SULPHUR AND PYRITE.

A SULPHUR DEPOSIT IN THE SAN RAFAEL CANYON, UTAH.

By Frank L. Hess.

The sulphur deposit described in this paper lies in southeastern Utah, in the canyon of San Rafael River, 18 or 20 miles west of the town of Greenriver. It was examined by the writer during a reconnaissance in July, 1911. The deposit is on the south side of the river, about 5 miles from the mouth of the canyon, and is in limestone débris through which rise a number of springs carrying large volumes of hydrogen sulphide gas from which the sulphur has probably been formed.

San Rafael River flows southeastward across the northern part of the San Rafael Swell and has cut a deep canyon with nearly perpendicular walls a thousand feet or more high which are in places impressively beautiful. Broad and narrow bands of red, white, and buff alternate in the sedimentary rocks of the walls, and with the bright blue of the sky and the green of the cottonwoods and brush on the floor of the canyon produce very striking color effects. The river rises a considerable distance west of the Swell and apparently follows the rule laid down by Dutton [1] for the high plateau region—that "the principal drainage channels are older than the displacements."

The San Rafael Swell is an oval elevation, the long axis of which runs somewhat east of north and is about 40 miles long; its breadth is from 10 to 20 miles. From the body of the Swell the rocks down to the lowest Triassic [2] have been removed. The canyon is cut still lower and gives excellent exposures of rocks which may be of upper Carboniferous age.

At the point where the sulphur deposit under consideration occurs the canyon widens until the floor is probably a quarter of a mile across. As the spot is approached in coming up the canyon the existence of the springs is indicated a mile or more away by the odor of hydrogen sulphide, possibly more because the spring water has mingled with that of the river than because the gas has been carried

[1] Dutton, C. E., Report on the geology of the high plateaus of Utah: U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1880, p. 163.
[2] Idem, pp. 19–20.

so far by the breeze. At the springs the river flows near the south side of the canyon. In the middle of the valley half an acre of bright green cane and rushes grow in the wet soil around one of the springs, and on the south side of the river is a smaller patch covered with cane. Up the river 100 yards the cane climbs 40 or 50 feet up on the bank, showing that seepages must occur, for in most places only a scanty, drought-resisting vegetation can exist on the slopes.

In the patch of cane on the south side of the river bottom is a spring occupying an area of about 15 by 20 feet, the water of which is of a clear light greenish-blue color. It is in constant ebullition from gas rising at more than a hundred points. The odor of hydrogen sulphide is strong, and the water, which is cool, tastes noticeably of the gas. It is not known whether carbon dioxide also is emitted.

The stream issuing from the spring is about 20 inches wide and 4 inches deep and flows with a velocity of about 1 foot per second, so that the discharge is probably a little more than half a cubic foot per second. The temperature is probably not above 60° F.

Up the river for a distance of 250 yards are other springs, perhaps a dozen in all, several of which would each fill a 2-inch pipe. All seem to be equally charged with hydrogen sulphide except the farthest, which apparently carries less of the gas but much iron oxide. The water of this spring, however, tastes strongly of hydrogen sulphide. It is about 25 feet above the river, but all the others are nearer the river's level. A dead spring 20 or 25 feet above the river and about 75 yards from the uppermost spring now flowing has built a terrace of travertine 20 feet high, which contains many impressions of cane leaves and stems. The large accumulation of travertine suggests that the spring may at one time have been hot, but the vegetable impressions show that the spring could not have been near the boiling point at the time they were made.

All the springs, except those in the flat, issue from impure limestone débris which apparently covers a thin-bedded stratum of limestone. Above the springs, particularly about the middle of the strip, the ground is impregnated with sulphur, much of which is in small crystals, but a large part of it, so far as is visible to the unaided eye, is amorphous and of a pale dirty yellow color. Where the sulphur occurs the limestone is partly altered to gypsum.

The deposit evidently belongs to the common type formed from the oxidation of hydrogen sulphide. Here the gas has diffused from the springs through the débris. The deposition of sulphur from the gas is supposed to take place according to the equation $2H_2S+O_2=2H_2O+2S$. Further oxidation takes place, changing part of the sulphur to sulphuric acid, which attacks the limestone and converts it to gypsum.

No selenium and no arsenic could be detected in the specimen collected.

If, as is supposed, the deposits are formed through the oxidation of hydrogen sulphide rising from the springs, they must be shallow and comparatively small. So far as could be seen in the hasty visit made, the strip bearing sulphur is only about 100 or 150 feet wide by 750 feet long. A little prospecting has been done by digging shallow trenches, but not enough to show much of the extent of the deposits. There is no doubt that sulphur can be extracted, but with fuel scarce locally, an 18 or 20 mile haul to the railroad, and a restricted market it is not likely that the deposits can at present be worked at much profit.

Sulphur deposits not accompanied by springs are reported to occur near San Rafael River 5 to 8 miles above the ones described. Others, 15 miles north of the upper deposits, are said to occur with cool springs on Cedar Mountain on a wash tributary to Price River. They are reached from Woodside.

The origin of the hydrogen sulphide in the water is unknown. The presence of the sulphur deposits at several places in the northern part of the Swell suggests the possibility that the Swell is underlain by a laccolith (a mushroom-shaped intrusion of igneous rock) the exhalations of which may furnish the gas directly. A laccolith is also suggested by the indications that the springs may have been formerly hot—by the shape of the San Rafael Swell and by proximity to the Henry Mountains, a known laccolithic mass 25 miles to the south. However, it is possible that the gas is derived from the sedimentary beds. Hydrogen sulphide is common in artesian water derived from sedimentary beds containing organic matter. The organic matter reacts upon sulphides to form H_2S.

SULPHUR DEPOSITS OF SUNLIGHT BASIN, WYOMING.

By D. F. Hewett.

INTRODUCTION.

The following description of the sulphur deposits of Sunlight Basin, Wyo., is based on an examination made during the summer of 1911. The presence of sulphur was noted by Arnold Hague,[1] of the United States Geological Survey, who studied and mapped the areal geology of the Crandall quadrangle, in which the deposits are situated. Recent exploitation of the deposits has appeared to justify more detailed examination. During the course of this examination the officers and employees of the Sulphur Mining & Milling Co. of Cody, Wyo., extended hospitality in this region of difficult access and placed claim maps at the disposal of the writer. Mr. Russell Kimball, of Cody, gave much assistance in the form of notes necessary for the construction of the accompanying map.

LOCATION AND EXTENT.

