to require no separate description. The metamorphosed calcareous rocks contain many features in common, although the Wallace and the calcareous part of the Striped Peak, being dominantly argillaceous, differ from the metamorphic product of the purer Cambrian limestone.

The igneous rocks that caused the exomorphism of the sediments are in no place severely endomorphosed. In a narrow zone close to the walls the intrusive granodiorite contains muscovite and has been rather intensely affected by sericitization and chloritization accompanied by the formation of considerable magnetite. Locally molybdenite and other sulphides formed in the endomorphic zone.

METAMORPHISM OF NONCALCAREOUS ROCKS

GENERAL FEATURES

The more intense metamorphism of the noncalcareous rocks has visibly changed them. They are commonly spotted, and crystals of biotite and muscovite a millimeter in diameter can be distinguished. The more argillaceous beds have become more resistant to erosion and make bold outcrops. The microscope shows that the old fabric of texture and structure has been very largely preserved, but the quartz and finely divided white mica have been replaced by oligoclase-albite with or without quartz. The feldspar crystals are of the same size as the former quartz grains and make a mosaic of interlocking anhedral grains. Irregularly distributed in this fabric are crystals of biotite, andalusite, tourmaline, apatite, zircon, and iron-rich chlorite and muscovite, most of which are of anhedral form and in general much larger than the quartz and feldspar. All were formed without regard to the boundaries of the feldspar and quartz and are clearly replacements of those minerals. Later finely divided sericite and chlorite were deposited by replacement of all these other minerals, and last of all magnetite, pyrite, and pyrrhotite were formed in the sericite and chlorite.

There were thus three rather well-defined periods of mineral formation—first a period of recrystallization and substitution of a sodic plagioclase for the mica and some of the quartz, later a period of formation of high-temperature silicates, and finally a period of sericitization with the formation of magnetite and sulphides.

Farther from the contact the changes that went on in the rocks differ only in degree from those just

[4] Walcott, C. D., Smithsonian Misc. Coll., vol. 53, pp. 191, 197, 1908.

described. The sodic plagioclase is present in subordinate amounts, and most of the interstitial mica of the load metamorphism remains. The biotite and iron-rich chlorite are present in small quantities, but magnetite and sulphides are more rare.

UNEQUAL DEVELOPMENT OF THE STAGES OF METAMORPHISM

The moderately metamorphosed rocks were not in general affected equally by the three stages of metamorphism. For example, a bed of white quartzite in the Wallace formation exposed on the shoulder of the spur on the north side of Dry Fork, near the mouth of Fleming Fork, was entirely recrystallized to an allotriomorphic aggregate of quartz and albite-oligoclase, the average grain size of which is about 0.05 millimeter. A few minute tourmaline prisms are seen in thin section, but there is no biotite, chlorite, sericite, or magnetite. Thus the rock was strongly affected by the first stage of metamorphism but hardly at all by the later stages.

Many other examples of this unequal development of the metamorphism could be given. The beds in Maiden Rock belong to the Blacktail formation and were recrystallized during the first stage, with the formation of much feldspar, but only a few rhombs of a late carbonate resulted at a later stage. The Blacktail beds at the summit of Chilco Mountain were not at all affected by the first stage, but biotite and tourmaline are abundant in them as replacement minerals. The Burke quartzite in the tunnel of the Phil Sheridan mine, on the north side of Granite Creek near its mouth, and in contact with the Granite Creek granodiorite at the lake shore, a short distance north of the mouth of the creek, was intensively metamorphosed only during the third stage of metamorphism. It contains pea-sized aggregates of late sericite, with chlorite, magnetite, pyrite, pyrrhotite, and some calcite. Only a little feldspar, biotite, apatite, and zircon were formed in earlier stages. At a point on the west side of the Chilco Mountain ridge the Blacktail quartzite was found to have been intensively metamorphosed during the third stage, so that the earlier metamorphic minerals, once rather abundant, were almost completely eliminated. This lack of relation of the stages of metamorphism affords one of the best proofs that the metamorphism took place in stages.

