the borders. Obscure evidence of deeply buried pipes is to be found in a few places; and such pipes appear to have been feeding channels of a number of oreshoots in shallower fissure veins. It is probable, though not proved, that most fissure-vein deposits in and near the fault belt were fed from deeply buried pipe channels.

Deposition of the ores occurred near the end of a sequence of structural events in which the principal processes were (1) the early faulting that outlined the down-faulted block, (2) intrusion of the volcanic pipes, and (3) development of the Red Mountain sag concurrent with general alteration of rocks. Some moderate movement along faults seems to have occurred after the invasion of pipes, but this deformation may be attributed to adjustments of the more massive rocks to the sagging and flow of the altered rocks. Many pipes within the belts of plastically deformed and tilted rocks have not been especially productive, a fact that may be attributed to effective sealing of their channels. On the other hand essentially all the most productive chimney ore bodies of the district are found along the boundary area between the highly altered rocks of Red Mountains Nos. 1, 2, and 3 and the less altered nearly horizontally lying rocks of the valley floor at altitudes between 10,000 and 11,500 feet. This belt is about half a mile wide and 15,000 feet in length, extending from the St. Paul, Congress, and National Belle mines at the south to the Silver Belle mine at the north. The two most productive pipes, the Yankee Girl and the Guston, are found in nearly horizontal rocks, which have been only moderately affected by general alteration though highly altered near the ore bodies.

There is substantial mineralogical evidence that the chimney ore bodies were concentrated within openings and by replacement of rocks previously attacked by hot waters of fumarolic or sulphate type. The mineral products diagnostic of this alteration include a number of kaolin minerals, of which dickite (and possibly nacrite) seems indicative of high local intensity. Other minerals of the more intensely altered rocks include diaspore, alunite, zunyite, beidellite, and the massive, fine-grained quartz of the silicified masses ("quartz ledges"). The silicified rock bodies are more widespread than ore, but commonly there is a tube-like envelope of silicified rock surrounding the chimney ore body. Pyrite, sericite, and stringers of the sulphides cut the kaolinized and silicified envelopes. Irregular cavities and channels within are crustified or filled with ore and gangue minerals. Some cavities in the outer parts of the envelopes of altered rock are partly filled with stratified clay materials.

The forms of the chimney ore bodies have been described by Ransome[21] and others and, as the larger, more typical of them are mined out and as only meager portions of the workings are now accessible, little can be added to the original descriptions. Ransome considered the term "chimney" somewhat misleading, as some of the bodies were lenticular, pod-shaped, or spindle-shaped, and completely enclosed by country rock. However, it is evident that although individual pipes of ore were much less regular in form than the volcanic pipes, the silicified rocks enclosing the ore bodies were originally penetrated by ramifying solution channels, fissures, and open breccia masses which provided continuous passages, at least within the vertical limits of the mine developments. The less altered rocks outside the envelope of the ore bodies were also much fissured, but in general the ground was "tight," and provided only sheeted zones, joints, and seams for the penetration of the altering solutions. The silicified rock grades outward into rock of the propylitic type, characterized by chlorite, and carbonates, and locally pyrite, clay minerals, and sericite. According to local observations the clay minerals of the beidellite type were formed mainly in intermediate positions between the propylitized rock and highly altered chimneys, but the distribution of the different clay minerals and their paragenesis have not been fully studied. Doubtless some clay minerals are also of late origin, as they

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[21] Ransome, F. L., Economic geology of the Silverton quadrangle: U. S. Geol. Survey Bull. 182, pp. 103-111, 214-240, 1901.

encrust or have filled cavities in earlier encrustations of sulphides.

The common ore minerals of the Red Mountain ores include pyrite, enargite, chalcopyrite, tennantite, chalcocite, covellite, stromeyerite, bornite, sphalerite, and galena. They are accompanied by some unidentified minerals. To the older lists may be added colusite, the tin-bearing tetrahedrite, which has been identified in the Yankee Girl and National Belle ores.

