productive veins of the district. The radial fissures extend for as much as 8 miles into the northwest exterior province adjoining the Silverton basin, and also at least partly across the belt of ring faults. The radial fissures of the Telluride and Sneffels districts range in strike from N. 70° W. to N. 15° W., with the axial trend of the swarm about N. 45° W. The dips are moderately steep to the northeast and southwest, and are commonly outward on either side of the axial line. Many older fissures of this system are occupied by dikes as well as veins. Some of the dikes are curved in strike and join with or are common to the radial dike system (4) of the Stony Mountain (or Mount Sneffels) center, but in part the radial systems of the caldera and outlying intrusive centers are separate.

Certain fissures of the radial systems are straight and hence trend diagonally in places to the curved fissures. Many of these straight fissures, which belong to a younger group and do not contain dikes, are represented by the so-called "flat veins" of the districts. They are related in origin to a radial axis of sagging, which is described under the Telluride and Sneffels districts.

The "spiral" and cone-fracture systems of the caldera (3) and of the Stony Mountain center (5) require special explanation, owing to the terminology and to the possible different forms of the fractures. Most of these are curved fractures that diverge at about 45 degrees from their positions of origin on the margins of central structures, such as the caldera, intrusive stocks, and volcanic pipes (see also under this heading). In some the degree of curvature decreases away from the center of origin; hence their form is roughly spiral as shown in figure 1, A, and C.

Where the evidence is clear the dikes occupying fissures of these systems prove to be older than those in the radial tension fissures. Dikes belonging to the cone sheet system dip inward toward their center of origin, as shown in figure 1, B. Such fractures are commonly attributed to tensional strains formed by an upward thrust of the invading igneous mass. However some of the steep curved

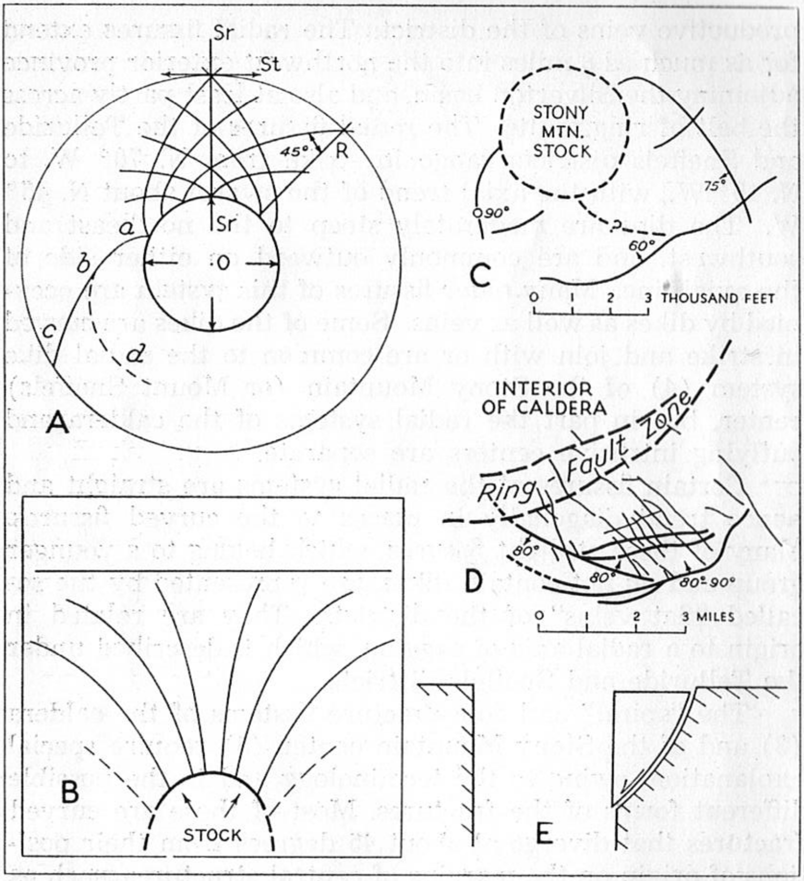

Figure 1.—"Spiral" fractures and cone fractures and their relations to centers of radial stress.

Part A represents ideal stresses about a circular center. Sr, radial stress; St, tangential or hoop stress; the curved lines which intersect the radial directions of principal stress, OR, at 45 degrees are directions of maximum shearing stress. Such lines are logarithmic spirals.

Part B shows a cross-section of cone fractures formed by the upthrust of an intrusive mass. Those nearer the center are commonly steeper. Cone fractures are believed to be of tensional origin. Their traces on the surface are commonly concentric with respect to the intrusive center.

Fractures belonging to these different curved systems are shown in parts C and D as heavier solid lines. Some of these such as the one South of Stony Mountain are occupied by intrusive rocks and dip inward toward the intrusive center and hence probably form cone sheets. Others are very steeply dipping and may represent spiral shear fractures.

