BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 35, PP. 507-534 SEPTEMBER 30, 1924

# CONTACT METAMORPHISM AT BINGHAM, UTAH[1]

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(*Accepted for publication by Publication Committee July 9, 1924*)

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## INTRODUCTION

It was held not long ago that the igneous metamorphism of a limestone involved no notable additions of material. This view is now generally abandoned, and it is recognized that the most far-reaching changes may

[1] Manuscript received by the Secretary of the Society June 23, 1924.

An investigation carried out by the aid of the National Academy of Sciences under the provision of the Bache Fund.

This paper was not presented at any meeting of the Society, nor does its title appear on any program. It was accepted, as indicated, by the Publication Committee under the authority conferred on it.—EDITOR.

take place involving very large additions of silica, as well as iron and other metals. It is also recognized that the limestone usually suffers a loss not only of carbon dioxide, but also of calcium oxide and sometimes other constituents. This has been abundantly proved by changes which alter a pure limestone into a heavy iron-lime silicate, such as andradite, and it has been shown that the volume, aside from pore space, remains substantially the same.

In case of an impure limestone the difficulty is greater because the average composition of the bed is rarely known and the exact additions and subtractions that have taken place remain more or less obscure.

My attention was first called to the metamorphism of the limestone at Bingham, Utah, some twenty-three years ago, when I first visited the mining district in the company of Mr. J. M. Boutwell, then of the U. S. Geological Survey.

In the thorough and detailed report on the district by Boutwell and Keith[2] it was suggested that additions of silica and magnesia have taken place during metamorphism. Although the relations shown were quite striking, the materials analyzed were specimens, and therefore no far-reaching conclusions could be drawn from them.

Later the geological conditions were summarized by a U. S. Geological Survey publication describing the ore deposits of Utah.[3]

Very recently the subject of metamorphism at Bingham has been treated by A. N. Winchell.[4] In this paper the transition rocks between limestone and sandstone are described. The lime-silicate rocks are proved to have originated from limestones. The fact that additions of material have taken place during metamorphism is stressed. It is shown that the unaltered and the metamorphosed limestones differ little in porosity. The average porosity of the nine specimens of the former is 3.7 per cent, the average porosity of eight specimens of partly altered limestones is 5.9 per cent, and the same relation for six specimens of completely metamorphosed rocks is 3.3 per cent. The evidence shows that a given bed of limestone can be converted into lime-silicate rock with no important change of volume, as the thickness remains unchanged. It is believed, therefore, that the change to silicates has occurred with no important change of volume.

The author concludes that the processes of silication and elimination of free carbon occurred at temperatures from 700° centigrade to 1,100°

[2] J. M. Boutwell and Arthur Keith: Prof. Paper 38, U. S. Geol. Survey, 1905, p. 184.

[3] B. S. Butler, G. F. Loughlin, and V. C. Heikes: The ore deposits of Utah. Prof. Paper 111, U. S. Geol. Survey, 1920, pp. 340-361.

[4] A. N. Winchell: Petrographic studies of limestone alterations at Bingham. Trans. Am. Inst. Min. and Met. Eng., New York meeting, 1924, pp. 16.

centigrade. The introduction of carbonates in veinlets in the limestone continued at lower temperatures and may, in fact, have been caused by meteoric waters. The main ore deposits were formed at lower temperatures. Silication is confined to the limestone beds and is not found in the fissure veins. With this last statement the present writer is not in complete agreement, for the Yampa vein (at the base of the Yampa limestone) contains both amphibole and garnet in places. This is, however, mainly a copper-bearing vein, while in the fissure veins and replacement deposits, which carry lead predominantly and are believed to have been formed at somewhat lower temperatures, there are no lime silicates at all, but only more or less of silicification and carbonatization.

## The present Investigation

The opportunity for the present investigation arose in connection with a lawsuit between the Utah Apex Mining Company and the Utah Consolidated Mining Company, which owned adjoining claims in the upper part of Carr Fork.[5] During this legal contest, which involved questions of the so-called law of the apex, it became necessary to study the conditions surrounding the origin of the ore deposits and to examine in detail the processes of metamorphism which the rocks had suffered. It was thought desirable to establish the content of the fresh and altered rocks in silver, lead, copper, iron, and sulphur. For this purpose many of the cross-cuts in the mines which exposed beds of limestone or quartzite were sampled according to the methods of mine sampling of large ore bodies. These beds dipped about 30 degrees northward, and the cross-cuts, therefore, extended approximately north and south. A groove sample was cut across the whole formation, say across the Yampa limestone—that is, a continuous groove was chiseled out with hammer and moil, the furrow being about 4 inches wide and 1 inch deep. The sampling was divided into 10 feet units horizontally, each sample weighing from 30 to 50 pounds. A series of samples were thus obtained across the bed; if the bed was 200 feet thick, the horizontal distance would be about 400 feet, and this would be represented by 40 samples. The samples were duly quartered, reduced and assayed.

Realizing that interesting results might be obtained by analyzing these cross-cut samples, composite samples were prepared by taking one gram from each assay sample and thoroughly mixing them, the composites being finally quartered down to quantities suitable for analyses. The

[5] For account of this lawsuit, see Orrin P. Peterson, Some geological features and court decisions of the Utah Apex-Utah Consolidated controversy, Bingham district. Trans. Am. Inst. Min. and Met. Eng., New York meeting, February, 1924, no. 1341 M.

complete analyses were not required for the purpose of the sampling, but I was fortunate in later obtaining a grant from the Bache Fund of the National Academy of Sciences to defray the cost of the chemical work. The analyses were made by Prof. L. F. Hamilton, of the Massachusetts Institute of Technology.

I believe this is probably the first time that analyses have been made from samples of wide beds obtained by these laborious and expensive methods, and the results, I am confident, are unusually accurate and reliable. The cost of the sampling alone was probably about $2,000.

Generally speaking, the assays in the unaltered rocks proved blanks, while those of altered rocks contained more sulphur and iron and frequently traces or small amounts of copper, lead, and silver. It should be added that the cross-cuts sampled were outside of the ore deposits, and in the rare cases, where a small vein or other deposit or a dike was met, such a sample was discarded in the composites here used.

## Geological Features at Bingham

It is well known that Bingham or West Mountain is one of the most important mining districts in the United States. The total production of gold, silver, copper, lead, and zinc is now not far from a value of $500,000,000 and the annual production in 1919 and 1920 approximated $27,000,000. The larger part of the output was derived from the disseminated ores in the open workings of the Utah Copper Company.

The ores are contained in replacement deposits in limestone, in veins, in disseminations in quartzite, and in disseminations in monzonite porphyry. The latter, represented by the Utah Copper property, have been enriched by chalcocite and covellite of supergene origin. Contact metamorphic ores of normal type with abundant silicates are present, but not abundant or important.

Briefly, the geological relations are as follows:

The predominant sedimentary rocks consist of about 8,000 feet of quartzite of Pennsylvanian (Upper Carboniferous) age, with several intercalated limestone beds or lenses. The beds are folded and faulted in a complex manner.

This series is intruded by irregular stocklike bodies, dikes, and sills of monzonite porphyry, which in large degree have suffered a hydrothermal alteration. The total area occupied by the intrusion is not large, probably less than two square miles.

## The Limestones

It is not always easy to correlate the various limestone lenses. Besides several minor beds, there are the Jordan, Commercial, Yampa, and

Highland Boy limestones, which, from an economic point of view, are the most important. The present paper deals with the Yampa and Highland Boy limestones as exposed in the Utah Apex and in the Utah Consolidated mines. The Yampa is the upper of the two and is well exposed in the upper part of Carr Fork. Its average thickness is 200 feet, and it dips at angles of 17 degrees to 25 degrees toward the north. In the deeper part of the mines this and accompanying quartzite beds make a sharp bend and acquire a steep dip. The Yampa limestone in its normal state as exposed in the underground workings is a black, dense rock, which often emits a fetid odor when struck with a hammer. It is very uniform, except that some minor quartzite beds are embedded in it near the top. The beds just above the Yampa limestone are calcareous quartzite, but in most cases the upper limit of the limestone is quite clearly marked. The limestone is an impure variety, with much silica and little magnesia.

Toward the west beyond the samples here investigated the Yampa limestone turns into a calcareous quartzite. Within the territory here discussed its thickness is very uniform and it contains few quartzite beds.

About 200 feet below the Yampa lies the Highland Boy limestone. This is equally well exposed in many workings and when unaltered has the same black color and fine-grained texture.