DISTRIBUTION OF MICROSCOPIC METAMORPHISM

Examples of beds that had not been metamorphosed were sought with care, in order to compare the entirely unmetamorphosed phases of each formation with the metamorphosed phases. During the early part of the field work it was not realized how widespread the metamorphism is, for except near the contacts of the igneous rocks the sediments are not visibly contact metamorphosed. When thin sections of rocks supposed to be unmetamorphosed were examined, it was found that the sodic plagioclase, biotite, chlorite, and minute prisms of tourmaline were of almost universal occurrence. Study showed, however, that these minerals were not of detrital origin, nor were they formed by regional load metamorphism. Where they occur the clastic texture of the rock has been somewhat obliterated, whereas in the rocks of the more typical clastic character these minerals are absent. Detrital feldspar occurs in some beds, but the grains are surrounded by a film of sericitic material. The sodic plagioclase occurs as fresh glassy crystals that interlock with one another or with the quartz. Foils of detrital biotite were found interstitially between clastic quartz grains; the metamorphic biotite has replaced the quartz grains, and a great many are larger than the average grain size of the rock. The tourmaline prisms have likewise replaced adjacent quartz grains. The tourmaline is remarkably widespread, being present at almost every point where specimens were collected. Calkins[5] found this universal distribution in the rocks of the Coeur d'Alene district, and he also considered it to be of metasomatic origin. Tourmaline was not found in rocks showing no other effects of metamorphism but was invariably accompanied by feldspar and biotite.

Proof that these minerals were not formed by recrystallization in the course of the load metamorphism that turned the old sediments into argillites and quartzites is afforded by the fact that such sericitic quartzites or siliceous argillites were shown by analysis to be low in soda, iron, and magnesia. Furthermore, so ubiquitous a distribution of tourmaline, if it was formed by recrystallization of an earlier detrital generation of tourmaline, demands the ultimate source to have been a metamorphic terrane, from which other metamorphic minerals should have been carried in with the tourmaline. No such minerals have been found as detrital or recrystallized grains in the rocks of the Belt series. The tourmaline must therefore indicate that igneous solutions have passed through these rocks.

Additional proof that the tourmaline, biotite, feldspar, etc., were formed by the action of solutions migrating from the intrusive granodiorite is afforded by the increasing abundance of the identical varieties of these minerals found in the same beds toward the igneous contacts.

Another mineral, rather widespread in the Belt rocks and also believed to have been formed by solutions from the igneous source, is a carbonate. A variety of ankerite was found to be the most abundant species, and the rhombic form the most characteristic of the occurrences. The carbonate was found in every

[5] Ransome, F. L., and Calkins, F. C., The geology and ore deposits of the Coeur d'Alene district, Idaho: U. S. Geol. Survey Prof. Paper 62, p. 101, 1908.

Belt formation except the Burke and is most abundant in the Wallace and in the Cambrian limestone. Because of the greater abundance in originally calcareous rocks it is probable that most of the carbon dioxide was derived from the sediment itself. As there was no apparent change in volume, some introduction of CO_2, Fe, and Mg must be supposed to make ankerite from calcite.

EXAMPLES OF INTENSE METAMORPHISM OF NONCALCAREOUS ROCKS

Contact of Prichard argillite with Granite Creek granodiorite.—The igneous contact is sharply exposed on the east shore of the lake north of Granite Point. The well-defined bedding of the sedimentary rock is obliterated for approximately 100 feet, and the hornfels is cut by many quartz veins. For 25 feet from the contact the rock is a dense aggregate of quartz and albite but contains also biotite, zircon, apatite, and ilmenite. The albite decreases in abundance away from the contact.

Chemical analyses of the adinole at the contact and of a sample of the argillite collected at some distance from it definitely prove that an increase in soda and a loss in potash took place during metamorphism. There was also an unmistakable increase in iron, phosphorus, and zirconia and probably in lime, magnesia, and titanium.

Analyses of metamorphosed Prichard argillite

[J. G. Fairchild, Analyst]

	Contact rock	Slightly metamorphosed rock [a]
Silica	66.95	69.06
Alumina	15.42	15.91
Ferric oxide	.63	1.21
Ferrous oxide	4.19	3.17
Magnesia	2.01	1.09
Lime	.62	None.
Soda	6.57	1.62
Potash	Trace.	3.96
Water (total)	1.96	1.98
Titanium oxide	1.00	.75
Carbon dioxide	None.	None.
Phosphorus pentoxide	.30	Trace.
Chlorine	None.	None.
Fluorine	None.	None.
Manganese oxide	.05	Trace.
Zirconium oxide	.07	[b] .03
	99.77	98.78

[a] Contains organic carbon, probably graphitic.
[b] Accuracy of the zirconium determination said by Mr. Fairchild to be 0.005.

Contacts of Granite Creek granodiorite with Blacktail quartzite.—A contact of Blacktail quartzite with the Granite Creek granodiorite is well exposed on the east side of the lake near the mouth of Fall Creek. The sediment near the contact is spotted with black knots of biotite 1 to 2 millimeters in diameter or is streaked and mottled with biotite and muscovite aggregates. The igneous rock contains visible crystals of muscovite and is seen under the microscope to have been also sericitized and enriched in magnetite.