Other curved fractures may represent boundaries of blocks that have subsided along shear fractures as shown in cross-section E.

dikes correspond in their general relation to radial dikes as shown by the shear planes in figure 1, A, and hence may occupy reopened shear fractures. Other dikes apparently split or turn from a fracture of the form "abc" to one of concentric direction, "bd." Fractures without dikes and of the form "abc" appear to be more common than radial tension fractures around the small volcanic pipes of the Red Mountain district. Their possible relations to the form and origin of the volcanic pipes are discussed in the following section on this district.

RED MOUNTAIN DISTRICT

The Red Mountain district lies mainly within the marginal zone of ring faults, but areas just north and west of the fault zone that are tributary to Red Mountain Creek are geographically a part of the district. As may be seen by reference to the topographic map of Ironton and vicinity, the district is divided into several physiographic parts: the group of the three Red Mountains at the southeast, Brown Mountain and Mt. Abrams ridge on the northeast, Ironton Park and the valley of Red Mountain Creek, and the mountain slope on the west that includes the outer margin of the fault zone. For convenience the last division will be referred to as the west slope or west part.

Faults

The fault belt that extends northeastward through the district forms the dominant structural feature, and as already indicated, is a portion of the ring-fault system of the caldera. Though the dominant pattern of structure is doubtless produced by the N. 25° to 65° E. fault lines, this is perhaps over-emphasized physiographically owing to the parallel northeast course of the trunk glacier that occupied Red Mountain Creek and Ironton Park Valley. Glacial scouring of the faulted and altered rocks has produced numerous parallel ridges and troughs representing the relatively hard and soft zones of fissured rocks. These more prominent northeast trends are, however, crossed by numerous though more obscure fissures and faults of the northwest radial system, and by complementary systems of N. 10° to 20° E. and E.-W. fissures. The fault belt as a whole may be considered as a shattered mass in which the rocks are broken into numerous vertical prisms of irregular shape. Many or most of the prisms have their longer horizontal axes parallel to the northeast system.

A number of the larger individual faults are marked by strongly brecciated or crackled rocks, especially in the more massive formations, such as the latite and andesite flows of the Picayune volcanic group. Such fault breccias, composed of angular fragments an inch or less in size set in a finely broken matrix, attain in places widths of 100 feet or more. At other places the fault lines are much more obscure. In areas of strongly altered rocks the faults cannot be followed far unless the textures of the abutting rock masses are sufficiently different to permit recognition despite their altered condition. Places of such obscure structure are present along either side of the main valley, as along the west slopes of the Red Mountains and in the short gulches and aspen-covered slopes on the west side between Spirit Gulch and Monument Gulch. Such portions of the fault pattern are, therefore, incomplete or sketchy.

The generalized structure across the valley and fault belt in two places, as shown in cross-sections B′-B″ and C-C′ of plate 2, is that of blocks dropped successively to the southeast, though some blocks may be dropped below those on either side, forming structural troughs or grabens. The displacement across the belt from the west slope to the ground beneath the Red Mountains seems to be at least 2,000 feet, but changes in thickness of formations laterally and effects of erosion between them render such an estimate subject to a large error. If, as may be supposed, a number of the formations thicken toward the center of basin, and downwarping and faulting were in part concurrent with the eruptions, the total displacement may greatly exceed the minimum suggested. In other parts of the ring-fault system minimum displacements in the shallower formations range from about 2,000 to 3,000 feet.

Sag of Red Mountain Valley

The simple step-fault structure across the valley is greatly complicated by a younger, superimposed sagging and tilting of the beds inward from either side toward the relatively broad valley floor. This structure as seen on the ground is expressed in a marked tilting of certain blocks of massive rock and in the development of a prominent secondary laminar or flow structure in some of the weaker beds. This structure is expressed in weathered outcrops by parallel fractures an inch or less apart and by the disintegration of the rocks into thin plates or even small flakes. The platy structure ranges in dip from 20 to 60 degrees. It may coincide locally with tilted bedding planes of tuff or with the original flow structure of the lavas, but it commonly is steeper. The steepness of the dip commonly increases inward toward the valley bottom, but where the rocks are exposed on the floor of the valley the secondary structure and tilt decrease or disappear entirely. These features are therefore particularly characteristic of the flanks of the sag structure.

Certain commonly observed relations between the tilted and deformed rocks, the faults, and the degree of alteration may be summarized before giving an interpretation of this feature.

(1) The most highly tilted rock masses are found in belts of strong rock alteration along both the east and west sides of Red Mountain Valley. (2) The rocks most strongly affected by the secondary laminar structure are beds of originally low cohesive strength, such as tuffs. These are very highly altered. (3) The tilting as well as the flow structure are evidently unrelated to fault drag. This is illustrated both by reference to grabens, for example along the west slope, where the tilt and the flow structure continue across fault planes with an inclination opposite to that expected from normal drag. Likewise, though the faults on the east side of the valley are interpreted from

all other geologic evidence to have their downthrow to the southeast, the tilted blocks and the secondary flow structure commonly dip west. (4) The massive tilted blocks of rock commonly do not have as high an inclination as the laminar structure in nearby weaker rocks, though the two effects appear related in strength. In some places the two may be essentially equal. Definite observations of this kind, however, are commonly hampered in the more massive blocks of lava by lack of reference structures that would reveal the amount of tilt. (5) Some tilted blocks of flow rocks appear to lie entirely detached in highly altered and sheared tuff, though the exact relations are commonly obscured by alteration.