At places examined by the writer on the 4th level of the Guston mine, a vein-like body composed mainly of fine-grained sheared galena ore lay to one side of large stopes occupied originally by the extremely rich copper-silver ores. The structural relations of the two kinds of ore were no longer determinable, but the lower-grade lead ore commonly occupied peripheral positions, and it is known that a rich inner core of silver-bearing ore has been removed from the stope. The galena continued upward from this level to the surface and formed most of the ore above the third level. Reconstructing the mined-out ore bodies, it seems that the galena ore formed a cap that extended down for several hundred feet along at least one side of the copper-silver bodies. In general the pyrite of the lower levels is capped successively by pyrite-chalcopyrite ore, by ore composed of copper-silver minerals, and finally by galena ore. This represents the same order as the deposition of the constituent minerals revealed by microscopic examination. Gold is associated mainly with the cupriferous ore. These changes occur within a vertical range of less than 1,000 feet. The zoning of the ore appears to have been to some extent radial as well as vertical.

As revealed microscopically the ores of the chimneys show evidence of comparatively rapid and overlapping deposition of the common minerals. However there appear to have been numerous reactions between minerals and enrichments of silver in the copper and lead zones. Gold though locally concentrated is not typically concentrated in the complex silver ores. As shown by Bastin[22] the enrichment of silver follows the expected results of supergene action of ground waters, but it is very doubtful if any appreciable volume of ore resulted from this cause. The massive character of the high-grade copper-silver ore and the intimate intergrowths of the minerals exhibit no evidence of any appreciable discontinuity in the ore-forming processes. If the sulphide bodies are to be considered mainly of supergene origin it appears necessary to assume, as did Ransome,[23] that the entire capping of the lower-grade silver-bearing pyrite and chalcopyrite is supergene, and hence that the thick topmost cap of nearly pure galena is likewise supergene. Ransome concluded, "It is hardly conceivable that the observed relation between the vertical variations in the ore bodies and the present topographic surface is a haphazard one. It is without doubt genetic."

This statement presupposes a somewhat closer relation between the present surface and the minerals of the "supergene suite" than appears justified by subsequent exploration. Covellite, for example, has been found in massive bodies at great depth below the surface in some of the deeper tunnels. There is, however, a general relation between the surface and the higher-grade ore bodies, but this applies to nearly all veins as well as chimney deposits of the San Juan region, and includes native gold as well as the sulphide ores. This genetic relation between the surface and high-grade ore is one commonly encountered in regions of comparatively recent volcanism where erosion since ore deposition has been comparatively slight. The average surface also tends to take the form of the main structural features, some of which influenced the localization of ore. Thus in the Red Mountain district the slopes of the valley sides closely follow the structural features of the Red Mountain sag.

It is believed that the origin of the ores may be accounted for satisfactorily by processes likely to occur down

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[22] Bastin, E. S., Silver enrichment in the San Juan Mountains, Colorado: U. S. Geol. Survey Bull. 735, pp. 98-109, 1923.

[23] Ransome, F. L., op. cit., pp. 135-140.

to depths of several thousand feet in belts of fumarolic alteration.

Structural relations

The structural relations of the ore bodies to the volcanic pipes are classifiable into several principal kinds. Two general classes, based upon position relative to the pipe, include ore bodies within the body of the pipe, and those outside of but localized by structures directly related to the pipe. Both chimney and vein deposits are represented. A third class may include vein deposits fed from underlying pipes. Though it has not been proved, many vein deposits close to or within the belt of volcanic pipes are suspected of belonging to this third class. A special class of ore bodies within or near the feeding channels of volcanic pipes is typified by the limestone replacement deposit of the Saratoga and neighboring mines.

The two classes of deposits within and exterior to pipes show an evident relation to the stage of pipe development. Those within the pipe are found chiefly in incipient pipes not completely plugged with porphyry. Those exterior to the pipes are associated chiefly with pipes in an advanced stage of development, which are commonly "plugged" by porphyry bodies.

As might be expected from conditions favoring concentration in feeding channels, the ore bodies lying within small or moderate-sized pipes include the most productive deposits of the district. These are represented by the Yankee Girl, Guston, Robinson, National Belle, and probably the Silver Belle. Ore bodies exterior to the pipes include the Hudson, St. Lawrence, Carbon Lake, and Congress chimney deposits. These and others are associated with the Koehler compound pipe (fig. 5). The St. Paul, however, is associated with small subsidiary pipes of porphyry and breccia. The Genessee-Vanderbilt ore body also appears to lie in a small pipe subsidiary to the large Champion Gulch pipe.