The Highland Boy limestone is likewise uniform in the territory here discussed, but to the southwest, like the Yampa, it tends to become thinner. In its unaltered state it is a black, fine-grained rock entirely similar to the Yampa and the bed is usually about 200 feet thick. It is not so uniform in composition as the Yampa, for in its upper part it contains at least two beds of quartzitic calcareous rock. It is remarkable that in spite of this the average composition of the Highland Boy limestone is almost exactly identical with that of the Yampa.

## The Metamorphism

Ascending Carr Fork, the Yampa limestone is first observed in the gulch about one and one-fourth miles west of Bingham Canyon town, and it continues west for about 3,000 feet, all of the part exposed being white and metamorphosed. The Highland Boy limestone is first seen farther up at the Highland Boy mine, and it is only exposed on the surface for about 1,200 feet; all of this exposure is also white, metamorphosed rock. The black Yampa limestone is found underground in the workings of number 7 tunnel, Utah Consolidated mine, where it is extensively exposed. It is also seen in the deeper workings of the Yampa mine and on the main tunnel level of the Utah Apex mine, still farther east. The

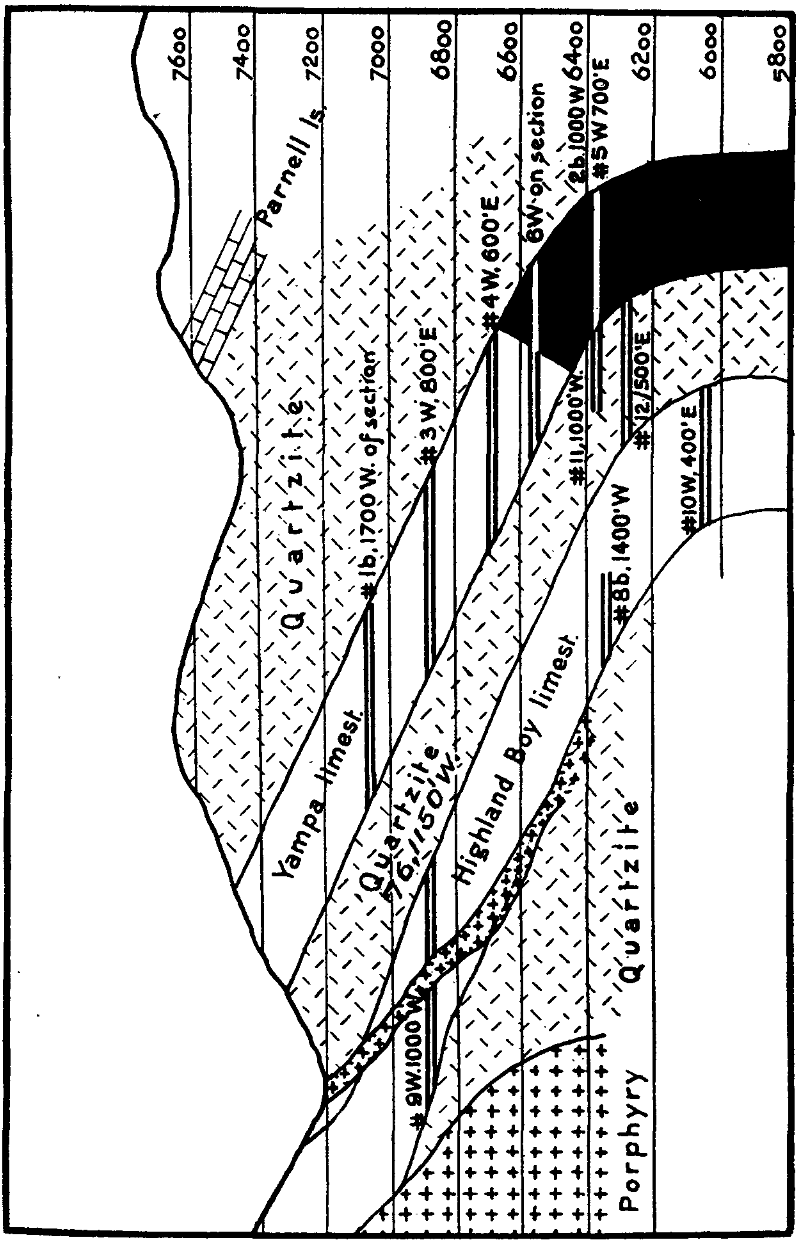


FIGURE 1.—*North-south Section 100 Feet West of Utah Apex Shaft, Bingham, Utah*

In this section the Highland Boy limestone is altered (white) throughout. The Yampa limestone is unaltered (black) in the lower part only.

contact of black and white limestone has a strong slant downward till near the Utah Apex shaft on the main tunnel level. From this level the contact dips steeper, apparently parallel to the Petro fissure, and is found actually farther west in the deep workings of the Utah Consolidated mine on number 13, 14, and 16 levels.

The general relations are shown in figure 1. On the whole, the western parts of the mines show black limestone, while the lower and eastern workings disclose metamorphosed white limestone.

The sections show that somewhat similar relations obtain for the Highland Boy limestone.

The section shows also that both limestones, in the western section at least, would soon encounter porphyry in their eroded upward extension. The strong dip of the contact toward the east would also seem to indicate that porphyry will be encountered in the deeper workings of the Utah Consolidated and the Utah Apex mines. Indeed, the Highland Boy limestone contains strong porphyry dikes on the 700-foot level and is almost wholly cut off by porphyry toward the east on number 13, 14, and 16 levels of the Utah Consolidated mine.

The elevations of the samples taken extend from 7,090 feet (number 1*b*) to 6,030 feet. Horizontally they extend over an interval of 2,400 feet.

The metamorphism consists in the enlargement of calcite grains and in the development in and between them of wollastonite, diopside, and fibrous tremolite; this growth often takes place between unaffected detrital quartz grains. Coarser aggregates appear in places with andradite and epidote, also pyrite and chalcopyrite. A little specularite is widely distributed. Apparently silicates and sulphides here crystallized in closely following stages. There are few, if any, pure crystalline limestones. Even specimens which so appeared contained in the clear calcite grains particles and prisms of garnet and tremolite. The amount of silicates varies considerably. Such metamorphosed limestones are shown in photograph in Boutwell's report[6] (plates 29, 30, and 34). Veinlets of later calcite often traverse the metamorphosed rocks. The metamorphism extends from a few hundred feet up to perhaps 2,000 feet from the porphyry contacts. The metamorphism invaded the limestone as an irresistible wave, leaving no unaltered sections and stopping short usually with an abrupt contact toward the black limestone, sometimes so sharp that the contact could be covered in one specimen. In other cases it spreads over some distance and for 50 or 100 feet the black limestone is spotted with white blotches and rings.

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[6] J. M. Boutwell: *Prof. Paper 38, U. S. Geol. Survey, 1905.*

There is no graphite or other forms of carbon in the metamorphosed part. The carbon has been eliminated as some volatile compound.

Alteration by later solutions has affected the metamorphosed limestone to some degree, which finds expression in a slight hydration, apparent in the analyses. There is a little kaolin, perhaps also leverrierite, and a large amount of material with an index of refraction lower than Canada balsam. Some of this has a low birefringence and may be a zeolite; other parts are evidently related to serpentine and show higher birefringence. The secondary nature of this material is evident.

The iron occurs as pyrite and ferrous carbonate in the black limestone. In the metamorphosed rock there is usually much more pyrite and the iron in the silicates is in large part in the ferric state (as in andradite and epidote) and to less extent in ferrous state in the metasilicates. This naturally suggests that the abundant carbon dioxide may have exercised an oxidizing action on the emanations and the fact is in line with many other observations on contact zones. There is also a little specularite in the white limestone, but, as far as observed, no magnetite. In the following calculations the iron has been calculated as a metasilicate, the result, therefore, being the norm, rather than the mode, but there is no way of estimating the amount entering into the various iron silicates.