It would appear from these different relations that the sag of the rock formations toward the valley is most intimately related to rock alteration and secondary flow structure. There are two belts of alteration that are well marked on either side of the valley, one parallel to the west slope between Commodore Gulch and Full Moon Gulch, and another along the Red Mountain ridges from Red Mountain No. 3 to Brooklyn Gulch and beyond on the slope of Brown Mountain. Along the valley floor and the lower slopes from Red Mountain Pass to the vicinity of the Joker tunnel, the rocks are not as strongly altered and the rock formations are but slightly tilted or horizontal. Farther northeast strong general alteration continues from either side to the valley floor, which is here covered with alluvium.

The San Juan tuff where exposed along the altered belt west of the valley is hardly recognizable. The altered rock breaks into flaky particles parallel to the laminar structure, is completely changed mineralogically, and its ordinary greenish or brownish gray color is reduced to a dull gray-white. The ghostly outlines of the fragments are, however, still recognizable locally. The minerals composing the rock are products of alteration such as clay minerals, hydrothermal micas (mainly (?) sericite), albite, quartz, carbonates, epidote, chlorite, and pyrite. From the general character and inclination of the secondary laminar structure one is justified in concluding that the tuff has undergone "plastic" flow,[11] which was induced by concurrent alteration and steeply inclined stresses. The lack of the drag effect where such structure crosses fault lines and the fact that in many places much alteration is later than the fissuring point to the conclusion that these highly developed secondary structures, and the tilt of massive rocks were produced concurrently to each other but subsequent to the main period of step-faulting.

Possible contributing causes of the sagging are the undermining of the fault zone by rise of igneous bodies and dropping of blocks in depth, the general reduction in

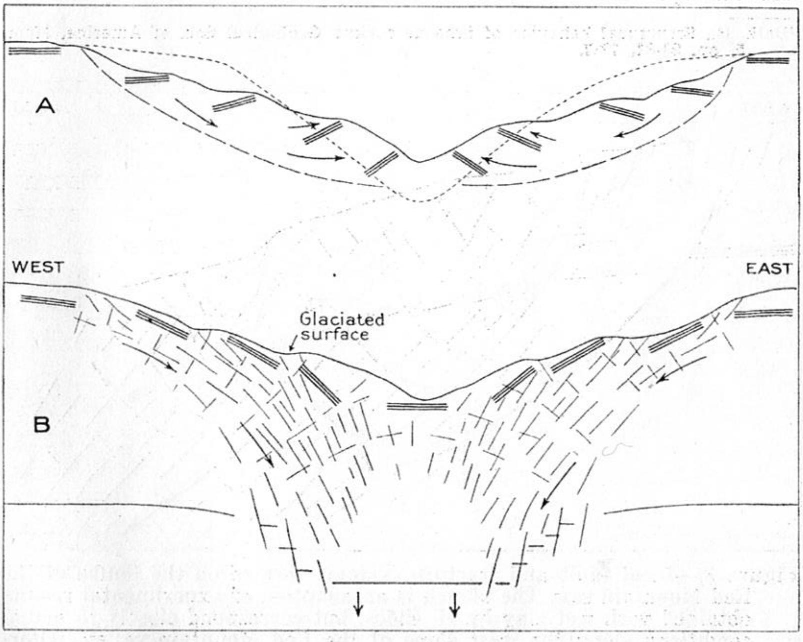

Figure 2.—Diagrammatic sketch of flow phenomena: A, in shallow landslides; B, as shown by the tilting and "plastic" flow of altered volcanic rocks of the Red Mountain sag. The lined plates show the tilt and displacements of more massive rocks under the influence of flow in underlying weaker beds.

---

[11] Griggs, D., Experimental flow of rocks under conditions favoring recrystallization: Bull. Geol. Soc. Amer., vol. 51, pp. 1023-1034, 1940.

strength of the rocks by volcanic emanations escaping at the sides of the dropped blocks, and a reduction in volume of the rocks by solvent action of the emanations. The schematic representation is shown in figure 2. The local tilting of beds on the flanks of the structure is attributed to a rotation of massive blocks concurrent with "plastic" flow of the weaker underlying or enclosing formations. As none of the rocks affected was reduced to a state of complete flow, rock bodies were actually subjected to fracturing and faulting during deformation. (See fig. 3). The faults, ab, designated "synthetic"[12] normal faults by H. Cloos, are nearly parallel to the directions of shearing. Where they steepen upward they may split into subsidiary step-faults. The latter are recognizable on the higher ridges west of the valley. The "synthetic" faults are not definitely recog-

---

[12] Balk, R., Structural behavior of igneous rocks: Geological Soc. of America, Mem. 5, pp. 29-31, 1937.