Several of the typical pipe outcrops may be very briefly described. The boundary of the Yankee Girl pipe is marked by 3 or 4 small bodies of porphyry, most of which lie against or not far from the envelope of the pipe. The largest of these porphyry bodies, lying at the southeast edge of the pipe, has a rather thick pod shape as represented in figure 4, A, at the bottom left. North of this porphyry is a body of altered breccia, probably an original pipe breccia. The shaft, which was sunk on one of the chimney deposits lies in the northeast corner of the pipe. The entire pipe is of oval shape, and about 500 feet in north-south diameter, by 400 feet or less east-west.

The mine is inaccessible, but workings[24] on several levels show crosscuts to the pipe rim and some drifting around the apparent envelope of the pipe. The "west ore body" of the mine apparently lies somewhere near the rim of the pipe. The major part of the mine workings is so closely circumscribed by the outcrop of the pipe as to leave little doubt that the pipe continues vertically to a depth of 1,000 feet with little change in diameter or shape.

Both the Guston and Robinson ore bodies appear to be within a single pipe, which is about 1,200 feet in its major north-south diameter. One highly altered body of porphyry is exposed along what is interpreted as the northeast rim of the pipe. The southwest rim is marked by a curved zone of highly sheeted and sheared rock. Several large bodies of unshattered rock lie within the limits of the pipe envelope defined by these boundary fractures. The ore bodies lay mainly along a N. 10° to 20° E. "break" connecting the two sides, but the silicified ledges in which the outcropping ore was found are not continuous along the break.

The Genessee-Vanderbilt pipe lies close to the southwest rim of the much larger Champion Gulch pipe, and may have formed after plugging of the larger one by intrusion of rhyolite. The outcrop of this pipe is merely a half-moon-shaped ledge of silicified breccia, and no porphyry is exposed. The accessible portions of the Genessee-Vanderbilt tunnel workings also fail to reveal porphyry

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[24] Private reports and geologic maps by Wilbur H. Grant have been consulted, through the courtesy of G. E. Collins.

associated with the pipe. There are bodies of mineralized breccia, and the north rim of the pipe may be indicated by a dike of breccia and a strong zone of sheeting that dips vertically to 70° inward. With the information supplied by the workings and geologic maps[25] the north-south diameter of the pipe is estimated at about 600 feet. With the possible exception of the Yankee Girl, the mine development work in the district is generally not sufficient to supplement surface information on the boundaries of the pipes.

The National Belle volcanic pipe is a small probably composite pipe (fig. 6) consisting of the main or larger mineralized pipe about 400 feet in major diameter, and a smaller northeast porphyry-bearing pipe about 300 feet in major diameter. All the main workings of the National Belle mine lie beneath the larger pipe which has a rim zone of highly silicified and leached rock. The knob of altered rock stands about 200 feet above the lowest part

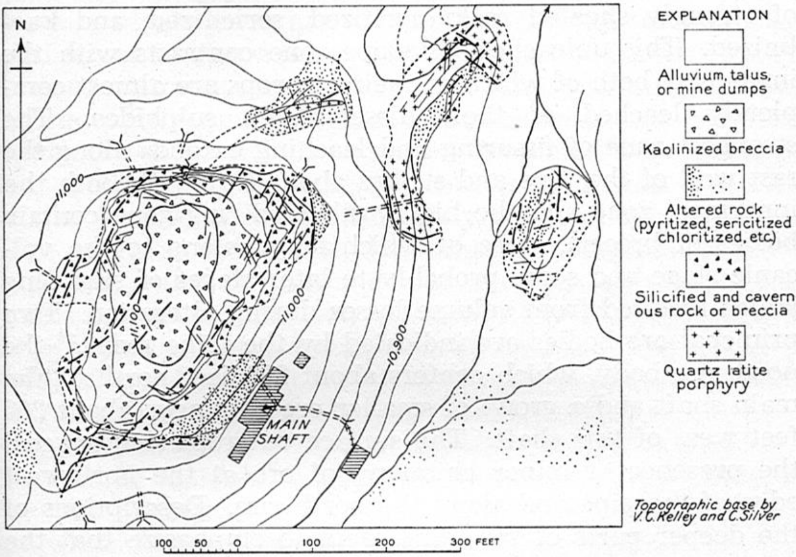

Figure 6.—Geologic map of the National Belle mineralized volcanic pipe.