The sediment has a groundmass of anhedral albite-oligoclase grains and quartz. These grains are about 0.05 to 0.075 millimeter in diameter, except exactly at the contact, where they are twice this size. Replacing this groundmass are larger quartz grains and abundant irregularly shaped grains of biotite, muscovite, and andalusite, many of which are several times as large as those of the groundmass. Much of the andalusite is partly altered to a finely divided greenish mica. Minute subspherical grains of apatite, rutile, and zircon are widely scattered in the rock. [illegible]rons of magnetite and ilmenite, about 0.05 millimeter in diameter and disseminated in the most random manner, were certainly the latest minerals to form.

On the west slope of Chilco Mountain the same formation is in contact with the Bayview batholith, but exposures are poor. The rock was recrystallized to an aggregate of quartz, microcline, and subordinate oligoclase-albite, with little increase in size of grain. Later larger crystals of muscovite, quartz, biotite, and andalusite formed, many of the grains of which are more than a millimeter in diameter. Minute crystals of zircon and blebs of an unidentified mineral having about the refractive indices and birefringence of pyroxene are abundant. Many of the andalusite grains are poikilitic, resembling a graphic intergrowth with quartz. In the later stages of the metamorphism the biotite was altered to chlorite with the separation of rutile needles, making sagenitic structures; the andalusite and feldspar were sericitized. In many of the large crystals of muscovite very peculiar spherulites of sericite formed, the individual needles of which are hairlike, and many are as long as 0.2 millimeter.

Intensely metamorphosed Striped Peak formation at Cape Horn.—Metamorphosed beds of the Striped Peak formation occur 1,700 to 2,000 feet above the lake on the south side of Cape Horn. The characteristic banding of the formation (as seen in section) is preserved, and the rock splits fairly well along the bedding. The dark bands are rusty brown; the light ones yellow-brown. Some of the light bands are marked with dark spots. The microscope shows that the three stages of metamorphism are well indicated. The groundmass consists of interlocking grains of quartz, microcline, and albite-oligoclase, in which larger and very irregular shaped crystals of biotite, muscovite, and tourmaline had developed at a later time. Small crystals of zircon and apatite are accessory constituents of the second stage of metamorphism. Magnetite, sericite, and chlorite formed later, as is indicated by the cross-cutting of the grains and the replacement by them of biotite and feldspar. The amount of feldspar that had formed during the early period was relatively less than in other similarly severely metamorphosed rocks. The tourmaline is more abundant and occurs in larger grains than were found elsewhere in the district.

Contact of Cambrian quartzite with Bayview granodiorite.—A contact of the Cambrian quartzite with the granodiorite is exposed in the field east of the summer residence known as Dromore, northeast of Bayview. The sediment at the contact is a gray rock flecked with minute biotite scales and having an average grain size of 0.5 millimeter. In places it is faintly banded. The same sequence of metamorphism is indicated as in other contact zones. There was an early crystallization of albite-oligoclase with the quartz, forming an interlocking groundmass, the grains of which average about 0.1 millimeter in diameter. The feldspar is not uniformly distributed, making solid masses in some parts of the thin sections, and being absent from other parts. Biotite, muscovite, andalusite, and tourmaline formed abundantly; the tourmaline is found in small grains, the others in large ones. Many of the biotite foils contain zircon crystals surrounded by pleochroic halos, and many foils are also altered to thuringite, with the separation of rutile needles. Sericitization had been intense and widespread, attacking most successfully the feldspar and andalusite. Magnetite and ilmenite are also abundant; many of the grains of the ilmenite are partly altered to leucoxene.

METAMORPHISM OF CALCAREOUS ROCKS

GENERAL FEATURES

The mineralogy of the metamorphosed Wallace formation and of the Cambrian limestone is so strikingly different from that of the rocks above described that it indicates the importance of the original character of the rock in determining the nature of the minerals formed by metamorphism. Albite, andalusite, a biotite with very high index of refraction, tourmaline, and thuringite are characteristic of the metamorphism of the noncalcareous sediments, but in those in which calcite was originally present garnet, diopside, a magnesian biotite, amphibole, epidote, and titanite are abundantly developed, and scapolite, vesuvianite, olivine, chondrodite, topaz, and fluorite were found in a few places. On the other hand, zircon, quartz, apatite, sericite, chlorite, magnetite, and sulphides occur in both kinds of rock.

There were two distinct processes in the metamorphism of the calcareous rocks, and like the stages of metamorphism in the noncalcareous sediments the degree of development of one is more or less independent of the other. There was first marmarization of the limestones on a large scale, which eliminated the bedding and the carbonaceous material. Later came the introduction of material from the igneous rock, which formed the contact silicates above mentioned. This second process is conveniently divided into two stages on a rough basis of temperature, with sericite and chlorite marking the beginning of the later stage. There were thus three stages also in the metamorphism of the calcareous rocks.