The location of these sulphur deposits as well as those near Cody[2] and Thermopolis,[3] Wyo., is shown on figure 48. The deposits here described are situated in the upper portion of Sunlight Basin, Park County, Wyo., about 32 miles in a direct line northwest of Cody and 14 miles east of the east boundary of the Yellowstone National Park. The district is accessible by a fair wagon road from Cody, by which the distance is 52 miles. A weekly stage service is operated between Cody and Painter, which is 12 miles east of the sulphur deposits. Transportation into or away from the basin is greatly hindered by a steep hill between Dead Indian Creek and Pat O'Hara Creek, over which the ascent amounts to approximately 2,000 feet in less than 2 miles. Though it is possible to construct a road with a lower gradient, the present road is the only means of access.

The sulphur deposits occur in seven isolated groups, six of which lie in a belt about 3½ miles long, which crosses the valley of Sunlight

[1] Absaroka folio (No. 52), Geol. Atlas U. S., U. S. Geol. Survey, 1899.

[2] Woodruff, E. G., Sulphur deposits at Cody, Wyo.: Bull. U. S. Geol. Survey No. 340, 1908, p. 454.

[3] Woodruff, E. G., Sulphur deposits near Thermopolis, Wyo.: Bull. U. S. Geol. Survey No. 380, 1909, p. 378.

Creek. The other deposit is situated on Little Sunlight Creek, about 4 miles northeast. Prospecting has been limited to digging numerous shallow trenches and pits, none of which has penetrated more than 12 feet below the surface.

SURFACE FEATURES.

The accompanying topographic sketch map (Pl. VII) shows the character of the region in which the sulphur deposits are found. This map has been constructed by determining by planetable methods the location and altitude of numerous prominent features and may be

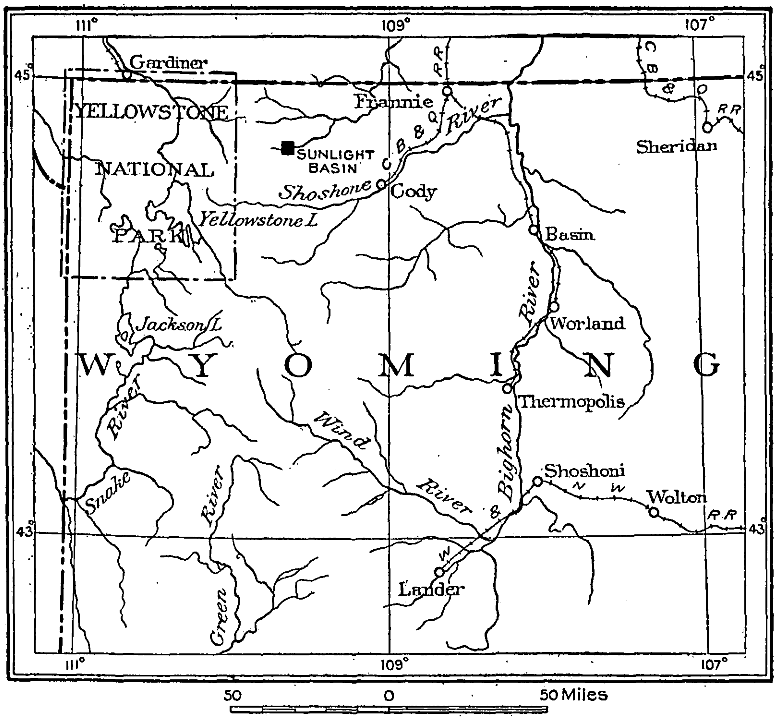


FIGURE 48.—Index map showing location of Sunlight Basin, Wyo.

considered relatively accurate for the central portion of the region adjoining the sulphur deposits. For the area beyond the limits of the higher surrounding ridges it has general value only, but is more reliable than the corresponding portion of the Crandall topographic sheet,[1] upon which the rugged ridges are shown with broadly sinuous contours.

Viewed from prominent ridges in the eastern portion of the valley, the basin is seen to be broad and flat, surrounded by steep ridges whose southern slopes are smooth but whose northern slopes are exceedingly rugged. The upper end of the valley, in the vicinity of the sulphur

[1] Absaroka folio (No. 52), Geol. Atlas U. S., U. S. Geol. Survey, 1899.

deposits, is narrow, but here, as below, Sunlight Creek meanders in the flat valley bottom. In the neighborhood of the sulphur deposits the slopes of the ridges are generally smooth below 8,500 feet, but, except for the meadows in the high glacial cirques, there are few smooth slopes above 9,500 feet. To the west, on the sky line, are the sharp, snow-covered peaks of the main divide of the Absaroka Mountains.

Sunlight Basin appears to owe its origin to the damming of a deep glacial valley by a terminal moraine, which is a prominent feature a mile below Painter post office and behind which an accumulation of glacial gravel and lake sediment has formed the present valley floor.

Timber line ranges in altitude from 9,000 to 9,500 feet, though there are a few groves in sheltered areas as high as 10,000 feet. The heaviest timber grows below 9,000 feet on north and east slopes and valley bottoms, but the south and west slopes are relatively sparsely covered.

GEOLOGY.

GENERAL FEATURES.

The geologic features of this region have been described by Hague, who also noted the presence of the sulphur. As the attention of the present writer was directed particularly toward the nature and extent of the sulphur deposits, only a small portion of his time was devoted to the study of the general geology of the region. So far as this was studied, however, the observations made confirmed those of Hague. The areal geology shown on the accompanying map is based on the observations of the writer.

With the exception of two small bodies of Paleozoic limestones in the eastern half of the area represented by the map, the outcropping rocks belong to the Tertiary early basic series of lavas and breccias described in Hague's report. Though the Threeforks (Devonian) limestone is probably present in the area of limestones shown on the map, the exposures did not permit its separation from the overlying Madison (Mississippian) limestone. Observations in the region east of the area mapped showed that the limestones are gently folded along axes extending northwest and southeast. On Plate I the beds are shown dipping at low angles to the southwest.

The Tertiary lavas and breccias lie upon a surface of the limestones which possesses features of relief much resembling those of the present surface. From this it seems highly probable that limestone underlies all of the area represented by the map, though it is not possible to estimate accurately the depth below the present surface at which limestone would be met at any particular place. Attention is called to this fact, because the examination of the sulphur deposits near Cody and Thermopolis appeared to indicate a relation between the presence of limestone where solfataric springs found an outlet and the deposition of sulphur. This relation, however, was noticed in superficial deposits and could hardly exist where the limestones are buried.

THE LAVAS.

Examination of the exposures on several of the ridges north of Sunlight Creek up to an altitude of 9,200 feet and south of it to 10,000 feet showed that the lavas could be divided into two groups, the upper being of distinctly more basic composition than the lower. The line of division is well defined on the south side of the creek, but not on the north.

The lower group, extending from the lowest exposures on Sunlight Creek to an altitude of about 8,500 feet, is composed of a number of interbedded lava flows and breccias of basic andesite. In hand specimens the lavas vary greatly in color as well as in texture, from greenish-gray rocks showing prominent phenocrysts of plagioclase and a few of augite in a finely crystalline groundmass to brownish-red and dark-purple rocks with only minute plagioclase crystals in a fine groundmass. No biotitic types were found, though hornblende was noticed here and there.