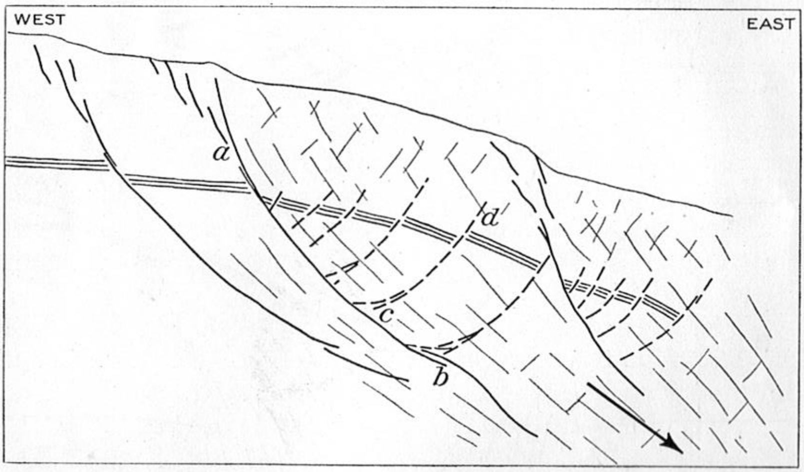

Figure 3.—Ideal fault and fracture systems formed on the flanks of the Red Mountain sag. The sketch is an adaption of experimental results obtained with wet clay by H. Cloos, but correspond closely to actual conditions along the west slope of the Red Mountain valley. Alteration and soil cover hinder detailed representation on the geologic map and cross-sections.
Faults of the kind, ab, are called by Cloos "synthetic" normal faults, those of the kind, cd, "antithetic" faults. Compare faults cd with tension fissures in figures 8 and 9.

nizable on the steeper valley slopes, but are probably represented by fractures in crosscut tunnels, and by the flat "slip planes" described in literature on the ore deposits.

The tension faults, cd, or "antithetic" faults of Cloos, are more readily recognizable on the surface. They dip into the hillslopes on the flanks of the sag, and are nearly at right angles to the secondary laminar structure. On the west slope of the district their effect is to fault the massive flows in the lower part of the Picayune volcanic group down against the underlying San Juan tuff, which occupies the down-slope positions. On the east side of the Red Mountain valley it may not be possible to distinguish these minor faults readily from the steeper ring faults, unless the dips of the fault planes or the displacements are measurable. In fact, the high degree of alteration to which all rocks have been subjected in the belts of stronger deformation seriously hinders interpretation of details in many places. Repetition of the several basic types of fault structure at widely scattered positions in the district has provided the key to the interpretation given.

To obtain the conditions now to be seen in the Red Mountain district, the structures described above must be imagined as superimposed upon earlier deformation produced by step-faulting of the ring system. The complications obviously possible indicate in some degree the generalization found necessary in constructing cross-sections of the district (pl. 2).

The general type of structure found on the flanks of the Red Mountain sag is evidently repeated in somewhat different form elsewhere around the Silverton caldera. For example, the "antithetic" tension faults are analogous to the so-called "flat veins" of the Telluride and Sneffels districts (compare figs. 8 and 9, pp, 218, 222). There the complementary "synthetic" normal faults are commonly missing as such, but their analogous position in the structural pattern is represented by nearly horizontal surfaces of shearing that occur along the stratification planes of sedimentary rocks immediately underlying the San Juan tuff.

The landslide hypothesis

This interpretation cannot be dismissed without brief reference to an interpretation[13] as landslides of the tilted and faulted blocks that form many parallel ridges and hummocks so characteristic of the Red Mountain topography. The ground surface of the district is locally covered with much debris broken loose or moved by glacier ice, by rock slides, and by mudflow action. In the midst of this debris are many of the hummocks and ridges underlain by the more massive and locally tilted volcanic rocks. Many of these blocks were interpreted by earlier workers to be of landslide origin and were so mapped over large areas, but under the present interpretation only the obviously shallow and jumbled blocks or accumulations of finer debris are mapped as landslides. In figure 2, A and B, tilted rock masses are shown diagrammatically, contrasting the condition to be expected from normal landslide action and that resulting from subsidence of the altered formations.

The main argument against landslide origin of the rock ridges is threefold:

(1) The tilted blocks and corresponding trenches are grooved and scoured by ice action, the softer altered rocks being deeply cut, whereas the hard rocks stand up as roches moutonnées or parallel ridges, which happen to imitate landslide topography; therefore, the topographic evidence on which the landslide hypothesis was mainly based is not valid.