EXAMPLES OF METAMORPHISM OF CALCAREOUS ROCKS

Metamorphosed Wallace formation.—The rock along the west shore of the lake, from Cape Horn northward under the Three Sisters, is all metamorphosed, but through much of this distance the exposures consist of the Blacktail formation. Farther north are found greenish and white quartzite beds, characteristic of the metamorphosed Wallace, the identity of which is established by the presence of the typical fretwork shown in section, which prior to metamorphism consisted of calcite structures of organic origin. The grains are very small, and the rock has a subconchoidal fracture. The green bands consist of a pale-green amphibole; the white bands are either of quartz and feldspar, quartz and scapolite, or diopside, which in some beds makes nearly solid masses. Zoisite, biotite, grossularite, titanite, zircon, apatite, and muscovite are accessory minerals.

The climb up the east side of Bernard Peak from West Gold Creek, at the south end of the lake, gives another instructive section of metamorphosed Wallace beds, there present as a capping over the Bayview granodiorite, which is exposed almost to the top of the tremendous cliff that rises abruptly from the shore. The same rock is also seen in the gap between Bernard Peak and Chilco Mountain. This rock is massive, is marked with white or white and green bands, and is notably heavy from the abundance of heavy silicates. The grain, however, is so fine that no minerals can be recognized with the hand lens. The mineral content is about the same as that of the rock along the shore under the Three Sisters, consisting of quartz, feldspar (both microcline and albite), diopside, zoisite, garnet, titanite, zircon, apatite, calcite, and magnetite. The pyroxene and amphiboles are distinctly later than the feldspar. Titanite is very abundant in some beds but occurs in minute grains. A pale-brown biotite makes up 30 per cent of some beds but is entirely absent from others.

Another area of intensely metamorphosed rocks is on the slope east of the Hewer mine, near the divide separating Chloride Gulch from the tributaries of the North Fork of Coeur d'Alene River, at the south edge of the district. No igneous rocks are exposed, but minute seams of pegmatite were found containing quartz, potash, feldspar, epidote, and magnetite. Beds at an altitude of 3,750 feet directly above the Hewer mine were studied. The rock is a dense greenish hornfels, consisting of a groundmass of quartz and microcline, in which are numerous finely divided prisms of the green amphibole, accompanied in some beds by a fibrous amphibole of lower refractive index.

Zircon, titanite, apatite, and magnetite are scattered widely through the rock.

In the metamorphic area just described but beyond the divide, in the North Fork drainage basin near the Lone Hand prospect, the difference between the minerals formed during metamorphism of calcareous and noncalcareous beds is convincingly demonstrated. In some laminae within a single thin section are quartz, sodic plagioclase, and andalusite, with sericite and chlorite—the typical mineralization of the siliceous sediment; whereas in adjacent originally calcareous laminae are epidote, diopside, amphibole, fluorite, titanite, and calcite. In some places the calcite forms pseudomorphs after the amphibole. During a mechanical separation of one unbanded specimen in bromoform, three-fourths of the powder sank, and of this fraction 95 per cent was amphibole.

Metamorphosed Cambrian limestone.—The Cambrian limestone is marmarized, or partly so, over large areas. At the lime quarries near Bayview, at the old quarries at the head of Cocolalla Creek and near Whiskey Rock, and in the headwaters of North Gold Creek the rock is marmarized but contains few silicates. The most interesting examples of more intense metamorphism were found in an included block of limestone on the south side of Cape Horn, in cliffs along the east shore between South Gold Creek and Port Rock, and at Vulcan Hill, east of Lakeview. These zones have a varied mineralogy and present the most interest to the mineralogist of all the contact zones in the district.

A number of prospects for ore on Vulcan Hill have made good exposures of the contact of the granodiorite and limestone. The sediment is a white marble in which many silicates and some ore minerals were locally developed so abundantly that the rock is entirely replaced by them. In some beds the rock is banded green and yellow and consists principally of garnet and augite but also contains vesuvianite, epidote, phologopite, amphibole, fluorite, quartz, sericite, chlorite, zeolites, magnetite, sulphides, and ankerite. In some closely banded shaly limestones the effect of alternating composition is again clearly demonstrated. Sodic plagioclase formed in the shaly layers, but at that stage of mineralization no silicate formed in the limestone beds, and the rock only recrystallized to a marble. Later biotite formed in the shale, and garnet, diopside, and amphibole formed in the limestone. The later sericite and chlorite formed in both without regard to the boundaries of the layers. In one bed a considerable quantity of corundum was found, apparently produced from the recrystallization of an impure bed in the limestone.