The more or less horizontal zones of breccia are extremely irregular. The zones are composed of fragments of basic andesite suspended in lavas of similar rock types so as to constitute about half of the mass. The fragments are angular to subangular and range in diameter from 2 to 6 inches, but there are localities in which the fragments are as much as 3 feet in diameter.

When examined in thin section under the microscope, the various types of lavas are found to show fewer differences than is suggested by the hand specimens. The feldspar is wholly basic labradorite, which with small amounts of augite forms about one-fourth of the rock. The texture is porphyritic and in the fine groundmass flow structure is generally pronounced. The lower group is therefore composed of similar types of augite andesite lava flows and associated flow breccias.

The basal member of the lower group where exposed along Little Sunlight Creek in the vicinity of the single isolated sulphur deposit is composed of basic andesitic tuffs in which vertical jointing is well developed.

The upper group of the Tertiary lavas under consideration is composed of basalt flows interbedded with flow breccias. The basalts are dark green, are generally vesicular, and commonly show augite and olivine as phenocrysts. The breccia fragments, in contrast to those of the lower group, are well rounded and range in maximum diameter from 4 to 20 inches. They resemble the rock types of the lower group, are gray to light red in color, and show plagioclase and augite, which is generally in greater amount than in the rocks of the lower group. The vesicular character and the structure prove the lavas of the upper group to be surface flows also.

The lavas are cut by numerous dikes, some of which are shown on Plate VII. These vary in width from 2 to 20 feet and several were traced for about 3,000 feet. They dip at angles varying between 45° and the vertical and, as is shown in a few places on the high ridges, cut the flows in a most intricate manner. Dikes of several rock types were found—pale green and gray andesites, dark-green olivine basalt, and gray orthoclase porphyry. In the group of five parallel dikes shown on Plate VII, cutting the ridges north of Sunlight Creek, there are two types of augite andesite porphyry and one of olivine basalt. The area probably contains more dikes than are shown on Plate VII, but they are either wholly covered with surface débris or poorly exposed. The order of intrusion of the dikes could not be determined, nor could any direct connection be established between the dikes and the sulphur deposits.

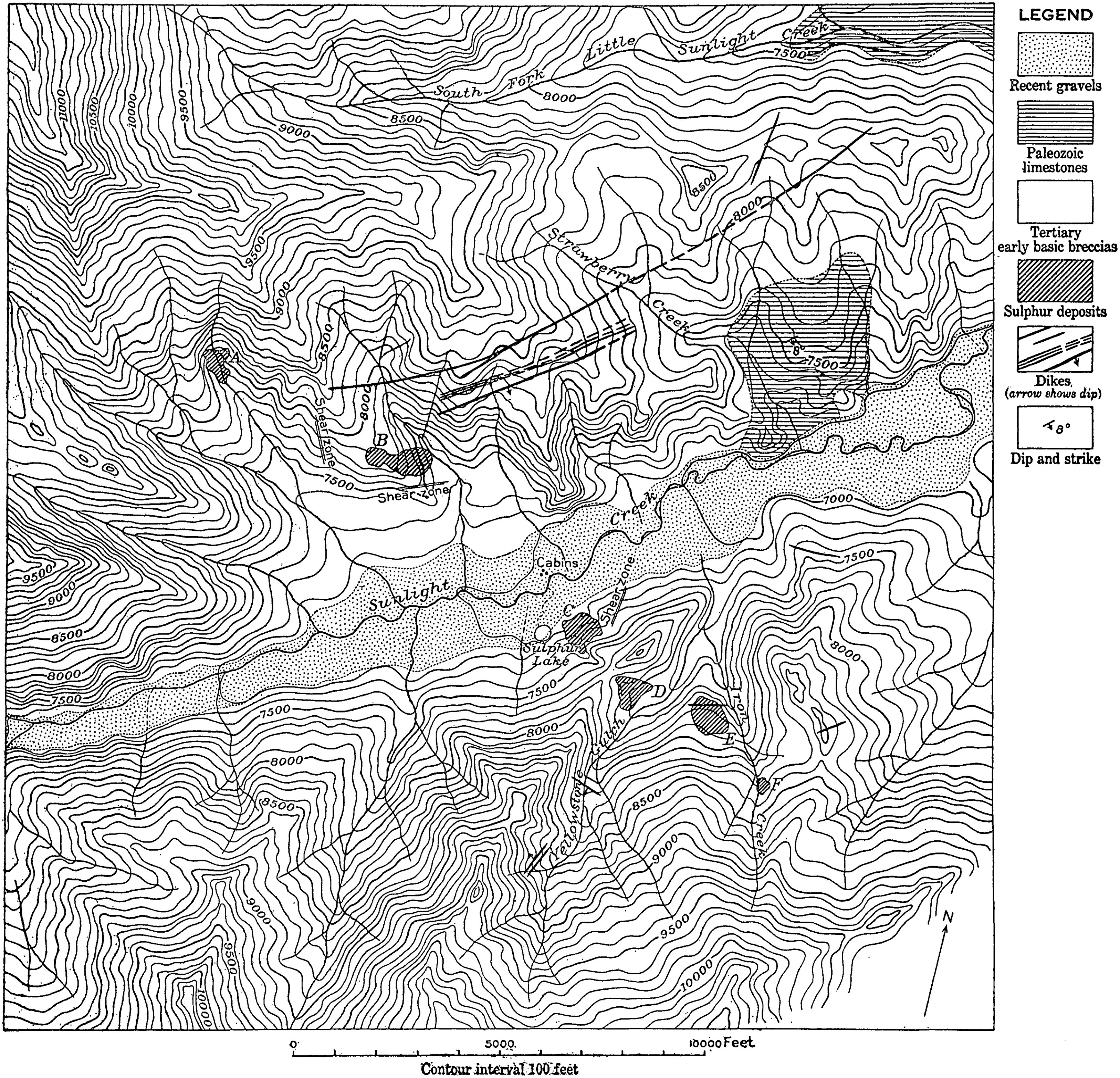
A feature of general geologic interest is the occurrence of zeolites in a large area south of Sunlight Creek, best shown in the upper basic group of lavas. The vesicles of the basalt flows, which range in diameter from a small fraction of an inch to 5 inches, contain thompsonite, heulandite, and analcite. Analcite was also found as an alteration product of the feldspars in rocks of the lower group of andesitic flows. Stilbite was found incrusting small fissures which cut both the lower and upper flows.

Hague does not mention the presence of zeolites in any of the lavas in the Crandall quadrangle, and it can not be stated whether or not they are restricted to this occurrence. From the fact that the portion of the area represented by Plate VII in which zeolites occur is not coincident with the zone of sulphur deposits, it is thought that the two are not directly related.