TABLE I.—*Analyses of unaltered and metamorphosed Limestone from Bingham, Utah*

(L. F. Hamilton, Analyst)

| | 1*b* | 2*b* | 3*w* | 4*w* | 5*w* | 6*w* | 7*b* | 8*b* | 9*w* | 10*w* | 11*b* | 12*w* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Silica ........................ $SiO_2$ | 28.47 | 29.11 | 36.66 | 49.27 | 35.20 | 33.33 | 29.34 | 27.28 | 24.22 | 28.11 | 78.80 | 83.44 |
| Iron di-sulphide.............. $FeS_2$ | 0.84 | 0.82 | 1.87 | 3.68 | 2.85 | 6.07 | 2.08 | 3.13 | 6.67 | 1.95 | 1.01 | 5.58 |
| Iron oxide .................... $FeO$ | 1.33 | 1.03 | 4.20 | 2.20 | 3.96 | 1.32 | 0.86 | 0.05 | 0.77 | 1.30 | 3.09 | 3.62 |
| Aluminum oxide ............ $Al_2O_3$ | 1.93 | 2.52 | 2.69 | 3.62 | 1.06 | 1.34 | 0.23 | 0.66 | 3.10 | 0.73 | 1.58 | 0.84 |
| Calcium ...................... $CaO$ | 36.02 | 35.92 | 34.14 | 24.17 | 41.35 | 31.06 | 37.02 | 35.59 | 33.25 | 42.48 | 4.06 | 0.97 |
| Magnesium oxide ............ $MgO$ | 0.69 | 0.65 | 2.86 | 2.64 | 2.88 | 2.03 | 1.77 | 1.45 | 5.60 | 1.71 | 2.53 | 0.61 |
| Sodium oxide ............... $Na_2O$ | 0.29 | 0.33 | 0.33 | 0.45 | 0.46 | 0.69 | 0.53 | 0.33 | 0.83 | 0.89 | 0.41 | 0.53 |
| Potassium oxide.............. $K_2O$ | 0.38 | 0.31 | 0.28 | 0.84 | 0.30 | 0.51 | 0.35 | 1.05 | 0.44 | 0.44 | 0.55 | 0.71 |
| Carbon dioxide............... $CO_2$ | 28.80 | 28.10 | 17.35 | 13.10 | 10.92 | 22.15 | 27.12 | 28.65 | 23.31 | 21.59 | 6.36 | 0.55 |
| Phosphorus pentoxide ........ $P_2O_5$ | not det. | ..... | ..... | ..... | 0.24 | 0.28 | 0.12 | 0.24 | 0.21 | 0.17 | 0.08 | 0.07 |
| Water 110° C................. $H_2O$ | 0.05 | 0.03 | 0.26 | 0.21 | 0.30 | 0.68 | 0.27 | 0.09 | 0.43 | 0.29 | 0.11 | 0.46 |
| Water 800° C................. $H_2O$ | 1.10 | 0.61 | 0.52 | 0.62 | 1.08 | 0.86 | 0.79 | 1.52 | 0.86 | 0.67 | 1.57 | 2.32 |
| Organic matter ................. C | 0.59 | 0.51 | none | none | none | none | not. det. | ...... | none | none | not. det. | ...... |
| | 100.49 | 99.94 | 101.16 | 100.80 | 100.60 | 100.32 | 100.48 | 100.04 | 99.69 | 100.33 | 100.15 | 99.70 |
| Specific gravity (powder).......... | 2.64 | 2.62 | 2.63 | 2.69 | 3.05 | 2.61 | 2.62 | 2.57 | 2.81 | 3.03 | 2.58 | 2.67 |

*THE ANALYSES*

1*b*. Yampa black limestone, number 5 level, Utah Consolidated mine, west end. Elevation, 7,090 feet. Composite of samples 539–588, or 500 feet horizontal distance across whole formation. Stratigraphic thickness, 200 feet. No quartzite beds included. Residue insoluble in HCl, 31.08 per cent. After extraction of calcite with acetic acid there is marked effervescence with 6N hydrochloric acid, solutions containing much iron and magnesium and very little calcium.

2*b*. Yampa black limestone, cross-cut 13th level, Utah Consolidated mine opposite 7–16 shaft. Elevation, 6,360 feet. Composite of samples 589–633, or 450 feet horizontal distance across whole formation. Stratigraphic thickness, 215 feet. Residue insoluble in HCl, 31.26 per cent.

3*w*. Yampa white limestone cross-cut in Y. E. tunnel, east part Utah Consolidated mine. Elevation, 6,900 feet. Composite of samples 265–312, or 480 feet across whole formation. Stratigraphic thickness, 200 feet. Residue insoluble in HCl, 46.50 per cent. After extraction with acetic acid solutions showed much calcium with very little iron and magnesium. Residue treated with 6N hydrochloric acid showed effervescence and solutions contained much iron and fairly large calcium and magnesium; 33 samples out of 48 show small fractions of 1 per cent copper; none show lead. Iron varies from 1 to 6.8 per cent, increasing toward base of formation at Yampa vein.

4*w*. Yampa white limestone, cross-cut in Craig tunnel, east end of Utah Consolidated mine. Elevation, 6,660 feet. Composite of samples 358–420, or 620 feet horizontal distance across whole formation. Stratigraphic thickness, 194 feet. This includes one thin bed of quartzite near top. Composite also by error includes five samples of basal quartzite and five samples of sandy limestone at top, therefore shows too high silica. Residue insoluble in HCl, 57.10 per cent. Thirteen samples show traces or fractions of one ounce of silver. Five out of 58 show trace to 1.57 per cent lead. Ten out of 58 show fractions of 1 per cent copper. Iron and sulphur increase toward top and bottom of formation.

5*w*. Yampa white limestone, 47th cross-cut, number 13 level, Utah Consolidated mine. Elevation, 6,360 feet. Composite of samples, 197–227, or 320 feet horizontal distance, equal to stratigraphic thickness of 150 feet. Top of formation not exposed. Limestone contains 6 veinlets of sulphides parallel to stratification. Residue insoluble in 6N HCl, 50.02 per cent. Extractions with 2N acetic acid, 28.88 per cent. Twenty-one out of 31 samples contain from traces to 0.94 ounces silver; none give assays for lead; four gave fractions of 1 per cent of copper.

6*w*. Yampa white limestone, Climax cross-cut, main tunnel level, Utah Apex mine. Elevation, 6,600 feet. Cross-cut through whole formation, including samples 55–111, or 570 feet; 55 to 81 in white, silicated limestone; 82–111 in black limestone. Analysis, therefore, shows a mixture of about 50 per cent black and 50 per cent white. See under discussion of analysis. Total thickness, about 200 feet. Extraction with 2N acetic acid, 52.63 per cent. Residue insoluble in HCl, 41.68 per cent. Copper to fractions of 1 per cent was contained in 31 samples, mainly near bottom, near Yampa lode, and near top of formation. Two samples out of 57 gave assays for lead.

7*b*. Highland Boy black limestone, cross-cut on number 7 level, Utah Consolidated mine. Upper half of Highland Boy limestone. Elevation, 6,900 feet.

Composite of samples 150–189, or 400 feet horizontal distance obliquely across formation. Contains two 30-foot beds of sandy limestone. Stratigraphic thickness, about 100 feet. Residue insoluble in 6N, HCl, 34.77 per cent. Extraction with 2N acetic acid, 61.50 per cent. None of the samples gave commercial assays for lead or copper.

8*b*. Highland Boy black limestone, cross-cut in west part Utah Consolidated mine, number 13 level. Elevation, 6,360 feet. Composite sample of lower half of Highland Boy limestone. Ignited residue insoluble in 6N hydrochloric acid, 30.01 per cent. Extraction with 2N acetic acid, 67.70 per cent. No assays made.

9*w*. Highland Boy white limestone, number 7 tunnel, Utah Consolidated mine, obliquely across lower half of Highland Boy limestone. Elevation, 6,900 feet. Horizontal distance, 350 feet. Stratigraphic thickness, about 135 feet. Contains two small mineralized streaks and three narrow porphyry dikes of maximum width of 8 feet. Residue insoluble in 6N hydrochloric acid, 35.22 per cent. Extraction with 2N acetic acid, 54.15 per cent. Seven samples near porphyry dikes gave maximum assay of 2.8 per cent copper. No samples gave assays of lead.

10*w*. Highland Boy white limestone, number 16 level, Utah Consolidated mine. Elevation, 6,030 feet. Composite of samples 326–355, excluding samples 338 and 339, which were porphyry dikes. Horizontal distance of 280 feet. Thickness of about 200 feet. Residue insoluble in 6N hydrochloric acid, 35.63 per cent. Extraction with 2N acetic acid, 52.50 per cent. None of samples gave assays for copper or lead.

11*b*. Black sub-Yampa quartzite, number 13 level, Utah Consolidated mine, cross-cut to 7–16 incline shaft. Elevation, 6,030 feet. Upper half of a bed of quartzite between Yampa and Highland Boy limestones. Stratigraphic thickness, about 100 feet. Ignited residue after extraction with 6N hydrochloric acid, 83.71 per cent. Extraction with cold 2N acetic acid, 8.20 per cent. No assay.