The garnet and pyroxene differ in composition in adjacent beds of the limestone and indeed in the same bed, as the garnets are zoned in some places. The difference in zoned garnets, however, is slight, but in adjacent beds grossularite and andradite are formed, and diopside and augite occur at different horizons.

In the garnet zones on Cape Horn a few rarer minerals occur in subordinate quantity, topaz, bytownite, and allanite being identified microscopically. Some marble cliffs on the east shore of the lake, between the mouth of South Gold Creek and Port Rock, also yielded additional minerals. At the east end of a little beach 100 yards south of the mouth of the creek the rock is a light-gray and green, partly recrystallized but still bedded limestone. Besides ankerite, scapolite, spinel, muscovite, and chlorite, considerable chondrodite is present in small pale-yellow crystals, a few of which can be seen with a hand lens. Farther southwest, beyond a fault, the rock is more thoroughly marmarized and contains diopside, phlogopite, and tremolite and in the more shaly layers sodic plagioclase and quartz.

The independence of marmarization and silicate formation was well shown at the last series of outcrops. Marble occurs without silicates, and silicates are found in bedded limestone that is but little marmarized. Where silicates occur in marble they indicate by their boundary relations, so far as these can be interpreted, that they were formed later than the marmarization. From these facts it is inferred that the marmarization took place principally during the first effusion of solutions from the magma, mostly of water, which mixed with and heated water of connate or of surface origin, whereas the silicates formed later, after the advance of crystallization in the igneous rocks had caused a concentration of the emanations by adding more material in solution.

ENDOMORPHISM OF THE IGNEOUS ROCKS

The writer[5a] has elsewhere briefly described the endomorphism of the igneous rocks and has connected it, at least in a general way, with the action of the same solutions that slowly soaked through the body of the igneous rock and made a number of postconsolidation changes. At few points are the rocks conspicuously endomorphosed, and except for some changes visible only under the microscope the rocks appear the same at the sedimentary contacts as elsewhere. The addition of large flakes of muscovite, an intense sericitization and chloritization, and the enrichment of magnetite were the endomorphic changes. The muscovite is not pyrogenetic, for it has replaced earlier minerals. If its time of formation in the igneous rocks can be fixed as contemporaneous with that in the adjacent sediments, the time of their metamorphism in relation to the crystallization of the igneous rock is relatively well established. It seems to the writer that the time of crystallization of the muscovite must have been contemporaneous on the two sides of a sharp contact

[5a] Gillson, J. L., Granodiorites in the Pend Oreille district of northern Idaho: Jour. Geology, vol. 35, p. 20, 1927.

between igneous rock and sediment. This assumption furnishes a basis for the dating of the stages of metamorphism in the sediments.

TABULAR VIEW OF THE METAMORPHISM

The metamorphism of the rocks in the Pend Oreille area can be shown in tabular form as follows:

Metamorphism of rocks in Pend Oreille district, Idaho

Stage	Igneous rock	Noncalcareous sediments	Calcareous sediments
1	Magma molten	A general and uniform recrystallization, with obliteration of the undulatory extinction of the quartz, elimination of the sericite, and the formation of more or less feldspar.	Marmarization, usually with no silicates.
2	Magma crystallizing and margin probably solid.	Pneumatolytic emanations carrying the elements known as mineralizers. The minerals that formed are andalusite, biotite, cordierite, tourmaline, quartz, apatite, and zircon.	Pneumatolytic emanations carrying the elements known as mineralizers. The minerals formed are phlogopite, biotite, spinel, diopside, grossularite, iron-bearing garnet, epidote, vesuvianite, fluorite, quartz, topaz, zircon, apatite, tremolite, and actinolite.
3	Igneous rock solid and attacked by abyssal pneumatolytic and hydrothermal emanations. The pyrogenetic minerals replaced by the new minerals muscovite, sericite, chlorite, magnetite (or ilmenite), pyrite, quartz, ore minerals, and ankerite.	Abyssal pneumatolytic and hydrothermal emanations formed muscovite, sericite, chlorite, magnetite (or ilmenite), pyrite, pyrrhotite, and quartz.	Abyssal pneumatolytic and hydrothermal emanations formed sericite, chlorite, magnetite, pyrite, pyrrhotite, quartz, [illegible] of metallic sulphides, drusy quartz, zeolites, ankerite, and stibnite.