THE SULPHUR DEPOSITS.

LOCATION AND MODES OF OCCURRENCE.

There are six groups of sulphur deposits in the area represented by Plate VII. A smaller deposit situated on the north fork of Little Sunlight Creek is not shown on this map. The six groups lie in an approximately straight line, and each is situated on the slope of a ridge, practically adjacent to a ravine. The sulphur deposits are irregularly distributed in areas of the bleached igneous rocks. The groups of deposits, when seen from the high surrounding ridges, appear as large bleached areas from 5 to 20 acres in extent, devoid of vegetation and standing in striking contrast to the well-wooded slopes surrounding them.



TOPOGRAPHIC SKETCH MAP SHOWING SULPHUR DEPOSITS IN SUNLIGHT BASIN, PARK COUNTY, WYO.

Where vegetation does not conceal bedrock outside of the thoroughly bleached portions, the rocks are intricately fractured and show a tendency toward spheroidal weathering. This fracturing is locally controlled by two systems of joints, but generally it is extremely irregular. Four minor shear zones were found and are shown on Plate VII, but it appears that the positions of the groups of sulphur deposits are determined by a broad zone of intricate fracturing on a small scale, rather than by an extensive shear zone, such as might be produced by faulting.

A series of rock specimens was taken near one of the deposits with the view of determining the character of rock alteration which accompanied the bleaching referred to above. Examination of thin sections of these rocks under the microscope showed that the fresh rock is composed of crystals of basic labradorite feldspar and augite in a glassy ferruginous groundmass. The intermediate specimens showed successive stages of alteration to the most altered specimen, taken nearest the vents, which was found to be practically wholly opaline silica. A few kernels of undecomposed augite remain, but the feldspar is completely decomposed and there remains only finely granular amorphous silica. There is neither evidence of metasomatic replacement of the feldspars nor of alunitization, such as often accompanies solfataric spring action. The original texture of the rock is practically obliterated.

Sulphur occurs in two forms—cementing surface débris and incrusting irregular open fractures in the lava. The first mode of occurrence is more widespread, superficially, than the second, but at numerous localities exploration has shown that the sulphur-bearing débris is merely a mantle covering smaller areas in which sulphur is found in the second form. The sulphur occurs as a clear lemon-yellow incrustation, the surface of which is covered with numerous minute crystals. Here and there it is greenish yellow, owing probably to the presence of mechanically included impurities, but none was found having reddish or brownish tints. Both alkali alums and ferrous sulphate were detected in the sulphur-bearing débris at numerous openings. Iron sulphide, probably marcasite, occurs as a thin incrustation on spheroidally weathering nodules of the lavas in the vicinity of two of the sulphur-incrusted fractures.

The débris of the first mode of occurrence is composed of angular fragments ranging from an eighth of an inch to 2 inches in diameter. It is roughly stratified throughout and, though generally less than 5 feet thick, it has not been penetrated at some localities by trenches and pits 9 feet deep. The thickness of the débris appears to depend on the slope of the surface and the situation with reference to gulch lines, as it is thin or wholly absent on steep slopes and 8 to 10 feet thick over areas adjoining the stream channels. This débris is of local origin, being washed to lower slopes as it is set free by weathering. It is almost certainly not more than 15 feet thick at any place. Sulphur fills the interstitial spaces of the débris in varying degree. It is not found over the entire surface exposures of débris, but appears to impregnate the mantle of this material irregularly, so that there are one or more small areas of sulphur-bearing débris within the larger areas of débris free from sulphur. The largest area over which sulphur is found in this condition is slightly in excess of 2 acres, but most of the deposits are less than half an acre in extrent.

Though no analyses have been made, inspection indicates that those portions of the débris nearest the present surface are richest in sulphur, their maximum content being about 60 per cent. The débris lying upon bedrock generally contains much less, the amount varying with the thickness of the entire cover of débris but as a rule not exceeding 10 per cent. The débris also contains twigs and trunks of small trees and other vegetable matter, such as seeds. The smaller pieces of wood are impregnated with sulphur, but there does not appear to be any evidence of replacement of the wood fiber by sulphur.

The odor of hydrogen sulphide was detected in the neighborhood of every deposit and was especially strong in the deeper pits. A heavy noncombustible gas, apparently carbon dioxide, has accumulated in the bottoms of most of the pits and trenches in the sulphur-bearing débris.

The second mode of occurrence of sulphur is seen both at the present surface where the bedrock is not covered with débris and where explorations have exposed bedrock under the débris mantle. It was observed in most of the groups of deposits and probably would be shown by thorough exploration to be present in all. The sulphur occurs as a clear-yellow incrustation upon the walls of open fractures in the lava and as an impregnation in the partly or wholly decomposed rock near these fractures. The incrustation varies from a small fraction of an inch to 3 inches in thickness and is practically pure sulphur, but the impregnated rock does not generally contain more than 10 per cent of sulphur and would probably average much less when considered in large masses.

In only one deposit has a series of sulphur-incrusted fractures been developed sufficiently to permit observations bearing on the extent of this mode of occurrence. A trench on the hill south of Sulphur Lake has explored a well-defined zone of fractures about 4 feet wide, having a strike of due north and a dip of 70° W. Sulphur incrusts the walls of all open spaces and completely envelops small fragments of rock which have fallen from the walls. The entire mass of material between the walls would probably yield 10 per cent of sulphur, but the wall rock contains little more than a trace. At several places there are roughly conical mounds, the largest being about 20 feet in diameter and 5 feet high, which are composed of angular fragments of decomposed andesite heavily incrusted with sulphur. The fractured and more or less altered bedrock surface surrounding these mounds contains only a trace of sulphur. At the center of each, where the accumulation of sulphur is greatest, there is an open vent from which gases containing hydrogen sulphide and carbon dioxide are issuing freely, and there can be no doubt that sulphur is being deposited at present. It is probable that these mounds stand in relief owing to the greater susceptibility of the fractured bedrock to weathering processes, as well as to the growth which would accompany deposition of sulphur. The size of these mounds indicates the small areal extent of this second mode of occurrence of sulphur when compared to the overlying mantle of sulphur-bearing débris.

Gypsum occurs locally as a thin crystalline incrustation on small fractures but is not found in large masses such as are formed where sulphur is deposited in limestone. Alkali alum and ferrous sulphate were found in most of the pits and trenches in bedrock.

GASES.

Gases are issuing from all the open fractures which were found. The rate of flow varies greatly among the vents and in several is sufficient to be clearly detectable several feet away from the opening. Gas also bubbles freely from the beds of several of the streams which adjoin the sulphur deposits. Chemical tests on the ground indicated that these gases contain hydrogen sulphide with a great excess of carbon dioxide, but sulphur dioxide was not noticed. The temperature of the gases, which was estimated at three places, was approximately that of the atmosphere, about 85° F., though in one place it was probably 10° higher.