12*w*. White sub-Yampa quartzite, cross-cut between Yampa and Highland Boy limestones, number 14 level, Utah Consolidated mine. Elevation, 6,250 feet. Composite of samples 242–263, excluding 245, which is a porphyry dike; in all, 220 feet horizontal distance. Stratigraphic thickness, 100 feet. Samples from lower part of quartzite bed not included, as it contains two small limestone beds. Residue insoluble in 2N hydrochloric acid, 93.44 per cent. Extraction with 2N acetic acid, 1.68 per cent. Of 22 samples 18 contained silver in traces or fractions up to 0.14 ounce. All samples contained copper up to 0.4 per cent. Iron is present from 3 to 10 per cent; sulphur from 1 to 6 per cent, one sample showing 9.17 per cent.

NOTE.—In all analyses the sulphur has been combined with Fe to $FeS_2$, there being no evidence of other sulphides or sulphates. For convenience the unaltered rocks are indicated by the letter *b*, the metamorphosed samples by *w*, thus 1*b* or 3*w*.

## Discussion of the black Yampa Limestone

It is evident that number 1 and number 2 of the original analyses, though taken far apart, are almost identical in composition. The average of the two analyses has, therefore, been accepted and is represented as number 13, recalculated to 100. Thin-sections show a very dark and fine-grained limestone, with numerous small rounded or subangular clastic fragments of quartz; orthoclase, and microcline. Organic remains are abundant, many of which consist of siliceous spiculæ of sponges. The silica is, therefore, present as quartz, as opal, or chalcedony, and as feldspathic silicates. Special tests show the presence of iron carbonate.

The determination of specific gravity of the powder proved difficult on account of floating organic substance. Five determinations averaged 2.61. Determination of specific gravity of fragments of the black limestone gave results varying from 2.67 to 2.72, the average being 2.71. The porosity of the unaltered limestones determined by A. N. Winchell[7] averaged about 4 per cent.

The calculation of non-porous rock gives 2.685, which has been accepted as basis for calculation of gains and losses.

TABLE II.—*Calculation of Analyses of black Yampa Limestone*

| | Number 13 | Mol. W. | Composition | |
|---|---|---|---|---|
| $SiO_2$ | 28.90 | .480 | $CaCO_3$ | 64.30 |
| $FeS_2$ | .83 | .007 | $MgCO_3$ | 1.42 |
| FeO | 1.49 | .021 | $FeCO_3$ | 2.44 |
| $Al_2O_3$ | 1.23 | .012 | FeS | .83 |
| CaO | 36.21 | .644 | Albite and orthoclase | 4.86 |
| MgO | .67 | .017 | Kaolin | .77 |
| $Na_2O$ | .31 | .005 | $SiO_2$ | 25.20 |
| $K_2O$ | .35 | .005 | C | .55 |
| $CO_2$ | 28.56 | .649 | | |
| $P_2O_5$ | .... | .... | | 100.37 |
| $H_2O-$ | .04 | .050 | | |
| $H_2O+$ | .86 | | | |
| C | .55 | .046 | | |
| | 100.00 | | | |

No. 13.—Average of number 1 and number 2.

Mol. W.—Molecular weights.

Composition.—Calculated mineralogical composition. There is 0.79 per cent water, which is not accounted for, and there is a deficiency of 1.98 per cent $CO_2$. The excess of water may be due to microscopic chlorite and sericite, which have not been calculated.

From the composition calculated for number 13, the specific gravity of the mixture may be determined. The figures adopted for the successive minerals are as follows: 2.71, 3, 3.8, 5, 2.6, 2.6, 2.64, and 1.

[7] Op. cit., p. 12.

Thus we obtain, by dividing the weights by the specific gravities, the following volumes:

| | |
|---|---|
| $CaCO_3$ | 23.73 |
| $MgCO_3$ | .47 |
| $FeCO_3$ | .64 |
| $FeS_2$ | .17 |
| Feldspars | 1.86 |
| $SiO_2$ | 9.55 |
| Kaolin | .30 |
| Organic | .55 |
| | 37.27 |

Now, as 37.27 is the volume occupied by 100 grams, the specific gravity is 2.683. In this the porosity has not been considered. Assuming 1 cubic centimeter pore space, or about 3 per cent, the bulk specific gravity of the limestone calculates to 2.61.

### Discussion of altered (white) Yampa Limestone

In discussing the four analyses of metamorphosed Yampa limestone (3, 4, 5, and 6) it should first be observed that, though in general they are entirely similar, number 4 contains much more $SiO_2$ and also more $Al_2O_3$ than any of the others; this is because several samples of basal quartzite were inadvertently introduced; also about five samples of the top rock, which is here a very siliceous limestone. An attempt has been made to correct this analysis (page 520). The others show, compared to the unaltered limestones number 1 and number 2, or the average of these, number 13, an increase of 5 to 8 per cent $SiO_2$, a distinct increase of $FeS_2$ and MgO, a strong but variable decrease in $CO_2$, and a removal of carbon. Alkalies and water are not greatly changed. Calcium oxide is lowered in two and increased in two of the analyses compared with the average of the unaltered rock.

Thin-sections show a coarsely crystalline limestone, with variable amounts of wollastonite and tremolite, generally in fine-grained, felted aggregates and embedded in calcite. Epidote and a garnet (andradite or grossularite) appear in spots, but are not abundant. The minutely distributed pyrite of the unaltered rock here appears in coarser grains or aggregates, and it is more abundant. Detrital grains of quartz and more rarely feldspar are almost always present. Some of the specimens are traversed by veins of coarsely crystalline calcite. No fossil remains nor carbonaceous matter are seen.

The specific gravity of the powder gave, as indicated, on the principal table 2.61, 2.62, 2.63, and 3.05, the last-named figure being obtained from the rock with least carbon dioxide.

TABLE III.—*Calculation of 3w, Yampa white Limestone*

| 3w | | Mol. W. | Mineralogical composition | | Specific gravity | Volumes in 100 grams |
|---|---|---|---|---|---|---|
| $SiO_2$ | 36.66 | 0.611 | Calcite | 39.40 | 2.71 | 14.53 |
| $FeS_2$ | 1.87 | ..... | Pyrite | 1.87 | 5.00 | .37 |
| FeO | 4.20 | 0.058 | Feldspar | 4.19 | 2.60 | 1.61 |
| $Al_2O_3$ | 2.69 | 0.026 | Kaolin | 4.64 | 2.60 | 1.79 |
| CaO | 34.14 | 0.610 | $CaSiO_3$ | 25.06 | 2.90 | 8.64 |
| MgO | 2.86 | 0.071 | $MgSiO_3$ | 7.10 | 3.20 | 2.22 |
| $Na_2O$ | .33 | 0.005 | $FeSiO_3$ | 7.66 | 3.70 | 2.07 |
| $K_2O$ | .28 | 0.003 | $SiO_2$ | 10.92 | 2.64 | 4.13 |
| $CO_2$ | 17.35 | 0.394 | | | | |
| $H_2O-$ | .26 | 0.029 | | 100.84 | 2.83 | 35.36 |
| $H_2O+$ | .52 | | | | | |
| | 101.16 | | | | | |

Assuming 4 per cent porosity, the volume of 100 grams would be 35.36 + 1.40 = 36.76, which corresponds to a specific gravity of 2.72.

The 4*w* analysis has been referred to above as including by error five samples of quartzite below the Yampa base, and therefore containing too much silica. In this section the uppermost part of the formation also contains some beds of siliceous limestone, which would tend to make the silica higher than normal. An attempt has been made to correct the analysis for the five quartzite samples, assuming a quartzite containing 90 per cent $SiO_2$. The recalculation leads to the following corrected percentages:

TABLE IV.—*Calculation of number 4w, Yampa white Limestone in Craig Tunnel*

| Number 16 | | Mol. W. | Mineralogical composition | | Specific gravity | Volumes in 100 grams |
|---|---|---|---|---|---|---|
| $SiO_2$ | 46.79 | .779 | Calcite | 30.70 | 2.71 | 11.32 |
| $FeS_2$ | 3.79 | .... | Pyrite | 3.79 | 5.00 | .76 |
| FeO | 2.27 | .032 | Feldspars | 9.00 | 2.60 | 3.46 |
| $Al_2O_3$ | 3.73 | .036 | Kaolin | 5.42 | 2.60 | 2.08 |
| CaO | 24.97 | .446 | Quartz | 23.82 | 2.64 | 9.59 |
| MgO | 2.73 | .068 | $CaSiO_3$ | 16.12 | 2.90 | 5.56 |
| $Na_2O$ | .46 | .007 | $MgSiO_3$ | 6.80 | 3.20 | 2.13 |
| $K_2O$ | .87 | .010 | $FeSiO_3$ | 4.22 | 3.70 | 1.14 |
| $CO_2$ | 13.53 | .307 | | | | |
| $H_2O-$ | .22 | .035 | | 99.87 | 2.78 | 35.94 |
| $H_2O+$ | .64 | | | | | |
| | 100.00 | | | | | |

Number 16.—Number 4*w* recalculated to 100 and corrected for excess silica.