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[25] Private reports by Wilbur H. Grant.

of the immediately surrounding topography. The surface outcrop of the mineralized chimney or pipe is composed of three main parts. An innermost part or core is exposed on the top of the topographic knob, which is composed of moderately silicified and kaolinized rock and contains locally some fragments of altered porphyry. Surrounding this core is a crude angular ring zone of strongly silicified rock that forms the cliffy steep sides of the knob. On the sides of this are found many open natural caves in which the leached and oxidized ores were first found. The outermost or envelope zone is poorly exposed owing to the talus covering, but it evidently surrounds the pipe and consists of strongly sheeted rock, pyritized, sericitized, and kaolinized. This unleached envelope zone contrasts with the inner two, both of which at their outcrops are almost completely leached of their disseminated sulphides. The strongest zone of fissuring and leaching extends along the east wall of the pipe and strikes about N. 35° E. Both the innermost zone and the highly silicified ring zone contain bodies of breccia, some of which may belong to the volcanic stage and some probably to later stages of slumping which resulted from volume losses during alteration. Two prinicpal ore bodies are indicated by the mine maps,[26] the north ore body, which centers about 200 feet north of the main shaft and a group of smaller ore chimneys about 200 feet west of this shaft. The surface outcrops also suggest the presence of minor chimneys of ore at the northwest edge of the pipe and along the north rim. Descriptions of the deeper parts of the mine seem to emphasize that the numerous open channels coalesced downward from their outcrops around the rim, and hence were funnel-like, but, as the deeper parts of the mine are no longer accessible, this possible structure cannot be seen at first hand. It would thus appear that the rim of silicified and channeled rock was formed by slumping that resulted from loss in volume of the underlying rocks during alteration. Possibly the silica leached from the rocks beneath was partly redeposited in the brecciated and silicified rim.

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[26] Ransome, F. L., (Bull. 182), pl. XVI, p. 231.

Within the upper levels accessible to observation the ores encrusted the walls of the solution caves, and impregnated and replaced rock surrounding the channels. Many of the larger shallow caves had never been completely filled. Both caves and ore bodies decreased in size with depth. The large north ore body was not found on the bottom level (4th) of the mine, and caves characteristic of the upper levels are said not to occur at this depth.

Down to an altitude of about 10,930 feet in the mine workings the sulphides within the caves and those that originally impregnated the walls have been removed by leaching. On the bottoms of some caves and lining the sides of others there are remnants of the less soluble original ore and gangue filling. These consist of porous spongy masses of minute quartz crystals, clay minerals, alunite, barite, partly oxidized galena, and remnants of enargite. Much of the material is encrusted or stained with limonite, but this is a very superficial coating or stain, and the walls of the leached caves are relatively free of limonitic stain. The enargite and pyrite that originally impregnated the silicified walls have completely disappeared from large masses of the silicified and kaolinized rock above the "level of leaching." The thoroughness of this leaching suggests hydrothermal rather than surface water agencies, although the moderate oxidation is doubtless the result of percolating surface waters. These features will be considered further in connection with the origin of the ore deposits.

These examples illustrate mineralized volcanic pipes in which the ore has been found mainly along or above strongly silicified channels that lie within the body of the pipe. In some, such as the Guston, a fissure controlled the positions of individual ore chimneys within the pipe. In others probably intersecting fissures, or fissures that intersected the walls of the pipe or of porphyry bodies seem to have been controlling features. It it said however that some chimneys or lenses of ore do not have associated fissures of any prominence, and it must be supposed that these channels were formed by pre-ore leaching of relatively more permeable rocks in which the structures were too feeble to be preserved. Breccias in volcanic pipes may have locally provided initial channels of greater permeability, but such channels, if they ever existed, are difficult to recognize because of later leaching and the additional brecciation that accompanied it.

The altered and mineralized breccia bodies within or near the pipes are not altogether the result of magmatic or premineral fragmentation. The strong alteration that preceded and accompanied the ore-forming stage extended brecciation by collapse of the rock bodies that became weakened and undermined by this alteration and leaching. This process is illustrated by the structure of the mineralized pipe in the National Belle mine. In the Guston ore body the shear or flow structure of the galena ore on the walls of the chimney is suggestive of a sagging or flow of weakened wall rocks during mineralization.