A sample of gas was collected from the bed of Iron Creek where it adjoins group F and was forwarded to the laboratory of the Bureau of Mines in Pittsburgh, where it was analyzed by G. A. Burrell with the following results:

Composition of gas from bed of Iron Creek.

Carbon dioxide	14.28
Oxygen	18.28
Carbon monoxide	.00
Methane	1.62
Nitrogen	65.27
Hydrogen sulphide	.00

The report accompanying this analysis states:

This sample had a very pungent odor and rather sweet taste. No hydrogen sulphide was present, but, it is believed, some sulphur dioxide. Not enough of the sample was available for a satisfactory quantitative determination of the sulphur dioxide. The carbon dioxide is high but as presented in the analysis includes the sulphur dioxide, or that constituent which gives the gas the pungent odor and sweet taste. Please do not accept the carbon dioxide as stated as official, but mail to the bureau at least a liter more of this gas, if you can obtain it, for a more searching examination. The oxygen content is high, but is puzzling because of the apparent indication of free oxygen in the sample. The bureau simply submits this report as preliminary, because not nearly enough sample was present for a precise examination of this unusual gas.

The absence of hydrogen sulphide from the sample may be explained by the fact that the sample was collected over running water, which may have extracted it. The odor of hydrogen sulphide is always stronger in the vicinity of the higher vents than near those which issue from or near the stream beds.

If the nitrogen present is considered as admixed air, the amount shown, 65.27 per cent, would require 17.28 per cent of oxygen, indicating an excess of 1 per cent of free oxygen in the gas. Though the sample was taken by water displacement, it is not certain that air may not have previously been mixed with the other gases. The presence of an appreciable amount of methane is interesting but not unusual in such gases.[1]

The presence of a large percentage of carbon dioxide, which was also indicated by numerous tests with burning matches in the fractures and pits, is not uncommon.

GENESIS.

Any statement concerning the genesis of these deposits must take several salient features into consideration.

The rocks containing the deposits are surface lava flows and associated breccias, and there is nothing to suggest the presence of a volcanic crater. No definite connection between dikes and sulphur deposits can be recognized.

The igneous rocks show no evidence of replacement by sulphur or sulphates such as alunite, but a tendency toward complete silicification.

Relatively dry gases, composed principally of carbon dioxide and hydrogen sulphide, are issuing from all the deposits. Sulphur is apparently being deposited from these gases at present.

Travertine and siliceous sinter are not present on the surface and there is no evidence of hot-spring action at any stage of the formation of the deposits.

The thin mantle of surface débris contains a greater amount of sulphur than the decomposed and fractured bedrock.

From these features it is thought that the sulphur deposits have been formed through the decomposition of hydrogen sulphide rising

[1] Clarke, F. W., The data of geochemistry: Bull. U. S. Geol. Survey No. 491, 1911, pp. 251, 255. A number of analyses of similar gases from Sicilian springs are here given.

through irregular fractures in the lava flows. This decomposition has probably taken place according to the well-known reaction $2H_2S + O_2 = 2H_2O + 2S$.

The amount of sulphur deposited in the bedrock lava is small, owing apparently to the inability of relatively dry gases to replace or dissolve siliceous rocks. Whether deposition of sulphur in the lavas below the drainage lines may be a factor is uncertain, but very improbable. Though the gases issuing from the vents are relatively dry, it is not impossible that any moisture which they may contain below the surface is condensed and joins the ground-water circulation. As every deposit is cut or bordered by a stream channel, any added water may be escaping under the stream gravel. There is no evidence that the limestone substratum has been dissolved nor that it has had any effect upon the gases. The presence of relatively high grade sulphur-incrusted débris on the surface is apparently due to the exceptional conditions favoring the relatively complete aeration and oxidation of the gases. It is thought that each deposit of this character covers one or more vents from which the sulphurous gases are escaping.

The alums and gypsum associated with the sulphur have been formed by the combination of sulphuric acid produced by the complete oxidation of hydrogen sulphide, with the bases of the igneous rock. The attack of the silicate minerals by sulphuric acid appears to have produced silicic acid, which by the loss of water has deposited the opaline silica that now constitutes the greater portion of the altered igneous rock.

The sulphur deposits are thought to be of relatively recent origin, probably being wholly postglacial. In one of the mounds from which gases are issuing freely at present the dead root of a cedar tree, similar to those growing near by, penetrates the fractured sulphur-bearing rock in such a manner as to make it certain that the tree once grew there. It is difficult to imagine the growth of a tree at the same time that the deposition of sulphur was taking place, so that it is thought that the sulphur at this locality at least is of extremely recent origin. This view is also favored by the discovery of twigs and other organic remains distributed through the débris.

The small lake adjoining group C is about 250 feet in diameter and it could not be determined whether its level is perceptibly higher than the water in the surrounding marshes and stream channels, or that there was a current issuing from it. No gas issues from the surface, though the water is noticeably warmer than that in the near-by marshes. The water is distinctly greenish blue, suggesting the presence of finely divided sulphur. It is possible that the lake owes its origin to a solfataric vent which has killed the vegetation in the vicinity.

DETAILS OF THE DEPOSITS.

The deposits of group A are located at the head of a narrow gulch at the northwest end of the belt. The area of bleached and decomposed lava is approximately 7 acres, within which there are four deposits, the largest covering about one-third of an acre. The sulphur is found incrusting the coarse bowlders in the gulch bottom and the surface débris of the surrounding slopes. There are but a few shallow trenches, and the maximum thickness of the mantle of débris has not been proved.

At group B the lavas and breccias are bleached over an area of 20 acres. There are three sulphur deposits, two about an acre in extent and the third much smaller. Most of the pits have passed through the cover of sulphur-bearing débris at a depth of 4 feet, and the decomposed bedrock underlying this material contains only traces of sulphur. Gas issues vigorously from the bed of the stream which adjoins the group on the east.

At group C the superficial extent of bleached débris and rock is approximately 10 acres, in which there are two separate deposits of sulphur-bearing débris, one 1 acre and the other half an acre in extent. Numerous pits and trenches have been dug, most of which have gone through the cover of débris. The thickness of this cover is variable, in most of the pits being from 5 to 10 feet. Its content of sulphur is also variable, ranging from a mere trace to about 60 per cent. Several open vents from which gases are issuing occur on the eastern border of the area, and others have been found under the cover of débris.

At group D the total area over which the lavas and débris are bleached is about 11 acres. Within this area is located the largest deposit of sulphur-bearing débris in the region, its size being due to its occurrence at the junction of two ravines. It has an area of about 2 acres, and as several pits 8 feet deep, where the surface is flat, have not gone through it, the maximum thickness probably exceeds 10 feet. Other pits on the steeper slopes near by prove this portion of the débris to be about 3 feet thick. The only other deposits in this group are two mounds of sulphur-bearing material surrounding open vents, within an area of fractured and decomposed andesite about half an acre in extent.