This analysis calculates very satisfactorily, there being no excess or deficiencies.

TABLE V.—*Calculation of 5w, composite Sample across Yampa Limestone, white and altered.*

| Number 5*w* | | Mol. W. | Mineralogical composition | |
|---|---|---|---|---|
| $SiO_2$ | 35.20 | .587 | Calcite | 23.70 |
| $FeS_2$ | 2.85 | .... | Pyrite | 2.85 |
| $Al_2O_3$ | 1.06 | .016 | Feldspars | 5.24 |
| FeO | 3.96 | .055 | Apatite | 0.50 |
| CaO | 41.35 | .738 | Kaolin | 1.57 |
| MgO | 2.88 | .072 | $CaSiO_3$ | 57.54 |
| $Na_2O$ | 0.46 | .007 | $MgSiO_3$ | 1.90 |
| $V_2O$ | 0.30 | .003 | MgO | 2.12 |
| $CO_2$ | 10.92 | .237 | FeO | 3.96 |
| $P_2O_5$ | 0.24 | .0015 | Quartz | none |
| $H_2O-$ | 0.30 | .059 | | |
| $H_2O+$ | 1.08 | | | 99.38 |
| | 100.60 | | | |

The analysis shows a slight excess of water and a decided deficiency in $SiO_2$. If all of the $CO_2$ is used for calcite, there is not enough silica to combine with remaining CaO, MgO, and FeO. Part of MgO and all of FeO remains unsatisfied, leading to the assumption of the presence of spinel, magnetite, or specularite in the rock. The extract with acetic acid—that is, calcite—is given as 28.88. The analysis looks of doubtful accuracy.

Calculation of specific gravity has not been attempted in view of these discrepancies. The figure is probably not far from 2.90.

This sample comprises about 40 per cent of white altered rock and 60 per cent of black unaltered limestone. Through an error a composite sample was made of both, the analysis thus showing an average of the composition of black and white rock. For direct comparison this analysis should not be used, but it is pointed out that the composition is in close correspondence to the requirements of such a mixture.

TABLE VI.—*Calculation of number 6w, Yampa white Limestone*

| Number 6w | | Mol. W. | Mineralogical composition | | Specific gravity | Volumes in 100 grams |
|---|---|---|---|---|---|---|
| $SiO_2$ | 33.33 | .555 | Calcite | 50.30 | 2.71 | 18.56 |
| $FeS_2$ | 6.07 | .... | Pyrite | 6.07 | 5.00 | 1.20 |
| FeO | 1.32 | .018 | Feldspar | 8.28 | 2.60 | 3.19 |
| $Al_2O_3$ | 1.34 | .013 | Apatite | 0.67 | 3.20 | 0.21 |
| CaO | 31.06 | .555 | $CaSiO_3$ | 5.34 | 2.90 | 1.53 |
| MgO | 2.03 | .050 | $MgSiO_3$ | 5.00 | 3.22 | 1.55 |
| $Na_2O$ | 0.69 | .011 | $FeSiO_3$ | 2.38 | 3.70 | 0.64 |
| $K_2O$ | 0.51 | .005 | | | | |
| $CO_2$ | 22.15 | .503 | | | 2.88 | |
| $P_2O_5$ | 0.28 | .002 | Quartz | 20.70 | | 7.80 |
| $H_2O-$ | 0.68 | .048 | | | | |
| $H_2O+$ | 0.86 | | | | | 34.68 |
| | | | Water | 0.86 | | |
| | 100.32 | | | | | |
| | | | | 99.60 | | |

This analysis is calculated without trouble. There is scarcely any excess of alumina. The water remains uncertain, probably entering into some sericite, serpentine, and chlorite.

Considering 4 per cent of porosity, we obtain an additional volume of 1.39 cubic centimeters, or 36.07, giving bulk specific gravity 2.77.

TABLE VII.—*Summary of Mineralogical Composition of Yampa Limestone, black and white*

| | 13 | 6w | 16 | 3w | 5w |
|---|---|---|---|---|---|
| Calcite | 64.30 | 50.30 | 30.70 | 39.40 | 23.70 |
| Magnesite | 1.42 | ..... | ..... | ..... | ..... |
| Siderite | 2.44 | ..... | ..... | ..... | ..... |
| Pyrite | .83 | 6.07 | 3.79 | 1.87 | 2.85 |
| Apatite | ..... | 0.67 | ..... | ..... | 0.50 |
| Feldspars | 4.86 | 8.28 | 9.00 | 4.19 | 5.24 |
| Kaolin | 0.77 | ..... | 5.42 | 4.64 | 1.57 |
| Carbon | 0.55 | ..... | ..... | ..... | ..... |
| Quartz | 25.20 | 20.70 | 23.82 | 10.92 | none |
| $CaSiO_3$ | ..... | 5.34 | 16.12 | 25.06 | 57.54 |
| $MgSiO_3$ | ..... | 5.00 | 6.80 | 7.10 | 1.90 |
| $FeSiO_3$ | ..... | 2.38 | 4.22 | 7.66 | [8]6.08 |
| | 100.37 | 98.74 | 99.87 | 100.84 | 99.38 |
| Specific gravity | 2.685 | 2.88 | 2.78 | 2.83 | 2.90 |

13.—Average of 1-2 black limestone.

6w.—Yampa white limestone. Sample is a mixture of 60 per cent limestone and 40 per cent white metamorphosed rock.

[8] 6.08 = MgO. 2.12 + FeO 3.96 unassigned.

16.—Yampa white limestone. Recalculated and corrected for excess silica from number 4*w*.

3*w*.—Yampa white limestone.

5*w*.—Yampa white limestone.

TABLE VIII.—*Gains and Losses in Grams per 100 cubic centimeters in Yampa Limestone*

(On basis of equal volumes)

| | 13*b* | 6*w* | 5*w* | 3*w* | 16 | 6–13 | 5–13 | 3–13 | 16–13 |
|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ ... | 77.60 | 95.99 | 102.08 | 103.75 | 130.08 | +18.39 | +24.48 | +26.15 | +52.48 |
| $FeS_2$ ... | 3.23 | 17.48 | 8.27 | 5.29 | 10.54 | +15.25 | + 6.04 | + 2.06 | + 8.31 |
| FeO ... | 4.00 | 3.80 | 11.48 | 11.88 | 6.31 | + 0.20 | + 7.48 | + 7.88 | + 2.31 |
| $Al_2O_3$ .. | 3.30 | 3.86 | 3.07 | 7.61 | 10.37 | + 0.56 | + 0.23 | + 4.31 | + 7.07 |
| CaO ... | 97.22 | 89.45 | 119.92 | 96.62 | 69.40 | — 7.77 | +22.70 | — 0.60 | —27.80 |
| MgO ... | 1.80 | 5.85 | 8.35 | 8.09 | 7.59 | + 4.05 | + 6.55 | + 6.29 | + 5.79 |
| $Na_2O$ .. | 0.83 | 1.99 | 1.33 | 0.93 | 1.28 | + 1.16 | + 0.50 | + 0.10 | + 0.45 |
| $K_2O$ ... | 0.94 | 1.47 | 0.87 | 0.79 | 2.42 | + 0.53 | — 0.07 | — 0.15 | + 1.42 |
| $CO_2$ ... | 76.68 | 63.79 | 31.67 | 49.10 | 37.61 | —12.92 | —45.01 | —27.58 | —39.07 |
| $P_2O_5$ ... | not det. | 0.81 | 0.70 | not det. | not det. | ..... | ..... | ..... | ..... |
| $H_2O+$.. | 2.30 | 2.48 | 3.13 | 1.40 | 1.78 | + 0.18 | + 0.83 | — 0.90 | — 0.52 |
| C ..... | 1.48 | none | none | none | none | — 1.48 | — 1.48 | — 1.48 | — 1.48 |
| | 269.38 | 286.97 | 290.87 | 285.46 | 277.38 | +18.15 | +21.79 | +16.08 | + 8.96 |
| Sp. G... (calculated) | 2.685 | 2.88 | 2.90 | 2.83 | 2.78 | | | | |

13*b*.—Black unaltered Yampa limestone. Grams per 100 cubic centimeters.

6*w*.—White metamorphosed Yampa limestone. Sample is a mixture of 40 per cent black and 40 per cent white limestone and does not represent the composition of normal white limestone.

5*w*.—White metamorphosed Yampa limestone.

3*w*.—White metamorphosed Yampa limestone.