Chimney ore bodies that lie outside of or in the envelope of volcanic pipes are illustrated by those near the Koehler composite pipe. The Congress and San Antonio ore chimneys lie on or very near the pipe envelope. The Congress chimney is said to be situated where the envelope is apparently intersected by a north-trending break. In the San Antonio chimney both north and east-trending breaks are evident. The ore minerals in both chimneys were chiefly enargite and pyrite with some gold, and it is of interest that galena occurred on the outer margins of the ore bodies to considerable depth. According to Ransome[27] enargite seen near the surface "had been partly brecciated and recemented by a very compact aggregate apparently composed largely of kaolin."

Ore chimneys along exterior fractures of the Koehler pipe are illustrated probably by the Hudson and St. Lawrence chimneys. Intersecting cross-fractures may be held responsible for the local premeability of these channels, and in general ore bodies associated with these exterior

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[27] Ransome, F. L., op. cit., p. 238.

fractures may lie above small porphyry pipes not yet exposed by erosion; for example, the St. Paul chimney (fig. 5) south of the large Koehler pipe is at the intersection of exterior cone fractures with northerly or northeasterly fissures. A small body of porphyry is exposed just south of the main chimney.

Some features of the mineralized chimneys that are believed to be of more than ordinary significance in their origin include the degree of silicification of the walls or "casings" of the ore bodies in relation to depth, and the size of the solution channels or caverns in relation to depth. Although the lower parts of only a few chimneys are now accessible, it is stated by many familiar with the district that the volume of silicified rock decreases noticeably with depth. The caverns and ore channels within this rock, whether filled with ore or not, likewise diminish with depth. Some of these relations can still be seen in tunnels beneath the Genessee-Vanderbilt and Carbon Lake (San Antonio) chimney outcrops. In the lower levels of the Yankee Girl pipe, nearly 1,200 feet beneath the outcrop, the volume of silicified rock is said to be comparatively insignificant.[28] It may be concluded therefore that the ore channels or "chimneys" taper downward like roots; also that the silicified casings form strong perforated cappings at the uppermost levels, where the lead ores were most abundant, but became tapering sheaths downward. It may be inferred that silicified and kaolinized rocks extended originally above the present outcrops of the chimneys, though possibly in large part barren of ore. This is suggested by the fact that on some of the highest mountain slopes there is much barren silicified and channeled rock, though the presence of ore beneath every outcrop of it has not been established.

Origin of the chimney deposits

Introduction.—The mode of origin of the Red Mountain chimney deposits bears directly upon problems of their prospecting and exploitation. Without an understanding of

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[28] Personal communication, G. E. Collins.

the geologic features that localized the ore in relatively small chimney-like bodies, exploration for additional ore is economically very hazardous compared to similar problems in connection with the vein deposits of this region. The widespread general fissuring of the district is by itself an inadequate guide. Although, as stated by Ransome,[29] "it seems most reasonable to regard the ore spaces of the Red Mountain district as a local modification of the general fissuring of the region," this offers little restriction to the economic limits of prospecting within the district. Even though the concentration of ore chimneys within and near the volcanic pipes somewhat restricts the ground most favorable to exploration, there remain problems of the apparent restricted distribution of the higher-grade ores, the absence of valuable concentrations of ore at the outcrops of many altered pipes, and the physical control of the altitude at which ore was deposited. The spaces occupied by ore are not entirely the result of mechanical processes, but are intimately related to some combined physical and chemical processes contemporaneous with ore deposition. This localized corrosive action of solutions is an important link in the chain of actions forming the final ore deposit; hence, in order to evaluate the different controls, the structural and chemical features must be coordinated into a general theory of origin.

It is believed that some advance has been made in an understanding of the origin of the deposits, even though it is not sufficient to answer all the prospector's problems. Inasmuch as the suggestions for prospecting depend to a considerable extent upon the interpreted origin of the deposits, the general arguments upon which they are based are presented below. The discussion is necessarily technical, and many aspects of the problems are subject to further investigation.

The origin of the Red Mountain chimney deposits has been a matter of debate in years past, and explanations have ranged all the way from deposition of ore in shallow

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[29] Ransome, F. L., op, cit., p. 108.