At group E the superficial extent of bleached rock and débris is about 15 acres, within which there are two deposits of sulphur, one about 1 acre and the other one-quarter of an acre in extent. Only the larger deposit has been prospected. The mantle of sulphur-bearing débris probably does not exceed 5 feet in thickness. Where explored by two pits 10 feet deep the underlying decomposed bedrock contains but a trace of sulphur.

Group F contains only one deposit of sulphur, within a bleached area of débris of about 3 acres. In the few pits which have been dug sulphur has been found only as an incrustation of the surface débris, the total area being about half an acre. The deposit adjoins Iron Creek, from the bed of which gas bubbles freely.

PRODUCTION.

No sulphur has been produced from these deposits, and it is extremely improbable that they will be sources of production until the transportation facilities of the region are greatly improved.

The amount of sulphur existing in the surface débris is capable of easy demonstration but is not thought to be great compared with that in workable deposits of sulphur in general. The maximum content of sulphur in material of this class can not exceed 50 per cent in large amounts of material, as it is governed by the pore space of loosely packed slide rock, which seldom exceeds 40 per cent. The amount of sulphur existing below this superficial cover is undoubtedly very much less, owing both to the relatively poorer chance for oxidation of the sulphurous gases and to the small amount of open space available for the deposition of sulphur. The occurrence of sulphur is distinctly superficial and it is not thought that the deposits will become important.

COMPARISON WITH OTHER DISTRICTS.

Sulphur deposits similar to those here described are found at Sulphur Bank, Lake County, Cal.;[1] on Cove Creek, Utah;[2] on an island in the Aleutian Peninsula;[3] and in northern Japan.[4] Of these the Cove Creek and Japanese deposits are being exploited at present. The deposits in Sunlight Basin bear a striking resemblance to the one at Sulphur Bank, which has been exploited for quicksilver. In both places the deposits occur in basic igneous rocks—basalt at Sulphur Bank, augite andesite in Sunlight Basin—and the character of alteration of the inclosing rock and the analyses of gases issuing from the deposit are strikingly similar. The deposits at Sulphur Bank were also noticed to contain marcasite, which, though not seen in most of the deposits in Sunlight Basin, was found in one of the few pits which penetrated to the level of ground water. The two groups of deposits differ, however, in that cinnabar, quartz, and pyrite are present at Sulphur Bank, but not in Sunlight Basin. It is stated that although sulphur is present at the surface at Sulphur Bank, it is confined to the

[1] Becker, G. F., Quicksilver deposits of the Pacific slope: Mon. U. S. Geol. Survey, vol. 13, 1888, p. 251.
[2] Lee, W. T., The Cove Creek sulphur beds, Utah: Bull. U. S. Geol. Survey, No. 315, 1906, p. 485.
[3] Lawton, N. O., Makushim sulphur deposits, Unalaska: Min. and Sci. Press, vol. 98, 1909, p. 259.
[4] Mining in Japan: Geol. Survey Japan, 1909, p. 114.

zone of oxidation, which extends to a depth of about 20 feet. Cinnabar, however, is absent near the surface and increases in amount toward the bottom of the zone of oxidation. In view of these facts it would be advisable to direct prospecting in Sunlight Basin toward the demonstration of the possible presence of cinnabar at a zone lower than that yet explored. In the Alaskan deposits sulphur is being deposited by sublimation and by the decomposition of hydrogen sulphide that issues freely from crevices around the crater of a volcano whose activity is waning.

TWO SULPHUR DEPOSITS IN MINERAL COUNTY, COLORADO.

By ESPER S. LARSEN and J. FRED. HUNTER.

INTRODUCTION.

The two sulphur deposits here described are located in Mineral County, Colo., about 25 to 30 miles southwest of Creede. They were examined during the summer of 1911 in the course of the geologic mapping of the San Cristobal quadrangle under the direction of Whitman Cross.

GENERAL GEOLOGY.

Both deposits are in volcanic rocks of Miocene age belonging to the Potosi volcanic series. These volcanic rocks extend for many miles to the north and east, but are now preserved for only a few miles to the southwest. The prevolcanic rocks to the southwest comprise pre-Cambrian granites, quartzites, and schists, and a great variety of sediments ranging from the Cambrian to the Cretaceous.

The Potosi volcanic series may be divided broadly into four parts. The lowest of these is made up chiefly of andesitic agglomerate, but contains massive rock and angular breccia near the base and the top. Its present thickness varies greatly but in a large area exceeds 1,500 feet. Overlying a rather irregular surface of this mater'al are thick flows of pink quartz latite with associated tuffs and thinner flows. The thickness of these latites is usually a thousand feet or more. Another series of andesitic breccias with associated flows and intrusives follows. This breccia is generally very chaotic and is made up of rocks which contain prominent tabular crystals of feldspar and some augite and hypersthene in a groundmass that is usually rather rich in orthoclase. A little quartz is present in some of the rocks and olivine in others. The thickness of the breccia may vary from 1,000 feet to the vanishing point within a distance of 1 mile. This variation in thickness is due to the irregular erosion which preceded the extrusion of the overlying flows of rhyolite and latite, constituting the fourth division of the volcanic series.

In general, the volcanic rocks are nearly flat, but only a short distance to the south of the sulphur deposits complex block faulting has given rise to local dips of 30° or more. To the east, west, and north of the deposits are other great faults. This main faulting took place later than the rhyolite flows and probably later than the deposition of the sulphur ore.

Both of the sulphur deposits are in the andesitic division which overlies the quartz latite and they are in all respects very similar.

TROUT CREEK DEPOSIT.

The Trout Creek deposit is about 25 miles southwest of Creede, and is reached from that town by a wagon road that is good over most of the distance.

The deposit lies entirely in the second basic division of the Potosi volcanic rocks, about 700 feet below the base of the overlying rhyolite. The underlying quartz latite is not exposed in the east fork of Trout Creek, but only a little over a mile to the northwest, just beyond the forks of the creek, the latite is faulted up. Farther down the creek, opposite the mouth of Copper Creek, 1,500 feet of this quartz latite lies between the two andesitic divisions.