16.—White metamorphosed Yampa limestone.

6–13.—Total gain, 40.32; total loss, 22.17; balance gain, +18.15.

5–13.—Total gain, 68.58; total loss, 46.79; balance gain, +21.79.

3–13.—Total gain, 46.79; total loss, 30.71; balance gain, +16.08.

16–13.—Total gain, 77.83; total loss, 68.87; balance gain, +8.96.

## SUMMARY DISCUSSION OF THE METAMORPHISM OF THE YAMPA LIMESTONE

The first thing that stands out is the striking similarity, almost identity, of the two analyses of unaltered limestones. These composite samples are 750 feet apart vertically and 700 feet horizontally. At both places the samples extend across the whole formation. The limestones contain throughout a little finely divided $FeS_2$, and chemical tests indicate that a small amount of the carbonates of iron and magnesia are also present. They contain 25 per cent quartz (with chalcedony), about 5 per cent feldspars in detrital grains, carbon, or hydrocarbons, 64 per cent calcite, and probably a little kaolin. They are, therefore, siliceous limestones.

Considering now the mineralogical composition (Table VII) of the four metamorphosed sections, it is apparent that they comprise a graduated series in which the decrease of calcite is more or less strongly marked. It is difficult to connect this with the distance from the intrusive, for, though probably the silicates are more abundant near the monzonite porphyry, there is no definite increase of silication up to the contact. On the whole, the contact is very sharp and the metamorphism appears to be about as complete close to the contact as away from it. In other words, the reaction stopped short at a certain point, and up to this point the limestone was apparently fully saturated with the emanations from the magma. Garnet and epidote are, however, more common in the vicinity of the intrusives. The contacts with the monzonite are not well exposed. The emanations appear to have come in part from the lower part of Carr Fork and in part from the long now eroded contact at which the limestone continued up on the dip bordered against the monzonite now shown on the south side of the Carr Fork.

The free quartz shows a gradual decrease from 25 per cent to 11 per cent and to nothing (in 5*w*). Probably analysis 4, recalculated as number 16, still contains too much silica on account of admixed very siliceous beds in the uppermost part.

Magnesite and siderite do not appear to be present in the altered rocks and indeed, with $SiO_2$ as the stronger acid, would not be expected to be stable. Pyrite shows a consistent and strong increase from 0.83 in the fresh rock to 6.07 per cent in number 6*w*.

Regarding the feldspars, some doubt may be admitted. Analyses 6*w* and 16 show a decided increase, but whether this is accidental or owing to introduced $Al_2O_3$ in some metamorphic mineral is not certain. On the face of it, it looks as though some alumina may have been added. Take, for instance, 5*w*, which shows that all of the quartz has been used up, for silicates still calculate to 5.24 per cent feldspars, or more than in the original rock. It is not probable that the detrital feldspars should have escaped some recrystallization any more than the quartz, and it seems likely that in this analysis the alkali feldspars have at least been recrystallized to some other mineral.

Kaolin is generally present in quantities larger than in the unaltered rock, and there is usually some combined water left after the calculation, which points to the probable existence of products like chlorite, serpentine, or asbestiform minerals impossible to identify.

The quartz has been largely used up for the new silicate minerals, but besides there has also taken place, as shown later, a decided introduction of new silica.

The new silicates are mainly wollastonite and tremolite and have been so calculated. The ferrous oxide has also been calculated as a metasilicate $FeSiO_3$. In places there is certainly epidote, garnet, and other silicates, but they are subordinate and could not well be accounted for in the calculation.

The Ca, Mg. Fe metasilicates range from 27.14 per cent in number 16 to 39.82 per cent in 3*w* and to a maximum of 65.52 per cent in 5*w*.

The calculated specific gravities have been adopted for subsequent calculations as more reliable than those determined by pycnometer in the powdered samples. It is probably very difficult to secure an exact determination in case of such a finely powdered material which forms suspensions and slimes.

## Summary Discussion of Gains and Losses on Basis of equal Volumes in the Yampa Limestone

In Table VIII the several analyses have been multiplied by the calculated specific gravity to obtain grams per 100 cubic centimeters under the assumption that no expansion or contraction has taken place during metamorphism. It should be recalled that number 6*w* is a mixture of black and white limestone. The table is arranged by increasing silica, which shows an addition of from 24.48 to 52.48 grams per 100 cubic centimeters.

The addition of pyrite is marked and unmistakable. The actual addition of pyrite in number 6*w* is 15.25 ounces per 100 cubic centimeters, or 150 kilograms per cubic meter. The addition of FeO is likewise perfectly evident. An introduction of alumina is very probable, but perhaps not conclusively proved.

Lime behaves erratically. Normally one would expect a loss, and this has taken place in three of the metamorphosed rocks, but in the fourth an addition of 22.70 grams per 100 cubic centimeters is indicated equivalent to about 20 per cent.

Magnesia is uniformly and consistently increased, the maximum amounts introduced being 6.55 grams per 100 cubic centimeters.

Soda has increased in all cases, but in regard to potassium the results are not at all consistent.

Carbon dioxide is uniformly decreased, as would indeed be expected, to a minimum of half of the original amount.

There is probably little or no change in phosphoric acid. No definite conclusion can be drawn as to the combined water. Normally it would decrease during metamorphism, but the altered rocks have been exposed to hydration, with the result of formation of hydrated silicates.

Carbon or the hydrocarbons are eliminated.

The final result is a gain of substance amounting to from 9 to 22 grams per 100 cubic centimeters. The total gains vary from 47 to 78 grams per 100 cubic centimeters; the total losses from 22 to 69 grams per 100 cubic centimeters.

Losses plus gains range from 27 per cent to 52 per cent of the original mass. This percentage has moved in or out of the rock. It is larger than the corresponding figures for the Highland Boy limestone.

## Discussion of the black Highland Boy Limestone

The two analyses, *7b* and *8b*, of the unaltered Highland Boy limestone are so closely alike that the average of the two can well be taken. This is given below under number 14. In silica, lime, and carbon dioxide the average is almost identical with number 13, representing the Yampa limestone. The only differences are somewhat higher pyrite and magnesia and lower ferrous oxide. Microscopically the two limestones are practically identical. The specific gravities given in the main table are probably too low, and for the same reason given above in the discussion of the Yampa limestone the figure 2.685 has been adopted.

Table IX.—*Calculation of Analysis of black Highland Boy Limestone*

| Number 14 | | Mol. W. | Mineralogical composition | |
|---|---|---|---|---|
| $SiO_2$ | 28.31 | .471 | $CaCO_3$ | 64.18 |
| $FeS_2$ | 2.60 | .... | (MgFe) $CO_3$ | 1.64 |
| FeO | 0.45 | .006 | $FeS_2$ | 2.60 |
| $Al_2O_3$ | 0.45 | .004 | Orthoclase | 8.80 |
| CaO | 36.30 | .648 | Albite | |
| MgO | 1.61 | .040 | Sericite | |
| $Na_2O$ | 0.43 | .006 | Apatite | 0.41 |
| $K_2O$ | 0.70 | .007 | Quartz | 22.51 |
| $CO_2$ | 27.88 | .634 | Organic carbon (assumed) | 0.55 |
| $P_2O_5$ | 0.18 | .001 | | |
| $H_2O-$ | 0.18 | .075 | | 100.69 |
| $H_2O+$ | 1.16 | | | |
| C | not det. | | | |
| | 100.25 | | | |

The volumes of the items of mineralogical composition obtained as before by dividing by the same specific gravities would yield:

| | |
|---|---|
| $CaCO_3$ | 23.68 |
| $Mg(Fe)SiO_3$ | 0.55 |
| $FeS_2$ | 0.52 |
| Feldspars and sericite | 3.40 |
| Apatite | 0.13 |
| $SiO_2$ | 8.52 |
| Organic (assumed) | 0.55 |
| | 37.35 |

This corresponds to a specific gravity of 2.685. Adding 1 cubic centimeter of assumed pore space, about 2 per cent, to the volume gives a total volume of 38.35, which corresponds to a specific gravity of 2.61, practically the same figures as were obtained for the Yampa black limestone.

The analysis is not quite satisfactory. It shows a small deficiency of $CO_2$ and $Al_2O_3$ and an excess of water. In part the $H_2O$ may belong to finely divided sericite or other hydrous silicates.

### Discussion of the altered (white) Highland Boy Limestone

The analysis 9*w* of an average across the lower 135 feet of the Highland Boy limestone includes three narrow porphyry dikes. Possibly the latter may have raised the silica and alumina slightly. The rock is white crystalline with some pyrite, but nowhere shows complete silication. Calcite was extracted with 2N acetic acid and amounted to 54.15 per cent.