SUMMARY OF THE EVIDENCE THAT THE METAMORPHISM WENT ON IN STAGES

1. The marmarization of the limestone and recrystallization of the siliceous sediments, with the formation of a sodic plagioclase and an elimination of the original potash mica, preceded the formation of all the other minerals, as shown by the mutual boundary relations and by the uniformly widespread distribution of the minerals formed by the early processes. The rock had been recrystallized to an allotriomorphic aggregate of even grain, and except in zones of most intense metamorphism the grain size is about the same as it was originally.

2. The second stage is represented by minerals the grains of many of which are much larger than those of the first stage and clearly replace them. In the noncalcareous sediments no order of crystallization of minerals of the second stage can be determined, and it is probable that they were in great part contemporaneous. In some of the garnet rocks, however, a definite sequence from pyroxene to amphibole was shown. Many of the minerals formed in the second stage are known to require a high temperature during their formation. The minerals are generally considered to be pneumatolytic, and many required the so-called mineralizers for their formation. The irregular distribution of these minerals in some beds and their grouping into spots and streaks imply that they resulted from solutions that passed through the solid rock with more difficulty than the first solutions.

3. The third stage is the only one whose results are to be found in both exomorphic and endomorphic zones, and this fact suggests that during the earlier stages either the igneous rock was not yet solid, or it was in equilibrium with the solutions that caused the metamorphism in the sediments. The later age of the minerals characteristic of the third stage is clearly proved by the boundary relations of the grains. The minerals of the third stage are [illegible] known to be late in most paragenetic sequences and to form at rather moderate temperatures, and their period of formation is generally spoken of as hydrothermal.

4. The points above given prove that the metamorphism of the sediments was progressive; but that the stages were to some extent independent of one another is proved by the finding of many places where the products of one of the stages have formed more abundantly than those of the others, without apparent regard to distance from contacts. Thus the [illegible] periods must be considered as overlapping.

MINERALOGY

No unusual species were found during the study. However, the species represented include a large proportion of those minerals generally considered to be commonly due to contact-metamorphic processes. Zircon had possibly not previously been considered a common contact mineral, but the writer has already published the evidence for knowing it to be here a contact mineral and has cited several other occurrences reported from contact zones.

At no point were large and well-formed crystals of any of the contact minerals found. In most specimens the grains are less than 1 millimeter in diameter, hence necessarily most of the study was made under the microscope. In addition to the examination of about 150 thin sections a considerable number of the specimens were crushed, the grains separated into fractions, and the properties determined by index liquids. Thus the constants of most of the minerals were determined from several specimens. The tabulation that follows may be of interest.

Minerals of the contact-metamorphosed rocks of the Pend Oreille district, Idaho

Mineral	Rock occurrence	Locality	Properties	Remarks
Sulphides				
Stibnite	Cambrian limestone	Baptist claims on Vulcan Hill.		Needlelike crystals in garnet rock.
Molybdenite	Packsaddle Mountain granodiorite.	McDonnah No. 2 claim, Vulcan Hill.		In endomorphosed zone.
Sphalerite	Cambrian limestone	Keno claims, Vulcan Hill.		Disseminated in limestone in small quantity.
Pyrrhotite	All rocks	General		Disseminated in small anhedral grains throughout metamorphosed rocks.
Pyrite	do	do		Disseminated in small crystals throughout metamorphosed rocks.
Haloids				
Fluorite	Wallace formation, Cambrian limestone.	Zones of intense metamorphism.		Not common. Seen only microscopically and in small quantity.
Oxides				
Quartz	All rocks	General		Found as veins in noncalcareous sediments and as a replacement mineral in calcareous rocks.
Corundum	Cambrian limestone	Keno Claim, Vulcan Hill.		Found in microscopic crystals in 1 specimen of an impure limestone.
Hematite	All rocks			Direct formation by contact metamorphism not proved.
Rutile	do	General		In minute quantities where found. Most abundant in the metamorphosed Blacktail beds at the mouth of Fall Creek.
Spinel	Cambrian limestone	Along southeast shore of lake and lower workings of Arcade group, Vulcan Hill.		Found in minute green crystals in thin sections of 2 specimens.
Magnetite	All rocks	General		One of the most widespread minerals due to contact metamorphism.
Ilmenite	do	do		Associated with magnetite and identified by chemical test.
Carbonates				
Calcite	Most of the rocks	Numerous places		Occurs mostly in the calcareous rocks and is there due to simple recrystallization. Also in subordinate quantities in a few specimens of other rocks.
Dolomite	Wallace and Striped Peak formations and Cambrian limestone.	do		Minute rhombs widespread in the Wallace formation and Cambrian limestone.
Ankerite	Wallace and Striped Peak formations, Cambrian limestone, and igneous rocks.	Widespread		Parallels dolomite in occurrence, but found also in veins. One of the last minerals in the metamorphic sequence.
Phosphates				
Apatite	All rocks	In zones of intense metamorphism. Rare but does occur in weakly metamorphosed rocks.	Biaxial in some specimens with a large optic angle.	
Silicates				
Microcline	All rocks but rare in the purely calcareous beds of the Cambrian limestone.	Many places		Disseminated in microscopic grains but is nowhere so abundant as the albite-oligoclase.
Albite to oligoclase albite.	All rocks except the purely calcareous beds of the Cambrian limestone.	General	Symmetrical extinction angles range from 5° to 13°, 10° being average.	Exceedingly widespread, forming the principal constituent of some adinoles.
Bytownite	Cambrian limestone	Overlying the granodiorite sill on Cape Horn.	Symmetrical extinction angles of 40°, β=1.570.	Found in microscopic crystals at one place.