hot-spring orifices to deeper environments in the throats of volcanic vents. S. F. Emmons[30] was the original proponent of a fumarolic origin in volcanic vents, but this theory was not considered favorably by Ransome,[31] who studied the deposits some years later. The results of the present study revive in some form a consideration of an origin related to volcanic vents, although the ores do not merely occupy the throats or breccias of these vents as suggested by Emmons. With regard to the hot-spring origin Ransome[32] says, "The supposition that the ascending heated waters which were primarily instrumental in forming ore bodies may have issued as hot springs, or even geysers, from a former surface, is of course perfectly tenable and difficult to disprove. But to argue that the knolls of silicified and impregnated andesitic breccia conspicuous in the topography of today are really mounds of siliceous sinter is to be carried away by an analogy of the most unessential and superficial kind." His explanation is summarized in the following statement,[33] "It seems most reasonable to regard the ore spaces of the Red Mountain district as a local modification of the general fissuring of the region. It is possible, however, that much of the minor, very irregular fissuring which is characteristic of the region may be due to contraction within the rock mass consequent upon the prevalent alteration of the volcanic rocks to aggregates of quartz, kaolin, and pyrite, with the removal of certain constituents, as more fully discussed on pages 114-131 (Bull. 182). Not only was the fissuring locally complex, but the ascending thermal waters had more chemical and probably physical activity than elsewhere within the quadrangle, whereby solution played an important part in enlarging zones or aggregations of fractures into ore spaces and in

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[30] Emmons, S. F., Structural relations of ore deposits: Am. Inst. Min. Eng., Trans. vol. 16, pp. 833-834, 1888.

[31] Ransome, F. L., Economic geology of the Silverton quadrangle: U. S. Geological Survey Bull. 182, pp. 107, 108, 1901.

[32] Idem, p. 108.

[33] Idem, p. 108.

metamorphosing the country rock to an extent not elsewhere observed in this region. The cause of this local intensity of chemical and physical activity is not known, although it is probable that the circulating intratelluric waters were here hotter than elsewhere. Some indication of the latter is afforded by the abundant strongly mineralized springs which issue from the ground in this district at the present day. There is, moreover, some geological grounds for believing that the Red Mountain region may have been formerly a local center of volcanic activity."

The explanation favored by the writer involves certain of Ransome's and Emmons' views, with emphasis upon concentration of fumarolic activity about volcanic pipes, and upon the very conspicuous solvent action of emanations that preceded and accompanied ore deposition.

An especially characteristic feature of the ore deposits is the concentration, or "telescoping," of the massive sulphide ore within a small vertical range. This is commonly attributed to high temperature gradients near the surface, resulting from volcanic action. For reasons to be enumerated below the writer believes that the deposition of ore minerals was dependent upon pressure and temperature relations rather than temperature alone, and was due more directly to evaporation of the ore-forming solutions. This can be stated in another way, however, by saying that volcanic heat raised the temperature of the rocks near the surface, that solutions rising from below reached positions very close to the surface without appreciable loss of temperature, and that their vapor pressures were above pressures that prevailed in the small open spaces encountered there. It is noteworthy that the spaces occupied by ore in this district are mainly the result of corrosive action of certain solutions, as noted also by Ransome, and that otherwise the fissures are relatively tight.

There are many factors that favor a discontinuity in the ore-forming and rock-altering processes, not the least of which is the strong solvent action of emanations that were given off in the immediate vicinity of the ore bodies themselves. Also, consideration must be given to analogies with the regions of strong fumarolic and hot-spring activity that have recently been studied by members of the Geophysical Laboratory, especially in view of the intense action of fumarolic waters and vapors on the rocks of this region. One cannot question the common coexistence of very hot waters and their vapors in such regions, and although some may prefer to believe that most of the primary vapors rose from deep positions within or very near the crystallizing igneous rocks, the conditions in the Red Mountain district point to a much shallower origin within several thousand feet of the surface where the structural conditions and consequent low external pressures favored an abrupt appearance of the vapor phase.

Perhaps the basic evidence in favor of shallow vaporization of hot solutions under pressure relates to (1) the sharp discontinuity between ore with its normal accompaniment of so-called alkalic gangues and the adjacent wall rocks that had been evidently altered by solutions or condensed vapors of the acid sulphate type, and (2) the major vertical separation between deeper-seated ground in which sulphide ore bodies are found and the slopes of higher peaks that exhibit evidence of attack only by relatively barren fumarolic emanations or corresponding waters. The local discontinuities between ore and leached rock and between ore-bearing ground and barren leached and altered ground are believed to be strong evidence in favor of a physical discontinuity between the types of solutions that must be called upon to produce such extremely diverse and normally unrelated types of rock alteration and ore formation.

