Lake vein into the Royal Tiger lode—that is, it was formed in continuous bodies of rock that were initially fractured under shearing stress during premineral movements. Continuation of movements along the fault zone seems to have caused much modification of the original forms of these fractures and resulted in very complex fissure systems. Ransome[31] in his description of the North Star characterized the lode as follows:

"The lode on the North Star property is a strong stringer lead, consisting of a zone of country rock traversed irregularly by ore-bearing stringers. At the croppings, near the summit of Little Giant Mountain, this zone is about 100 feet wide. The vein as a whole has no walls, and the stringers are usually not accompanied by gouge. The country rock is that found in the Silver Lake Basin and belongs to the Silverton series. The hard massive sheets of andesite are found to be less favorable for the deposition of ore than the softer breccias. The character of the lode makes it very difficult to work. Ore-bearing stringers may be encountered anywhere within the zone of fissured country rock, and frequent crosscutting is a necessity."

The ridge extending south from Little Giant Mountain on the footwall side of the Shenandoah-Dives vein was found to be traversed by numerous fissures, much in the manner of the Silver Lake footwall, and some of the larger fissures are shown on plate I. Small diverging fractures in the footwall are noticeable about 2,000 feet northwest of Little Giant Mountain and become more prominent at a position nearer the top of the peak. Most of the fissures extending into the footwall are small and, except close to the main lode, are characterized at the surface by comparatively weak and low-grade mineralization. Although they were probably produced by stress conditions similar to those in the Silver Lake footwall, the properties of the rocks either did not favor their development into wide fissures, or for some other reason the forces of fissuring were concentrated along the main fault through Dives Basin. The main fault or fissure zone extends southeastward from Little Giant Mountain across Dives Basin through the Shenandoah, Mountaineer, and Lookout claims into Mountaineer Gulch, where the final feathering of the fault system begins, a distance of 6,000 to 8,000 feet from the crossing of the Arabian Boy dike on Little Giant Mountain; so that

[31]Ransome, F. L., op. cit. (Bull. 182), p. 164.

perhaps much of the energy was expended along the main fault zone rather than in fracturing the more distant parts of its walls. The final feathering out of the Silver Lake fissuring began only about 4,000 feet southeast of the Arabian Boy dike, but its footwall fractures are much more strongly developed than those of the Shenandoah-Dives system.

Examination of a small part of the workings beneath the Dives claim in the center of Dives Basin showed that the lode consists here of early quartz-sulphide veins with some barite, occurring in overlapping or parallel streaks. At several accessible places the ore fills fissures that were formed in the rocks without much or any production of gouge. These earlier veins are succeeded, however, by a vein of calcite and fluorite, which crosses them in a weaving course from one wall of the lode to the other. In addition several late branching fissures that are characterized by gougy filling also follow or intersect the earlier veins, but at this position they were confined chiefly within the hanging wall. Some of these gouge-filled fissures show late striations on the walls that pitch 5°-25° NW. in opposite direction to most of the movements in the extreme northwestern part of the Shenandoah-Dives vein system (Mayflower, Slide, etc.). They are perhaps chiefly post-ore faults and seem to indicate some reversal of earlier movements of the walls. Although there may be some intermineralization gouges, such as occur in the northern part of the vein system, they are not as conspicuous. It may perhaps be concluded from these relations that toward the southeast those hanging-wall movements that occurred during periods of relaxation become less intense and less of a factor in localizing ore shoots. If this is a correct conclusion, the ore channels, at least in the shallower formations, where the fissured zone is wide, would be characterized by more pronounced vertical dimensions and steeper pitch of their axes. The workings are not sufficiently deep, however, to indicate the general pitch of ore channels at this place. (Plate V, B.)

Considerable evidence provided by surface exposures, by underground maps, and by descriptions of the mines permits consideration of the mechanical principles that controlled the

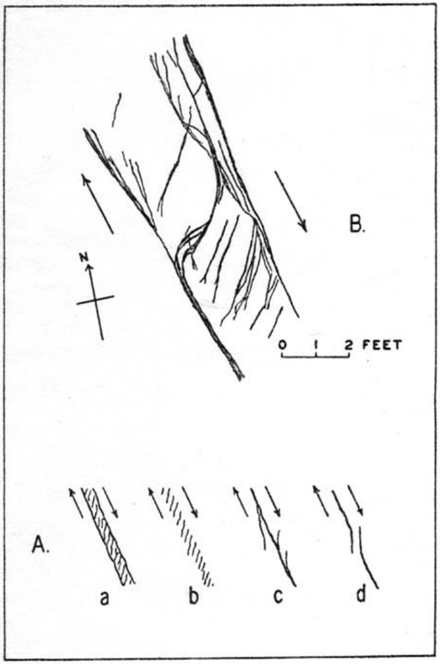

Figure 3. A. Types of surface cracks associated with the horizontal fault slip which caused the California earthquake of April 18, 1906. Arrows show direction of movement of underlying crust blocks. From G. K. Gilbert, Prof. Paper 153, p. 13. B. Characteristic cross-fracturing between shear planes observed in Dives Basin.