Minerals of the contact-metamorphosed rocks of the Pend Oreille district, Idaho—Continued

Mineral	Rock occurrence	Locality	Properties	Remarks
Silicates—Continued				
Diopside and augite.	Only in calcareous rocks.	In all strongly metamorphosed beds of Wallace formation and Cambrian limestone.	β=1.690 to 1.710; color from white to green.	Always found in small anhedrons.
Hornblende	Wallace formation	In all strongly metamorphosed beds.	β=1.635 to 1.645, pleochroism weak, Z slate, X nearly colorless, $c \wedge Z$ about 25°.	In minute prismatic grains, forming felted masses.
Actinolite	Metamorphosed carbonate vein in old fault zone in the Wallace formation.	West side of NW. ¼ SW. ¼ sec. 3, T. 54 N., R. 2 W.	Strongly pleochroic in green tints.	Long needle-like crystals in quartz.
Tremolite	Cambrian limestone	At many places, most conspicuously in the cliffs along the southeast shore.	Clear white. β=1.620, $c \wedge Z$ 15°.	
Pyrope, grossularite andradite.	Only in calcareous rocks.	In most strongly metamorphosed beds.	Conspicuously zoned, alternately anisotropic at Vulcan Hill n=1.700 to 1.82. Colorless, or yellow to deep red.	Composition differs markedly in adjacent beds.
Olivine	Cambrian limestone	At one place on the south side of Cape Horn.	Optically +	In microscopic crystals, altering to serpentine.
Scapolite	Cambrian limestone and Wallace formation.	Baptist claim, Vulcan Hill; shore below Three Sisters.		Wernerite, found only in small crystals.
Vesuvianite	Cambrian limestone	Keno claim, Vulcan Hill.	ω=about 1.720; pleochroic in yellow tints.	Disseminated in microscopic anhedrons. One large crystal found.
Zircon	All rocks	General		In very minute crystals. See Am. Mineralogist, vol. 10, pp. 187–194, 1925.
Topaz	Cambrian limestone	Overlying sill on south side of Cape Horn.	α=1.620, γ=1.628	Microscopic crystals in one specimen of garnet rock.
Andalusite	All noncalcareous rocks	In all strongly metamorphosed zones.	Typical	In microscopic crystals many of which were more or less altered to finely divided mica flakes.
Zoisite	Calcareous rocks	Abundant in some beds of intensely metamorphosed Wallace, west shore below Three Sisters.	β=about 1.710	
Epidote	Endomorphosed igneous rocks and in calcareous rocks.	Many places	Typical	In microscopic crystals and anhedrons.
Allanite	Cambrian limestone	Over sill on south side of Cape Horn.		Rare accessory in one specimen.
Chondrodite	do	In cliffs along southeast shore south of South Gold Creek.	α=1.635, β=1.648, γ=1.665, X pale yellow, Y, Z colorless. 2V near 90°, optically +.	Common at the one locality in microscopic crystals.
Muscovite	All noncalcareous rocks	General	2V about 25°–40°	Very widespread.
Lepidomelane	do	do	In noncalcareous sediments; β=1.640 to 1.655, 2V 0. Pleochroism to deep brown.	Do.
Biotite	Calcareous rocks	Typical in the Wallace on west shore below Three Sisters.	β=about 1.620. Pleochroism in pale tints of brown.	Abundant locally.
Phlogopite	Cambrian limestone	Cliffs southeast shore of lake and at Vulcan Hill.	α=1.560, γ=1.600, X yellow, Y, Z greenish to pale yellow, 2V 0.	Rare.
Sericite	All rocks	General		Distinguished from muscovite by minute size of flakes and belongs to a later generation.
Cordierite	Blacktail formation	North side of Cape Horn.	Identified by optic sign, pleochroism, and habit.	Found in only one specimen.
Tourmaline	All noncalcareous sediments.	General	ω=1.660 to 1.670, ϵ=1.630 to 1.635. Pleochroism from colorless to blue, green, or brown.	A microscopic constituent in all moderately metamorphosed beds. Absent from severely metamorphosed beds except locally.
Aphrosiderite	Many beds of the noncalcareous sediments.	do	β=1.620. Optically + also −	Widely distributed especially in the moderately metamorphosed beds.
Thuringite	do	do	β=1.645. Optically −	Do.