In addition, however, the ore bodies themselves in many places show evidence of the alternate activity of the two opposed types of solutions, and this extends in some examples from the beginning to the end of ore deposition. If coexistence and proximity in space of the two kinds of solution are not conceded then it is necessary to call upon the alternate passage of one solution and then another at certain positions, or upon some kind of wall rock reaction that changes the solutions from one type to another. None of these more complex explanations satisfactorily accounts for the distribution of the variously altered and mineralized ground, nor for the vertical and horizontal distribution of the major zones and types of alteration.

The validity of the explanation to be proposed rests mainly upon the soundness of several basic propositions, of which the following three are outstanding:

(1) the correctness of the analogy between the Red Mountain environment and that of typical fumarolic regions;

(2) the reality of two extreme types of solutions: (a) the sulphide type which is instrumental in forming the ore bodies, together with sericite and other alkalic gangue minerals, and in producing metasomatic alteration, but rarely leaves evidence of appreciable leaching action; and (b) the so-called sulphate type which forms kaolin minerals, alunite, diaspore, and related alteration products, and under certain conditions strongly leaches the silicate rocks;

(3) the production of the sulphate type of solution from the sulphide type under the environmental conditions inferred.

The first of these premises will be discussed at some length because of its primary importance in the formation of the ore deposits.

Environment of ore deposition.—The concentration of volcanic pipes along the highly faulted border of the caldera together with the extreme local alteration of the volcanic rocks in this belt are features that in themselves provide adequate evidence of shallow phases of volcanic activity. However, somewhat more specific estimates may be made of the actual position of the former surface during this latest volcanic activity. Ransome[34] estimated that the thickness of material removed by erosion probably exceeds 2,000 feet. From the local thickness of the Potosi volcanic series, the youngest of the volcanic formations

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[34] Ransome, F. L., op. cit., p. 137.

in nearby areas, and from the average altitude of the late Tertiary volcanic surface in the western San Juan Mountains, certainly not less than 1,500 feet of rocks have been removed from above the highest peaks of the Red Mountain district. Possibly not all of this erosion took place after ore formation, but, granting that some rocks were removed before, the surface could scarcely have been less than 3,000 feet above the deepest ore deposits of the Red Mountain valley floor.

From a level at least 1,000 feet below the valley floor to the tops of the peaks, through a vertical extent of 4,000 feet or more, the rocks were attacked by volcanic emanations that leached out many of the more soluble constituents and left aggregates of quartz, clay minerals, hydrated ferric oxide, alunite, diaspore, and other less soluble products of rock decomposition. These are the products of most intense attack, but there are of course large bodies of rock less strongly leached and altered. Large bodies of breccias and other relatively porous rocks have been intensely silicified and kaolinized, and form steep-sided exposures that cap some of the peaks and ridges. Open channels and solution caves in the altered rocks are not uncommon. Some of the original openings are now filled with bedded clay materials. The general character of this alteration is like that encountered at the surface today in regions of solfataric alteration where the more active solutions are of the acid-sulphate type.[35]

It is known from observations of modern volcanic activity that in general eruptive activity may be followed by solfataric and fumarolic activity within a comparatively short span of time. Hence the interval between the eruption of the Red Mountain volcanic pipes and the subsequent fumarolic activity may not have been long. The fact that most of the intrusive rocks are altered in one place or another suggests that there was no appreciable repetition of the eruptive stage, though this may have overlapped the beginning of rock alteration.

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[35] Day, A. L., and Allen, E. T., The volcanic activity and hot springs of Lassen Peak: Carnegie Inst. of Washington, Pub. No. 360, pp. 110-115, 137-145, 1925.

The interval of time involved cannot be guessed, but it is clear that, during alteration of the rocks and the leaching of fumarolic channels in them to the depths of the present ore bodies, the entire belt of altered rocks sagged downward many hundreds of feet. The effect of this sag upon the superficial activity of escaping volcanic vapors as well as upon the deeper channels through which they were fed must have been very appreciable. The topographic changes at the surface above the belt of sagging must have provided a large catchment basin in which meteoric waters circulated to such depths as were permitted by the local pressures of the escaping hot vapors from below. As emphasized by Allen,[36] the effects of topographic basins upon the nature of the surface phenomena of fumarolic and geyser action is fundamental to an understanding of the processes involved. What happened at the surface above the Red Mountain rocks can only be imagined by analogy with regions of modern activity, such as the Yellowstone Park.