(2) A number of deep and shallow crosscut tunnels running through and under rock masses included well within areas previously mapped as landslide encountered only solid rock, though locally much fissured and altered. Major fault lines on the surface above correlate in proper position with those exposed in the tunnels. Many shafts also penetrated the so-called landslide masses but encountered only continuous rock. This condition was explained as being due

---

[13] Cross, W., and Howe, E., Description of the Silverton quadrangle: U. S. Geol. Survey, Geol. Atlas of the U. S., Silverton folio (no. 120), p. 14, 1905. Howe, E., Landslides of the San Juan Mountains, Colo.: U. S. Geol. Survey Prof. Paper 67, pp. 25-26, 1909.

to the situation of shafts on knolls around which the slides flowed, but there are so many of these that the explanation loses much of its possible validity as an accidental or local factor. It appears, therefore, that nearly all of the so-called landslide blocks are bedrock masses.

(3) The tilting of the blocks where determinable is opposite to that commonly resulting from landslide action, especially where large masses of rock are involved, as shown by comparison of figure 2, A and B.

Owing to the highly altered condition of the rocks in the district and the consequent rapid sapping of cirques by glacial action, the local ice was overloaded with debris. There are consequently numerous shallow landslide masses, which, lubricated by the large amount of clayey alteration products, appear to have moved as mud slides. These fail to show the rock ridge and trench topography cited as characteristic of the so-called landslide areas.

Here and there large massive and jointed ridges of flow rocks nearly surrounded by much altered rocks and debris have been superficially shattered and moved by late glacial or by mudslide action, and in such places interpretation of the structure may be very difficult. In many places at least this shattering appears to result from differences in direction between early trunk-glacier movement during maximum glaciation, and late ice or mudslide movements, which were directed down the valley slopes at right angles to the movement of the trunk glacier. Consequently, narrow ridges reduced to a stable streamline form under northeasterly longitudinal movement of the main trunk glacier of the valley were unable to withstand the side pressures of tributary glaciers that were active after stagnation or withdrawal of the main ice. The tops of such ridges were therefore shattered and some blocks are believed to have been moved down-slope from a few tens of feet to possibly two hundred feet. Nearly all such examples lie just below some of the major tributary cirques.

The preglacial or postglacial origin of many rock ridges has been determined by careful search for glacial striae beneath the soil and vegetation around their borders. Where the rocks were much softened by alteration or strongly jointed, the striae were evidently quickly destroyed by frost action and other weathering. Even on many ridges of harder rocks striae are now found only along the lower sides, from which the soil has been washed away since deforestation.

Volcanic pipes

The structural features having closest association with ore deposits in the Red Mountain district are the volcanic breccia pipes and their related intrusive rocks. The structure of these pipes and their possible origin will be discussed at some length as they may have bearing on future prospecting in the region other than within the Red Mountain district itself. The pipes are nearly vertical cylindrical bodies of slightly elliptical cross-section, occupied by breccias, and by intrusive bodies of quartz latite porphyry and rhyolite. The simpler pipe-like bodies are occupied by small plugs of the porphyry, some of which are only a few tens of feet in diameter. The more complex pipes are typified by the large rhyolite-bearing pipe of Champion Gulch, or by the composite pipe of the Koehler tunnel area near Red Mountain Pass (figs. 4 and 5).

In the more complex pipes the age relations of the rocks show that breccia was formed first and was followed by intrusions of quartz latite porphyry and finally of rhyolite. Movement and formation of breccia bodies evidently continued concurrently with intrusive action, for all recognizable kinds of intrusive rocks, as well as some not exposed, are represented in the more complex breccias. Other more homogenous breccia grades into bodies of relatively unbroken or slightly crackled country rock. One may infer from these general relations that the country rock within the envelope of the cylindrical body became gradually incorporated into the breccia composing the fully formed pipe. In order to make way for the intrusive rock or other bodies of foreign breccia, this brecciated country rock must either have moved aside, sunk, or have become assimilated either in rising solutions or in the molten rock itself.

The form of the intrusive bodies and the mechanism by which the envelope of the pipe was established bear most directly upon problems of structure within mineralized pipes, and upon search for undiscovered ones. Some stages in the development of pipes may be inferred by comparing changes in form between the incipient intrusive bodies and the more complex, fully developed pipes. A not uncommon form of small intrusive body, as represented particularly by the quartz latite porphyry, is shaped much like a crescent or quarter-moon cut in half, but with the blunt end rounded off. The pointed end passes into a narrow dike or wedge. A number of bodies of this general shape are illustrated in figure 4, A.