Minerals of the contact-metamorphosed rocks of the Pend Oreille district, Idaho—Continued

Mineral	Rock occurrence	Locality	Properties	Remarks
Silicates—Continued				
Antigorite	Cambrian limestone	Cliffs along southeast shore.	β=1.555; birefringence weak.	In veinlets or as minute masses in the limestone.
Chrysotile	do	Lime quarries at Bayview.	α=1.500, γ=1.520	Asbestiform material along seams.
Heulandite	do	Upper adit of Arcade group Vulcan Hill.	α=1.495, γ=1.503. Optically +, 2V small.	Crystals in open cavities with ankerite.
Unidentified zeolite.	do	do	n=low. Birefringence 0.015.	Found with heulandite.
Titanite	All calcareous rocks	General	Typical	Microscopic crystals locally abundant.

CONCLUSIONS

The conception that contact metamorphism went on in stages is simply a division of the long-continued process into overlapping periods. The idea of stages in contact metamorphism was perhaps first suggested by Spurr, Garrey, and Fenner [6] and has subsequently been advanced by several others. Umpleby [7] used the word "stages" in describing the metamorphism at Mackay, Idaho, and the idea is also expressed in the paragenetic tables of Eckerman.[8] The descriptions of the Edwards zinc mine by Smyth [9] and by Wade and Wandke [10] speak of stages in the metamorphism.

The knowledge that contact metamorphism was produced by a long procession of solutions that came out from the igneous rock has succeeded the old idea that it was a simple recrystallization of material already present, caused by the baking heat transmitted by conduction from an adjacent intrusive. This knowledge is of importance not only in itself but also because of the light that it throws upon the process of crystallization of the igneous rocks and the nature of the residual liquids given off during crystallization.

Although contact metamorphism was not a simple recrystallization, this study of the rocks in the Pend Oreille district shows that the nature of the original rock was a very important factor in determining the kind of product resulting from the metamorphism. It shows further that, except very locally, the amount of material introduced permanently was not great in proportion to the mass of the rock. The paragenetic sequence of the minerals due to contact metamorphism suggests that the progress of crystallization of the igneous rock and the resulting metamorphism was somewhat as follows:

1. During intrusion and early crystallization of the magma, which marked the first stage, steam carrying soda and some potash was given off in considerable quantity from the whole magma and caused the country rocks to be recrystallized. Limestones were turned to marbles, and sericitic quartzites and siliceous argillites became adinoles. Connate and surface water played a part in this recrystallization.

2. With the progress of crystallization of the igneous rock, which marked the second stage, the emanations given off from the residual liquid became richer in the so-called mineralizers. In addition iron, phosphorus, zirconia, and silica, probably magnesia, rare earths, and titanium, and possibly alumina and potash were also carried. Before this stage was over the igneous rock was solid at its borders, endomorphic muscovite had formed, and throughout the body of the igneous rock deuteric titanite, allanite, and probably apatite and zircon had crystallized by replacement.

3. After final consolidation of the main mass of the intrusive which introduced the third stage, when the temperature had become lower, hot waters rich in potash and iron and later in carbon dioxide, sulphur and base and precious metals were given off from greater depths. Sericite, chlorite, and magnetite formed both in the igneous rock and in the sediments and were followed by sulphides, carbonates, and zeolites.

[6] Spurr, J. E., Garrey, G. H., and Fenner, C. N., A contact-metamorphic ore deposit; the Dolores mine, at Matehuala, San Luis Potosi, Mexico: Econ. Geology, vol. 7, pp. 471–474, 1912.

[7] Umpleby, J. B., Geology and ore deposits of the Mackay region, Idaho: U. S. Geol. Survey Prof. Paper 97, p. 65, 1917.

[8] Eckerman, H. von, The rocks and contact minerals of the Mansjö Mountain: Geol. Fören. Förh., 1922, p. 343.

[9] Smyth, C. H., jr., Genesis of the zinc ores of the Edwards district, St. Lawrence County, N. Y.: New York State Mus. Bull. 201, p. 28, 1917.

[10] Wade, W. R., and Wandke, Alfred, A big zinc mine in New York State: Eng. and Min. Jour. Press, vol. 116, p. 96, 1923.

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