The division near the sulphur deposit is an angular breccia of dark-colored andesites. Most of the rocks have phenocrysts of labradorite, augite, and hypersthene, and the groundmass is glassy to rather coarsely crystalline. It usually contains abundant orthoclase and in places also quartz. Much of it which lacks the fluidal and other textures of lavas may be called latite porphyry. Many of the beds are made up almost entirely of one kind of rock. The rock is always bleached and much altered for a distance of 20 feet or more from the sulphur deposit. The less-altered rock is bleached white and the dark minerals are completely removed, being represented by cavities partly filled with pyrite. The plagioclase phenocrysts and the othoclase of the groundmass are still fresh. On more intense alteration the plagioclase is partly or entirely replaced by opal and in extreme decomposition the rock becomes an aggregate of opal, chalcedony, pyrite, and locally barite, with only a suggestion of the original texture. Another type of alteration consists in the replacement of the pyroxene by a brown pleochroic serpentine-like mineral, and the introduction of much pyrite. In such places the feldspars may still be fresh. A more intense alteration of the same type gives a rock which shows only remnants of the original feldspars and consists of quartz, chalcedony, and a sericite whose lowest index of refraction is nearly equal to that of Canada balsam.

Abundant pyrite and a considerable amount of apatite are also present. The sericite is scattered throughout the mass, but also occurs in veinlets together with the apatite. In addition to occurring in the veinlets, grains of secondary apatite are collected in bunches scattered through the rock. Pyrite is present here and there between rock fragements of nearly fresh breccia. Gypsum was seen in fractures associated with partly oxidized pyrite, but sulphates are rather unusual and were found in only a few places. The sulphur rock exposed in the tunnels is reported to be in contact with "black clay with angular and rounded bowlders and pebbles of various eruptive rocks."

The sulphur rock is remarkably well banded and except for the presence of sulphur the specimens resemble well-bedded tuff. The bands are less than half an inch wide and are either drab or yellowish gray. Narrow bands or lenses of yellow sulphur and of gray chalcedony are present. Yellow sulphur also lines fractures in the ore. The drab bands have a conchoidal fracture and a vitreous luster and burn readily. The yellowish-gray bands have a dull luster and resemble siliceous sinter. Some of the ore consists of brecciated fragments of the banded ore cemented by similar material. Thin sections of the ore show that the drab bands are nearly pure sulphur in very minute crystals and the yellowish-gray bands are opal in which are embedded numerous minute crystals of sulphur. The yellow sulphur is more coarsely crystalline and is probably secondary. In addition to sulphur, opal, and chalcedony, which are the only minerals observed by the writers, gypsum and iron sulphide are reported as occurring sparsely in some parts of the deposit. A determination of sulphur on an average sample of the material taken from the ore bins was made by R. C. Wells and showed 63.4 per cent of sulphur and no selenium. The remaining 36.6 per cent is almost pure silica, as it showed a residue of less than 1 per cent on ignition after treatment with hydrofluoric and sulphuric acids.

The underground workings are east of the east fork of Trout Creek, a few hundred feet above the creek bed, and just above an alluvial flat along the creek. As they were not accessible at the time of the writers' visit, the available information regarding the form of the deposit and its relations to the country rock is limited to that obtained from a hurried observation of the surface workings and the statements of reliable persons who examined the property several years ago.

The deposit is on a northwesterly fissure which appears to be the extension of a fault clearly exposed only 2 miles northwest of the main deposit, where the top of the quartz latite is thrown down about 500 feet on the northeast side of the fault. On the line of this fault there is an altered zone which passes through the sulphur deposit and continues to a point half a mile beyond, where it appears to go under the rhyolite flow that overlies the andesitic breccia. It is reported to reappear from under the rhyolite in a gulch about a mile to the southeast, but to go under the rhyolite again within a quarter of a mile; that is to say, the line of alteration continues to the southeast beyond the limit of visible faulting. Other areas and zones of alteration are common farther down Trout Creek.

Some of the bodies of sulphur rock exposed in the surface pits appear to have filled irregular, nearly vertical underground openings, but this could not be definitely determined. Much of the material is fractured and recemented. The banding is irregular, but it was thought on the whole to be nearly vertical. The available data on the deposits as exposed in the tunnels, however, indicate that it is a surface deposit about the opening of a series of hot springs arranged along the northwesterly fault. The sulphur rock exposed in the tunnels appears to be irregular in thickness and somewhat discontinuous. The greatest observed thickness was about 16 feet.

The principal underground workings are an upper and a lower tunnel, with some drifts and shafts. For the reduction of the sulphur rock, it was loaded on steel cars which were run into a cylindrical retort and treated with steam under pressure. The sulphur was drawn from the bottom of the retort. The mill was operated for only a very short time, and it is believed that little or no sulphur was placed on the market.

MIDDLE FORK DEPOSIT.

The Middle Fork deposit is located about 5 miles south of the workings on Trout Creek, on the south side of the Continental Divide, at an elevation of about 11,000 feet, in the flat basin at the head of the west branch of the Middle Fork of Piedra River. It is exposed in the bed of the stream in the eastern part of the basin, just southwest of the peak whose elevation is marked as 12,080 feet on the topographic map of the San Cristobal quadrangle. The deposit is just north of a northwesterly fault which throws up the quartz latite to the southwest. Exposures are poor, but so far as could be seen the deposit is entirely in the second andesitic breccia and is associated with a zone of intense but irregular alteration which runs about N. 20° W.

Sulphur was found in two places, only a few hundred yards apart. The upper exposure has been uncovered for about 10 feet just south of the creek by a surface prospect. Its contacts are not exposed, and but little could be learned of its relations. The sulphur-bearing mass is in all respects similar to that of the deposits in Trout Creek and needs no special description.

Lower down, on the south side of the creek, there are a few short tunnels, now caved in. They are located in a white altered rock which carries in places a few scattered grains of yellow sulphur. The altered rock retains evidence of the original porphyritic texture of the andesite, but it is now a mass of opal, chalcedony, and kaolinite. A little pyrite is present in all the rock, but is much more abundant in the type which contains the sulphur and there exceeds the sulphur in amount; the opal and chalcedony are also more abundant in this phase of the rock.

About a mile to the northwest of these exposures is a large area of more or less decomposed breccia, which is probably closely related in origin to the sulphur deposit, although no evidence of sulphur was found. The final stage in the alteration of this andesitic breccia has given rise to quartz-alunite rocks and less often to quartz-gypsum rocks; pyrite is everywhere present and kaolinite is locally abundant. In this area of altered rock are veins of finely granular quartz and some hard, dense chert which resembles some of the brecciated sulphur ore in the manner of banding and brecciation.

GENESIS OF THE ORE.

The typical banded ore is made up almost entirely of sulphur and opaline or chalcedonic silica and is characteristically free from sulphates, sulphides, or carbonates. A complete analysis was not made, but a partial analysis shows a remarkable resemblance to a hot-spring deposit from Lamar River, in the Yellowstone National Park.[1] This analysis, together with the approximate partial analysis of ore from Trout Creek, follows:

Analyses of sulphur ore from Trout Creek, Colo., and hot-spring deposit from Lamar River, Yellowstone National Park.