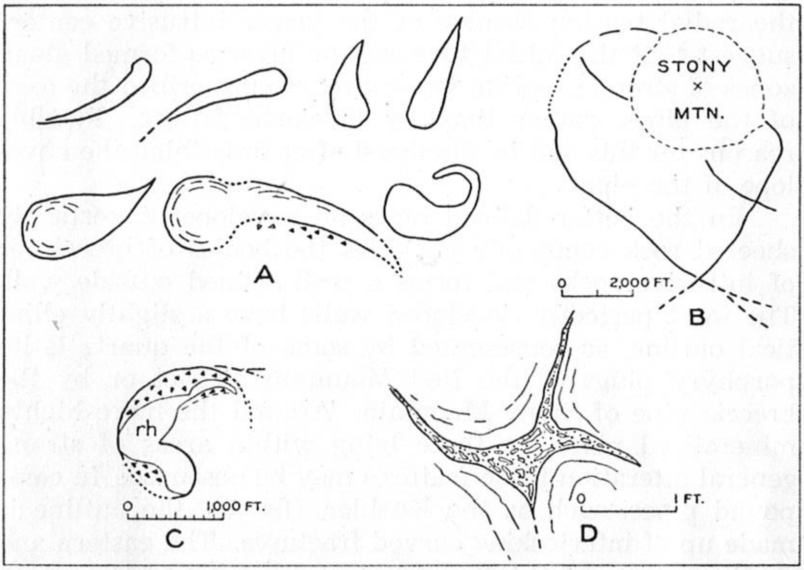

Figure 4.—Structural forms of volcanic pipes and related features. A, Forms of incipient intrusive plugs of the volcanic pipes. B, "Spiral" fractures of the Stony Mountain center. C, Champion Gulch volcanic pipe. D, Sketch of incipient brecciation of volcanic rocks under influence of altering solutions and locally unbalanced stresses.

The general form of these incipient bodies invites comparison with the "spiral" and cone types of fracture, already mentioned as the earliest fissure systems of the Stony Mountain intrusive center (compare fig. 4, B).

The shapes of small breccia bodies are not so well known because of lack of opportunities for special study, but in the more advanced stages of pipe formation a resemblance to this general form is also apparent. This may be illustrated by the Champion Gulch pipe (fig. 4, C) in which the breccia is now largely displaced by rhyolite. Figure 4, D illustrates growth of brecciation, from a sketched detail within a partly brecciated rock body; but the sketch represents only a few square feet. Around the small latite pipes on the west slope of Mount Abrams and around the Koehler composite pipe there are further examples of external curved fissures associated with the main bodies of the pipes. The known relations of the "spiral" curves to the radial tension fissures of the larger intrusive centers suggest that the initial fractures or breccias formed along zones of strong shearing stress that circumscribed the axes of the pipes, rather than by tensional failure. Possible reasons for this will be discussed after describing the envelope of the pipe.

In the better defined pipes an envelope of vertically sheeted rock commonly encircles the bodies of breccia or of intrusive rocks and forms a well-defined outside wall. The most perfectly developed walls have a slightly elliptical outline, as represented by some of the quartz latite porphyry plugs of the Red Mountain district or by the breccia pipe of Stony Mountain. Around the more highly mineralized pipes, or those lying within areas of strong general alteration these features may be obscured. In compound pipes, such as the Koehler (fig. 5), the outline is made up of interlocking curved fractures. The eastern and southern sides of the Koehler pipe are marked by a zone of inclined sheeting or shearing that dips inward 40 to 60 degrees toward the center. This sheeting involves both the intrusive rock within the pipe and the country rock

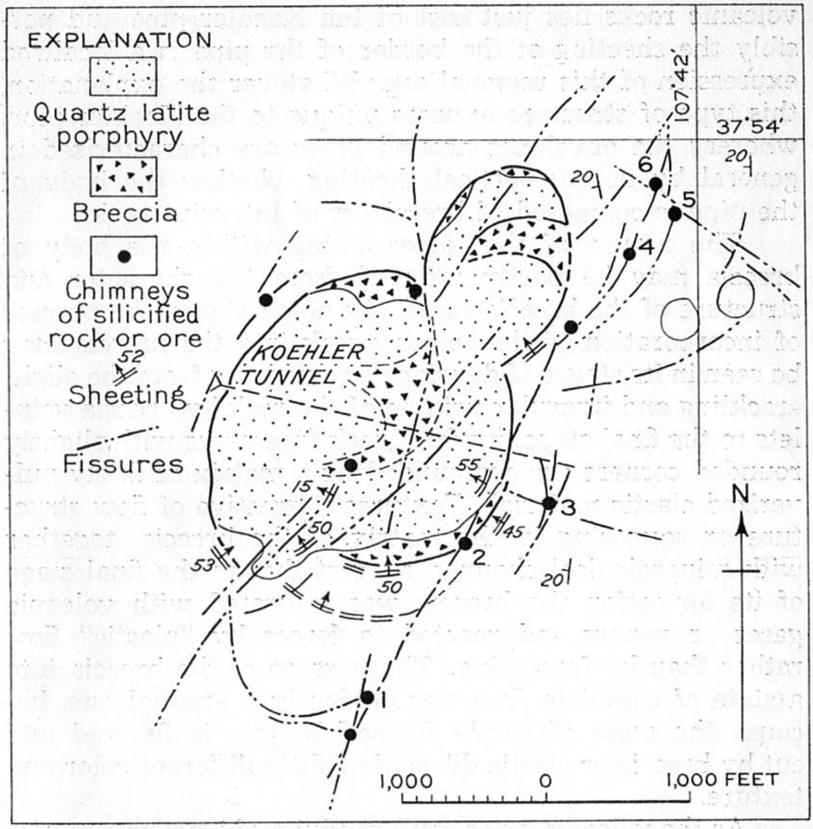

Figure 5.—Plan of the Koehler compound volcanic pipe and associated structural features. (1) St. Paul, (2) Congress, (3) Carbon Lake, (4) Hudson, (5) St. Lawrence, (6) Enterprise.