Table X.—*Calculation of 9w, composite Sample of lower Highland Boy altered, white Limestone adjoining 7b*

| | 9*w* | Mol. W. |
|---|---|---|
| $SiO_2$ | 24.22 | .404 |
| $FeS_2$ | 6.67 | .... |
| FeO | 0.77 | .010 |
| $Al_2O_3$ | 3.10 | .030 |
| CaO | 33.25 | .593 |
| MgO | 5.60 | .140 |
| $Na_2O$ | 0.83 | .014 |
| $K_2O$ | 0.44 | .004 |
| $CO_2$ | 23.31 | .530 |
| $P_2O_5$ | 0.21 | .001 |
| $H_2O-$ | 0.43 | .047 |
| $H_2O+$ | 0.86 | |
| Organic | none | |
| | 99.69 | |

Under the assumption that little or no siderite or magnesite is present, the mineralogical composition would be as follows:

| | | Specific gravity | Volumes in 100 grams |
|---|---|---|---|
| Calcite | 53.00 | 2.71 | 19.53 |
| Pyrite | 6.67 | 5.00 | 1.33 |
| Apatite | 0.48 | 3.20 | 0.15 |
| Feldspars | 10.00 | 2.60 | 3.85 |
| Kaolin | 3.10 | 2.60 | 1.19 |
| $CaSiO_3$ | 6.96 | 2.90 | 2.39 |
| $MgSiO_3$ | 14.00 | 3.20 | 4.38 |
| $FeSiO_3$ | 1.32 | 3.70 | 0.36 |
| Quartz | 3.72 | 2.64 | 1.41 |
| | 99.25 | 2.89 | 34.59 |

Assuming that the rock has a porosity of 4 per cent, we obtain specific gravity 2.69.

The calculation leaves a small excess of $H_2O+$, which it is assumed enters into hydrated metasilicates.

TABLE XI.—*Calculation of 10w, composite Sample of upper Part Highland Boy altered white Limestone*

| 10*w* | | Mol. W. | Mineralogical composition | | Specific gravity | Volumes in 100 grams |
|---|---|---|---|---|---|---|
| $SiO_2$ | 28.11 | .468 | Calcite | 49.10 | 2.71 | 18.12 |
| $FeS_2$ | 1.95 | .... | Pyrite | 1.95 | 5.00 | 0.39 |
| FeO | 1.30 | .018 | Apatite | 0.34 | 3.20 | 0.11 |
| $Al_2O_3$ | 0.73 | .007 | Feldspars | 10.00 | 2.60 | 3.85 |
| CaO | 42.48 | .759 | $CaSiO_3$ | 30.74 | 2.90 | 10.60 |
| MgO | 1.71 | .043 | $MgSiO_3$ | 4.30 | 3.20 | 1.34 |
| $Na_2O$ | 0.89 | .015 | $FeSiO_3$ | 2.38 | 3.70 | 0.64 |
| $K_2O$ | 0.44 | .004 | Quartz | 2.28 | 2.64 | 0.85 |
| $CO_2$ | 21.59 | .491 | | | | |
| $P_2O_5$ | 0.17 | .001 | | 101.09 | 2.80 | 35.90 |
| $H_2O-$ | 0.29 | .054 | | | | |
| $H_2O+$ | 0.67 | | | | | |
| | 100.33 | | | | | |

The excess in the addition is due to deficiency of alumina for feldspars in the analysis.

Assuming a porosity of 4 per cent, the total volume would be 35.90 + 1.40 = 37.30 and the bulk specific gravity would be 2.68.

TABLE XII.—*Summary of mineralogical Composition of Highland Boy Limestone, black and white*

| | 14 | 9w | 10w |
|---|---|---|---|
| Calcite | 64.18 | 53.00 | 49.10 |
| Magnesite, Siderite | 1.64 | ..... | ..... |
| Pyrite | 2.60 | 6.67 | 1.95 |
| Apatite | 0.41 | 0.48 | 0.34 |
| Feldspars | 8.80 | 10.00 | 10.00 |
| Kaolin | ..... | 3.10 | ..... |
| Carbon | 0.55 * | ..... | ..... |
| Quartz | 22.51 | 3.72 | 2.28 |
| $CaSiO_3$ | ..... | 6.96 | 30.74 |
| $MgSiO_3$ | ..... | 14.00 | 4.30 |
| $FeSiO_3$ | ..... | 1.32 | 2.38 |
| | 100.69 | 99.25 | 101.09 |
| Specific gravity | 2.685 | 2.89 | 2.80 |

14.—Average of 7*b* and 8*b* Highland Boy black limestone.
9*w*.—Altered white Highland Boy limestone.
10*w*.—Altered white Highland Boy limestone.

TABLE XIII.—*Gains and Losses in Grams per 100 cubic centimeters in Highland Boy Limestone*

(On basis of equal volumes)

| | 14 | 9w | 10w | 9–14 | 10–14 |
|---|---|---|---|---|---|
| $SiO_2$ | 76.01 | 69.99 | 78.71 | — 6.02 | + 2.70 |
| $FeS_2$ | 6.98 | 19.28 | 5.46 | +12.30 | — 1.52 |
| FeO | 1.21 | 2.23 | 3.64 | + 1.01 | + 2.43 |
| $Al_2O_3$ | 1.21 | 8.96 | 2.04 | + 7.75 | + 0.83 |
| CaO | 97.46 | 96.09 | 118.94 | — 1.37 | +21.48 |
| MgO | 4.32 | 16.18 | 4.79 | +11.86 | + 0.47 |
| $Na_2O$ | 1.16 | 2.40 | 2.49 | + 1.24 | + 1.33 |
| $K_2O$ | 1.88 | 1.27 | 1.23 | — 0.61 | — 0.65 |
| $CO_2$ | 74.86 | 67.36 | 60.45 | — 7.50 | —14.41 |
| $P_2O_5$ | 0.48 | 0.61 | 0.48 | + 0.13 | ..... |
| $H_2O+$ | 3.12 | 2.48 | 1.88 | — 0.64 | — 1.24 |
| C | not det. | none | none | ..... | ..... |
| | 268.69 | 286.85 | 280.11 | +18.15 | +11.42 |

Number 14.—Average of 7*b* and 8*b*. Unaltered black limestone × 2.685.

9*w*.—Altered Highland Boy limestone × 2.89. Total gains, 34.39; losses, 16.14; balance, +18.15.

10*w*.—Altered Highland Boy limestone × 2.80. Total gains, 29.24; losses, 17.82; balance, +11.42.

* Assumed.

## Summary Discussion of the Metamorphism of the Highland Boy Limestone

There are two analyses of the average composition of the unaltered Highland Boy limestone. They agree almost exactly, although number *7b* is only from the upper half of the limestone and number *8b* is from the lower half of the formation. The average in number 14 is extremely close to the average of the Yampa limestone, and the composition consists of calcite, with a small amount of siderite and magnesite, but with a somewhat higher percentage of pyrite than in the Yampa limestone. The feldspars are also notably higher than in the Yampa.

Considering now the mineralogical composition of the metamorphosed sections, there are only two analyses available. The first, number 9*w*, represents the altered lower part of the formation adjacent to number *7b*, which includes the upper half of black limestone. The second, number 10*w*, is from the deepest level (number 16) of the Utah Consolidated mine, about 900 feet below number 9.

Comparing the mineralogical composition of the fresh and altered rocks (Table XII), it appears that calcite decreases from 64.18 per cent to a minimum of 49.10 per cent. Pyrite increases strongly in 9*w*, but is actually less in 10*w*, which is heavily silicated. Magnesite and siderite are believed to be absent in the metamorphosed rocks. The calculation shows apparently that the feldspars remain about the same, while the quartz may be almost wholly gone. This is unlikely and suggests that new alkaline aluminum minerals not readily visible may have been formed. Quartz is almost wholly recrystallized to silicates in 9*w* and 10*w*. The metasilicates in the last two analyses are 22.28 and 37.42 per cent respectively. In 9*w* the unusual condition obtains that the magnesium silicate is in excess of the calcium silicate.

## Summary Discussion of Gains and Losses on Basis of equal Volumes in the Highland Boy Limestone

In Table XIII the several analyses have been multiplied by the calculated specific gravities to obtain grams per 100 cubic centimeters. In regard to silica, there has been comparatively little change, certainly no consistent increases as in the Yampa limestone. One analysis shows a slight loss, the other a slight gain. Ferrous oxide is decidedly increased. In the case of 10*w*, where a decrease of pyrite has taken place, the total iron is nevertheless increased. There seems to be a decided gain of alumina, though in 9*w* three small included porphyry dikes doubtless contribute to the unusually large $Al_2O_3$. Lime in 9*w* remains about the same, while a very strong addition has occurred in 10*w*.