The changes in structural conditions at deeper levels beneath the downwarp can be partly inferred from the nature of the deformation and from rock alteration. A number of pipe channels that had hitherto been connected with surface vents were probably sealed off by plastic flow of the surrounding rocks. Thus pipes within belts of plastic deformation have been less productive. Although escape of the emanations was not stopped by this deformation, paths followed by them evidently became more complex and dispersed, and large additional masses of highly fissured rocks were subjected to chemical attack. The favorability of large bodies of rocks to concentrations of ore was consequently impaired or destroyed.

The width of the structural basin at some positions appears to have been nearly 3 miles, as shown by an appreciable sagging of beds within this span. The depth of the sag cannot be estimated accurately, but at some positions, as across section B′-B″ (pl. 2), the total depth of sag approximated 500 feet. Hence it would appear that, with the

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[36] Allen, E. T., Geyser basins and igneous emanations: Econ. Geol., vol. 30, pp. 1-13, 1935.

sagging of the rocks along the border of the main caldera, a belt several miles in width would be formed in which a narrow but long groundwater blanket might have existed in porous beds and tuffs of the youngest rhyolitic formations. Possibly the waters may have penetrated the joints of the underlying latitic and andesitic formations for some depth, but the volume of such water must have been small because these formations do not possess the same porosity as the rhyolites.

The inferred surface conditions during fumarolic activity may be compared directly to those now existing in the Yellowstone National Park. As stated by Allen:[37]

"There are two principal types of hydrothermal areas; the sulphate tract, characterized by thin sandy or mealy deposits (generally quartz and other crystalline varieties of silica, but in places opal) dotted with small, shallow, and commonly muddy springs with little aggregate outflow. The spring waters are dilute solutions of silica, sulphates of the common rock-forming metals and in many places free sulphuric acid, more or less choked with a sediment of opal and clay which is intermixed here and there with sulphur, pyrite, or hematite. The other important type of hot area is the geyser basin. Generally more extensive it is distinguished by springs of the deep, clear variety, generally large and of high aggregate discharge." Continuing, Allen inquires, "How can we neglect the fact that the alkaline areas of high discharge occur in well-defined basins, where the most surface water would be expected, while the sulphate springs are found on steep slopes where much rainfall would be lost as run-off, or in shallow depressions where only thin zones of groundwater could accumulate?"

By comparison with these two principal types of areas defined by Allen, the structural basin of the Red Mountain Valley would correspond to the geyser basin of the Yellowstone, whereas the structurally higher belts of alteration on either side of the valley and especially that on the east side would correspond to the sulphate tracts of the Yellow-

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[37] Allen, E. T., Geyser basins and igneous emanations: Econ. Geol., vol. 30, no. 1, p. 2, 1935.

stone. It may be significant, therefore, that the main belt of productive chimney deposits of the Red Mountain district lies beneath a former surface tract that corresponds in structure to the geyser basin.

If, as suggested in the introductory paragraphs, the ores of these deposits were precipitated at positions where the ore-forming solutions vaporized, then this correspondence is of considerable significance. The presence of a large blanket of ground water in a basin above fumarolic channels must have an important control upon the vapor pressures in them.

Regarding the delicacy of this control in the eruptivity of geysers, Day[38] says, "It is just possible that an explanation may be found in the nice adjustment between maximum steam pressure within the chamber and the overlying load, which encounters no disturbing factor sufficient to release it for a longer or shorter period. This possibility is suggested by the fact that certain of the geysers may be set in activity arbitrarily by vigorous stirring at the surface or by dipping out a few pails of water or by the addition of a small quantity of soap, factors so small in terms of the total energy impounded that no conclusion suggests itself but that we are dealing with a rather precise balance between two forces requiring a very small counter-weight to upset it."

Certainly one is justified in raising the question as to the possible influence of delicately controlled pressure conditions on the localization of nearly all of the highly productive chimney ore deposits in the belt along the axis of the Red Mountain sag. Although there is a total difference of about 1,000 feet in the altitudes of ore bodies between the northern and southern ends of the belt, the group of richer deposits at the northern end are closely accordant in their altitudes. These ore bodies also have about the same vertical range. In contrast to this uniformity the many small chimneys outside the central belt exhibit great variation in their position and characteristics. Very few

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[38] Day, A. L., The hot spring problem: Bull. Geol. Soc. Amer., vol. 50, no. 3, pp. 335-336, 1939.