forming the walls. In places the vertical flow structure of the quartz latite porphyry is cut diagonally by the inclined sheeting, and indicates that the sheeting is of later origin than the outline of the intrusive body. The close spacing of these sheeting planes suggests that they resulted in part from shear rather than pure tensional stresses, and hence may be due either to sagging of the pipe body in later stages of its history or to an upthrust of the intrusive mass. A northeasterly belt of strong westward sagging of the volcanic rocks lies just east of the Koehler pipe and possibly the sheeting at the border of the pipe is a localized expression of this regional sag. Whatever the explanation, this type of structure appears unique to the Koehler pipe, whereas the envelopes around pipes are characterized in general by nearly vertical sheeting whether the body of the pipe is composed of breccia or of intrusive rock.

The nature of the forces acting within the body of breccia may be partly inferred from the character and structure of the breccia itself. As noted above, the process of incorporation of the country rock into the breccia may be seen in its stages of development, ranging from the slight crackling and irregular veining of the rock by breccia veinlets to the final stage in which rock fragments with slightly rounded corners are surrounded by a matrix of finely pulverized clastic material. Textures suggestive of flow structure or squeezing in the matrix of the breccia, together with mineralogical changes, suggest that in the final stage of its formation the breccia was saturated with volcanic gases or vapors and reacted to forces by "plastic" flow rather than by fracturing. The passage of the breccia into a state of complete flow was evidently a gradual one, because the mass of partly formed breccia is fissured and cut by breccia or clastic dikes of slightly different color and texture.

As the volcanic pipes were conduits of igneous material and heated emanations from depth, and as the great bulk of igneous emanations are composed of water, the manner by which the rocks were reduced to masses of plastic breccia may be compared directly to the experiments and theoretical deductions of Griggs[14] and Goranson[15] cited above.

The breccia pipe and its cylindrical envelope are comparable to the results of plastic flow in hollow cylinders or in flat metal plates pierced by a central hole and sub-

---

[14] Griggs, D., Experimental flow of rocks under conditions favoring recrystallization: Bull. Geol. Soc. Amer., vol. 51, pp. 1001-1022, 1940.

[15] Goranson, Roy W., "Flow" in stressed solids: an interpretation: Bull. Geol. Soc. Amer., vol. 51, pp. 1023-1034, 1940.

jected to radial stresses.[16] Centrifugal forces sufficient to reduce the metals to a plastic state of flow produce an internal ring or cylinder of plastic material that widens to include the entire volume of the plate or cylinder when the stress exceeds certain critical values. The most nearly comparable but theoretical case is that of yielding around a cylindrical cavity in an infinite elastic body.[17] Under internal pressure the highest tangential stress exists along the boundary between an inner plastic zone and the outer elastic body. The radial stress is at a maximum at the edge of the cavity, but falls to about the value of the tangential stress at the boundary between the plastic core and the surrounding body.

The manner by which some initial fracture or breccia body develops into the complete cylindrical pipe is not entirely evident from what is known of the intermediate stages of development, but the process may be related to some final attainment of equilibrium between forces within the body of pipe breccias and those in the surrounding country rock.

From the geologic evidence one might conclude that the breccia core developed at the beginning by "plastic" deformation that spread outward along planes of maximum shearing stress, that is, the "spiral" directions. The unbalance of stress that resulted in the surrounding country rocks was gradually compensated and restricted in its spread by the formation of an encircling envelope of strong tangential or hoop stress. This counterbalancing stress not only limited the outward growth of the "spiral" shear planes, but tended to deflect them into concentric directions. The conditions are somewhat different from those holding in the metallic materials referred to above, in that the strength of the rock near the core of the pipe was reduced below that in the surrounding rock by the action of emanations from the intrusive bodies.

This inferred mechanism is of more particular economic interest in connection with the chimney ore bodies of the district which are similar in form to the volcanic

---

[16] Nadai, A., Plasticity, pp. 186-214, New York and London, 1931.

[17] Idem, pp. 199, 200.

pipe. As will be described later, these ore bodies formed along vertical axes of strong hydrothermal leaching of the volcanic rocks, and hence their internal pressures were probably much less than the surrounding rock pressure. Except for possible differences in this pressure relation the mechanism of formation of the ore-bearing chimneys may closely parellel that of the volcanic pipe.