Magnesia is increased, soda likewise. Potassium appears slightly reduced, but no definite conclusion can be drawn from the figures. Carbon dioxide is lost to the extent of 7.50 and 14.41 grams per 100 cubic centimeters out of 74.86 in the black limestone.

Combined water seems slightly reduced, and, of course, carbon or hydrocarbons are removed.

As a general result, there has been a notable loss of carbon dioxide, a slight gain or loss in silica, a decided addition of ferrous oxide, also of magnesia, alumina, and soda. Lime has remained stationary in one analysis and has been greatly increased in the other.

The final result is a gain of substance amounting to 11.42 and 18.15 grams per 100 cubic centimeters respectively. The total gains are 29.24 and 34.29 respectively; the total losses, 16.14 and 17.82. Losses plus gains amount to about 17 per cent of the original mass. This percentage of matter has moved in or out of the rock, disregarding movements of matter that has remained in the limestone.

## Porosity

The discussion so far has disregarded porosity for the reason that it can not be accurately determined for the whole thickness of rocks. Reference has been made above to the determinations by Prof. A. N. Winchell. He obtained for unsilicated rocks with 25 per cent quartz the average of 1.8 per cent, for partly silicated rocks an average of 5.9, which is probably too high, as it includes one determination out of ten which showed an apparently abnormal porosity of 18 per cent. In completely silicated rocks the porosity was only 3.3 per cent in average. These data agree in general with my observations.

If the rocks have a porosity, the effect will be to reduce the calculated specific gravity. Assuming, for instance, that the porosity of the black limestone (number 13 and number 14) is 3 per cent, this will increase the calculated volumes 37.27 by 1 cubic centimeter, making the total volume 38.27, and also reduce the calculated specific gravity 2.685 by 0.7 or to 2.615. This again will reduce the grams per 100 cubic centimeters (Tables VIII and XIII) by about 2.5 per cent.

In a similar way, in analysis *3w*, assuming a porosity of 6 per cent will reduce the calculated specific gravity from 2.83 to 2.68, a reduction of 0.15. This again, in Table VIII, will reduce the grams per 100 cubic centimeters by about 5 per cent. Consequently the gains will be decreased and losses will be increased by about 2.5 per cent, which again will tend to reduce the balance gains. The general results, as outlined above, will not be materially affected by porosity even if averaging 6 per cent in the altered rock.

### Comparison of Metamorphism of Yampa and Highland Boy Limestone

Though the compositions of the Yampa and the Highland Boy limestones are practically identical, the metamorphism of the two has proceeded on different lines. In the Highland Boy formation the quartz has been almost completely used up for the development of silicates, whereas in the Yampa limestone much $SiO_2$ has been added, and the silicates have mainly been formed from the silica contributed by the magma. In the case of number *5w* in the Yampa limestone, about 65 per cent of silicates have formed, using up all of the detrital quartz and a magmatic gain of 24 grams per 100 cubic centimeters in addition. As silicates will be more easily formed from the fluid or gaseous silica than from detrital grains, it would seem to follow that the Highland Boy limestone had been exposed to higher temperatures than the Yampa. This is probably true, for it includes large masses and dikes of porphyry.

### Consideration of Errors

It is well to realize that the figures tabulated above are mere approximations, say within 5 to 20 per cent of the actual figures. The sources of errors are many: in the sampling, in the preparation and mixing of the samples, in the chemical analyses, and in the determinations of the specific gravity. Even considering all this it is certain that the results outlined above will stand, generally speaking, and that the actuality of magmatic additions of silica, ferrous and ferric iron oxide, magnesia, and iron sulphide are proved.

### Change of Volume

During the progress of the field examinations preparatory to the trial in the courts there was general agreement between the geologists that no measurable decrease of volume had taken place during the metamorphism. This was specially well established in the case of the Yampa limestone. In case of the composite samples *1b, 2b, 3w,* and *4w* of the Yampa limestone, where the thickness could be accurately measured, it was found to be respectively 200, 215, 200, and 194 feet. This conclusion has been confirmed by Prof. A. N. Winchell[9] as follows: "The numerous vertical

[9] Petrographic studies of limestone alterations at Bingham. Trans. Am. Inst. Min. and Met. Engs., New York meeting, February, 1924, pp. 6 and 7.

sections through the Highland Boy limestone and other formations, carefully worked out for the lawsuit, show that there has been no decrease of volume as a result of the change of the limestone to lime-silicate rock."

Microscopic evidence shows also, and again I agree with Professor Winchell "that the original quartz is not used (at least in all cases) in the formation of lime silicate, for in some thin-sections the calcite matrix has been converted completely into lime-silicate minerals with no encroachment on the rounded outlines of the detrital quartz grains."

The equation $CaCO_3 + SiO_2 = CaSiO_3 + CO_2$ would call for a reduction of volume of 31.48 per cent, provided the silica was a solid in the limestone. If the silica was introduced from the outside as a fluid, there would be an increase of volume of 10.81 per cent.[10] I hold, however, that during replacement there has been no change of volumes in general, the volume of replaced material equaling that introduced. As a matter of fact, if there has been no change of volume the above equation is incorrect, and the reaction involves a loss of CaO as well as of $CO_2$.[11] This finds expression in the fact that in the altered rocks lime as well as $CO_2$ is carried away. But in metamorphic action like that here described the movement of matter has been intense and variable. Two of the six analyses of altered rocks show a strong addition of CaO.

## Alteration of sub-Yampa Quartzite

The last two analyses in the general table (11*b* and 12*w*) represent respectively unaltered black sandstone and altered white rock of the same kind. It has not been thought worth while to recalculate these. In general, the black sandstone consists of detrital quartz and feldspar grains and contains about 7.2 per cent calcite, 5.12 per cent magnesite, 1.28 per cent siderite, and 1.01 per cent pyrite, leaving about 2 per cent of FeO unaccounted for.

The alteration consists in an increase of silica, iron oxide and pyrite, and a very marked removal of carbonates. Only a small amount of calcium or magnesium silicates can be present. A considerable mineralization has, therefore, taken place with the introduction of sulphur and silica. Almost every sample showed silver and copper from traces to a fraction of one per cent.

[10] C. R. Van Hise: Metamorphism. Mon. 47, U. S. Geol. Survey, 1904, p. 239.

[11] W. Lindgren: The nature of replacement. Economic Geology, vol. 7, 1912, pp. 521-535; Volume changes in metamorphism. Jour. Geology, vol. 26, 1918, pp. 542-554.

## Conclusion

The chemical investigations in this paper show that at Bingham, as a consequence of metamorphism, the siliceous limestones of the Yampa and the Highland Boy formations have gained silica, sulphur, iron magnesia, alumina, and soda, and that carbon dioxide and (generally) lime have been carried away. There has been a well defined gain of substance amounting to from 4 to 8 per cent. The additions range from 8 to 29 per cent and the losses from 4 to 20 per cent. The volume of the limestone has remained approximately constant.

While strong silication, and especially the development of garnet, seems favored by the proximity of the contact with the intrusive, silication in this case has proceeded right up to the sharp contact with unaltered rock. There are in these limestones no separate masses in which marmorization has been effected without silication.

On account of the great irregularity of the intrusions, it is difficult to say just how far from the contact the metamorphism has proceeded. Generally speaking, it extends from a few hundred feet to a maximum of two thousand feet from the igneous contact.

The metamorphism was accompanied by the introduction of pyrite and chalcopyrite, probably also other sulphides, but only to a moderate extent. They formed practically simultaneously with the silicates. The ore deposits of importance were formed at a distinctly later stage in part with the development of silicates, but continuing to form until the temperature had fallen far below the point of silication. The calcareous quartzite has likewise been metamorphosed, and apparently quartz has developed in it with pyrite and a small amount of calcium silicates.

In closing, the difference between dynamic and igneous metamorphism might well be emphasized. In recrystallization under pressure silication may likewise take place in siliceous limestone, but these changes are slow; the solutions percolate with minimum speed and the final result may take a million years. The recrystallized rock has little porosity. Plenty of time is available for the development of a solid non-porous rock. In igneous metamorphism, on the other hand, the recrystallizing agents or fluids rush out from the intrusive and pass through the limestone like water through a sponge. The reactions and interchanges take place rapidly; sometimes solutions run ahead of precipitation and porosity may develop. The whole process might well be completed in a few years. This expresses the difference between slow and fast work by the processes of nature.