	Trout Creek.	Lamar River.
SiO_2		29.23
H_2O	35.5	3.03
C, organic		1.04
S	63.4	64.29
Al_2O_3		....
Fe_2O_3	1	1.91
MgO		.07
CaO		.50
		100.07

Dr. Hague kindly examined some of the specimens of the Trout Creek ore and said that they might easily have come from the Yellowstone National Park. Hot sulphur springs are still abundant in this part of Colorado, there being large springs at Pagosa Springs, others some miles farther up the Piedra, and another group at Wagon Wheel Gap, several miles below Creede, on the Rio Grande. These facts lead to the conclusion that the banded sulphur ore was deposited by

[1] Clarke, F. W., The data of geochemistry, 2d ed.: Bull. U. S. Geol. Survey No. 491, 1911, p. 197, analysis F. For further information regarding this deposit the writers are indebted to Mr. Arnold Hague.

ancient hot springs or geysers connected with the igneous activity of the period, partly in the vents of the springs and partly on the surface about them. The sulphur deposits are thought to be younger than the second andesitic breccia but older than the overlying rhyolite. The volcanic rocks are known to be Miocene in age.

An understanding of the solutions and conditions of deposition at the Lamar River locality would do much to aid in interpreting the deposits of Colorado, but data other than the analysis of the deposit are not available.

The composition of the Colorado deposits and the alteration of the country rock accompanying them indicate the action of a solution very rich in sulphur and silica but undersaturated in respect to all other oxides. The pyrite of the altered rock is hardly sufficient to account for the iron of the original rock, and in the typical altered rock the Al_2O_3, Na_2O, K_2O, CaO, and MgO have been almost completely removed. Sulphates and carbonates were not observed in the ore and are very uncommon in the altered rock. It is believed that if sulphates had been abundant in the solution alunite would be found in the altered country rock, as it is a common mineral elsewhere in the altered rocks of this region. Alunite is abundant at a locality less than a mile from the Middle Fork deposit, where it is believed to have been formed at about the same time as the sulphur deposits but under somewhat different conditions.

The conditions which give rise to the deposition of sulphur from hot springs have been discussed by Chase Palmer,[1] who has suggested the following possibilities: (1) The oxidation of H_2S; (2) the action of certain bacteria; (3) the action between $CaCO_3$ and H_2S; (4) the decomposition of polysulphides or thiosulphates. In addition the competency of solutions to carry colloidal sulphur has recently been shown by Raffo and Marncini,[2] who found that a solution of the composition S (colloidal) 2.79–2.60 per cent, H_2SO_4 6.43–7.00 per cent, and Na_2SO_4 3.75–3.92 per cent is stable and that a change in the concentration of the salt causes precipitation of sulphur.

If the oxidation of H_2S with the formation of S and H_2SO_4 were the dominant factor in forming the Trout Creek deposit there should be more sulphates, such as gypsum and alunite, associated with the ore.

The action of bacteria may account for some sulphur and likewise some silica, but the banding of the deposit and the absence of gypsum, which should be a result of this action, indicate some other origin for most of this sulphur. The complete absence of carbonates eliminates the action of H_2S on $CaCO_3$, but a modified form of this reaction in which silicates take the place of carbonates may have been

[1] Woodruff, E. G., Sulphur deposits at Cody, Wyo.: Bull. U. S. Geol. Survey No. 340, 1908, p. 455.
[2] Zeitschr. Chemie Ind. Kolloide, vol. 9, 1911, p. 58.

important. The decomposition of the readily changeable polysulphides and of thiosulphates might also have been a factor. However, it is believed by the writers that most of the sulphur was deposited from a colloidal solution, as was also the silica, and that both were probably brought up from below in that form. The evidence in favor of this view lies in the cryptocrystalline character of the sulphur and the opaline character of the silica, the intimate association of the two, the banding of the ore, and the poverty of the ore and the altered country rock in all other minerals, especially sulphates and carbonates. The fact that the solutions precipitated the iron of the wall rock as pyrite and the association of pyrite and sulphur in the altered wall rock may be explained as due to the action of S and H_2S on the $FeSiO_3$ of the iron-bearing silicates,[1] after the equation $FeSiO_3 + H_2S + S = FeS_2 + H_2O + SiO_2$. Ferric silicate would first be reduced to ferrous silicate thus: $Fe_2(SiO_3)_3 + H_2S = 2FeSiO_3 + H_2O + SiO_2 + S$.

PROBABLE EXTENT OF THE DEPOSITS.

The surface deposits of hot springs have not, as a rule, great persistency but are commonly formed as a number of separate lenslike deposits, more or less closely related. The size of such individual deposits may vary greatly and their form would in general be lenticular but in detail very irregular. The deposits within the vents of such springs would be irregular in form and the sulphur would probably not continue to a great depth.

[1] Allen, E. T., Crenshaw, J. L., and Johnston, John, The mineral sulphides of iron: Am. Jour. Sci., 4th ser., vol. 33, 1912, p. 173.

SURVEY PUBLICATIONS ON SULPHUR AND PYRITE.

The list below includes the important publications of the United States Geological Survey on sulphur and pyrite.

These publications, except those to which a price is affixed, may be obtained free by applying to the Director, United States Geological Survey, Washington, D. C. The priced publications may be purchased from the Superintendent of Documents, Government Printing Office, Washington, D. C.

ADAMS, G. I., The Rabbit Hole sulphur mines, near Humboldt House, Nev.: Bull. 225, 1904, pp. 497–500. 35c.

DAVIS, H. J., Pyrites: Mineral Resources U. S. for 1885, 1886, pp. 501–517. 40c.

ECKEL, E. C., Gold and pyrite deposits of the Dahlonega district, Georgia: Bull. 213, 1903, pp. 57–63. 25c.

——— Pyrite deposits of the eastern Adirondacks, New York: Bull. 260, 1905, pp. 587–588. 40c.

LEE, W. T., The Cove Creek sulphur beds, Utah: Bull. 315, 1907, pp. 485–489.

PHALEN, W. C., Sulphur pyrite and sulphuric acid: Mineral Resources U. S. for 1911, pt. 2, 1912, pp. 937–964.

RANSOME, F. L., Geology and ore deposits of Goldfield, Nev.: Prof. Paper 66, 1909, 258 pp. [Sulphur, pp. 109–110; pyrite, pp. 113–114.]

RICHARDS, R. W., and BRIDGES, J. H., Sulphur deposits near Soda Springs, Idaho: Bull. 470, 1911, pp. 499–504.

RICHARDSON, G. B., Native sulphur in El Paso County, Tex.: Bull. 260, 1905, pp. 589–592. 40c.

SPURR, J. E., Alum deposits near Silver Peak, Esmeralda County, Nev.: Bull. 225, 1904, pp. 501–502. 35c.

WOODRUFF, E. G., Sulphur deposits at Cody, Wyo.: Bull. 340, 1908, pp. 451–456.

——— Sulphur deposits near Thermopolis, Wyo.: Bull 380, 1909, pp. 373–380.