There is, however, no direct evidence that pressures within the volcanic pipes exceeded or even equalled the surrounding rock strength at all stages of development; on the contrary, the absence or weak development of radial tension fissures around many pipes suggests that the internal pressure alone was insufficient to deform the surrounding rock. The peripheral sheeting of the pipe's envelope could have resulted from yielding induced either by a temporary low internal pressure less than the stored elastic stress in the envelope walls, or, by a local reduction in strength of the core by the action of volcanic emanations. Perhaps an explanation of the development of early spiral shear fractures around some pipes and intrusive bodies is to be found in a local weakening of internal stresses in the pipe cores by solvent action of volcanic emanations prior to final occupation of the core by igneous rocks. In larger stocks and pipes such as Stony Mountain and the Koehler pipe, the later injection of igneous material raised the internal pressure suffiiciently to produce radial tension and cone fractures that cut across the earlier fractures.

Daly[18] has called attention to the "limital size" of volcanic necks, the average being well under 300 meters (about 1,000 feet), and attributes this to "the available supply of heat along the axis of the vent." Other possible limiting factors may be suggested, namely, (1) the internal pressure of the volcanic emanations along the axis of the pipe, and (2) the stored elastic stress in the surrounding rocks. Elastic energy stored in the surrounding rock, for example, might be considered as a counteracting force; the

---

[18] **Daly, R. A., Igneous rocks and the depths of the earth, pp. 380, 381, New York, 1933.**

magnitude of this would depend upon depth, physical properties of the rocks, and structural factors.

There is no convincing evidence on the possible effects of explosive action at the volcanic orifice on the origin of the pipe form. In the Champion Gulch pipe large blocks of rhyolite and quartz latite porphyry are incorporated in the chaotic breccia surrounding the rhyolite plug. Both because of the large size of this pipe, and the enormous range in size of fragments in the breccia, it may readily be imagined that explosive eruption at the orifice was responsible for a sudden release of pressure and consequent rise of breccia in the pipe, followed by eruption of the fluidal rhyolite. On the other hand the small incipient pipes fail to show either such effects of violent action or of strong flow. The gradation of breccia into country rock along irregular fractures with only slight rotation or displacement suggests a comparatively gentle activity. Furthermore the almost perfectly symmetrical forms of the smaller pipes and the nearly hairline boundaries do not suggest an explosive penetration of the vertical core.

The writer, therefore, follows the views of Daly[19] that hot juvenile gases rising along joints or fissures were probably responsible for forming the pipes of central volcanic vents, "with or without a crater of explosion at the surface."

The inferred history of pipe formation may be briefly summarized up to the point of complete development of the pipe, but ending prior to the later activity of mineralizing solutions within the body. The passage of magmatic emanations up through favorably jointed and fissured rock may have caused certain chemical or volume changes along some vertical axis of greatest concentration, which impaired the strength of the rock and induced local crackling and crumbling. The zone of disintegration spread outward from the axis along generally curved surfaces—first as the "spiral" form, controlled by yielding of the rock along planes of maximum shearing stress, and later as the

---

[19] Daly, R. A., op. cit., pp. 358-361.

concentric form, controlled by the increasing influence of the concentric stresses surrounding the plastic core. As the breccia mass spread into the surrounding rock it tended to assume the form either of a ring zone, or of a cylindrical core. When the breccia core became partly displaced with intrusive rock, as in the Koehler and other large pipes, further external fracturing ensued as a result of upthrusting by the intrusive body. Some pipes extended upward probably to the surface and doubtless resulted in eruptions of latite, rhyolite, bouldery tuffs, and pulverized rock material. Some compound forms, such as the Koehler pipe or the twin pipes, suggest that the process may have been repeated when the first vent became sealed by consolidation of igneous rock and the conducting capacity of the channel thereby lost.

The possibility that ore bodies can form in breccia and porphyry pipes that have only feeble surface expression is an important aspect of the mineralization of pipes in the district. An example is afforded by the Colorada pipe at Cananea,[20] in which the ore body lay 500 to 800 feet below the surface, whereas, except for slight alteration, a weak crescentic zone of quartz veinlets, and the outcrops of porphyry, neither the ore nor the breccia pipe had conspicuous surface expression.

LOCALIZATION AND ORIGIN OF THE RED MOUNTAIN ORE DEPOSITS

General features

The exposed volcanic pipes and their associated ore deposits are confined mainly to the belt of altered and fractured rocks in the ring-fault belt of the caldera. Small plugs of quartz latite porphyry lie short distances outside the fault belt. Most ore deposits of the fault belt are closely associated with the pipes; some in them and others around

---

[20] Perry, V. D., Applied geology at Cananea, Sonora: Ore deposits of the Western States (Lindgren volume): Amer. Inst. Min. & Met. Eng., pp. 701-709, 1933. Kelly, V. C., Paragenesis of the Colorada copper sulphides, Cananea, Mexico: Economic Geology, vol. 30, p. 665, 1935.