Both illustrations are plans.

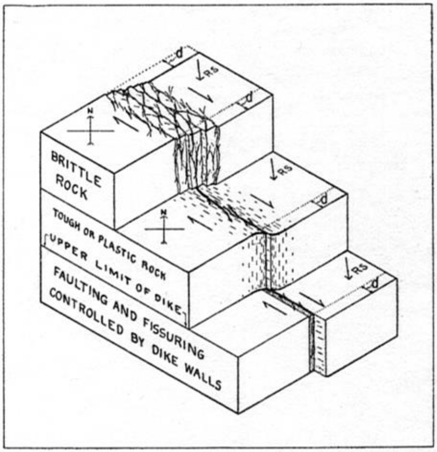

Figure 4. Diagrammatic illustration of change of character of fissuring under different geologic settings. RS, regional stress; d, relative displacement of walls in horizontal direction.

fracture systems along these zones of shears. Two extreme types of ore bodies are clearly represented in this area. The simpler type occupies a single fissure or perhaps several fissures that are close together and generally parallel to the direction of the principal shear plane. The more complex type occupies a zone of fissuring that may be 100 feet wide, as at the North Star, and the extreme hanging and footwall fissures are essentially parallel to the principal shear plane, but the fissures between them may be in part parallel and in part diagonal to this plane. It may be assumed from evidence already presented that this shearing began with nearly horizontal shifting of the walls, controlled by movements in depth either along dike walls or some other comparatively simple fracture surface. Under this condition the nature of the fissures produced in the shallower formations within reach of observation would be controlled largely by the physical properties of the different formations subjected to shearing stress.

These phenomena may be compared with the surface cracks produced in the mantle of earth by the horizontal fault slip that caused the California earthquake of April 18, 1906.[32] The movement that produced this earthquake was essentially horizontal along a fault plane trending northwest, and the visible fissuring occurred in the surface mantle of earth overlying the shifting crustal blocks. These surface cracks are illustrated in figure 3, A, copied from Gilbert.[33] The relative movements of the underlying crustal blocks are indicated by the arrows. It will be noted from plate I and figure 3, B, that very similar types of fracturing are found in the volcanic rocks in the vicinity of Dives Basin, and that movements of the crustal blocks relative to the direction of diagonal fissuring are the same. Movements along the diagonal fractures can rarely be determined where these are small or along veins where alteration and later faulting may have obscured or changed the original relations, but on the north side of Dives Basin, about 1,200 feet northeast of the tunnel to the Dives

[32]Gilbert, G. K., Studies of Basin-Range structure: U. S. Geol. Survey Prof. Paper 153, pp. 12, 13, fig. 2, 1928. Reid, H. F., Report of the (California) State Earthquake Investigation Commission: Carnegie Inst. Washington Pub. 87, 1910.

[33]Gilbert, G. K., op. cit., p. 13.

and Shenandoah mines, there is an excellent large-scale representation of the same phenomena. The Arabian Boy dike crosses in turn several fissures striking N. 5°-10° W. and a larger fault fissure striking N. 40° W. The displacement of the dike by the N. 40° W. fissure shows that the northeast wall moved 150 feet or more to the southeast relative to the footwall, but on one of the diagonal north-south fissures the dike has been displaced about 10 or 12 feet toward the north in the east wall of the fissure. On the other two crossings talus obscured the actual displacement, although it must have likewise been small. This displacement is opposite in direction to that on the main fault and possibly but not certainly indicates that blocks bounded by the diagonal fissures rotated slightly in a clockwise direction. The Arrastre dike was similarly displaced where it was crossed by the Iowa and East Iowa veins near Silver Lake (fig. 2 and pl. I). The conditions of stress causing fissuring along zones of shearing are like those in the footwall of the Silver Lake fault, except that the body of rock between the parallel shears is comparatively narrow. As shown by figure 3, B, some of these diagonal cracks, probably produced by combined tensional and shearing stresses, are deflected as they approach the shear planes and join them at an acute angle, much as the footwall veins join the Silver Lake.

The country rocks exposed at the surface in Dives Basin consist chiefly of flows and interbedded breccia beds of the Burns latite, and near the top of Little Giant Mountain the pyroxene andesite forms one wall of the North Star fissure zone. The greatest range in physical properties of the different rocks is that between the massive facies of the Burns flows and the breccia beds or the fluidal facies. In the quotation given above Ransome stated that the hard massive sheets of "andesite" were found to be less favorable for the deposition of ore than the softer breccias. Ransome used the term "andesite" for all the massive flows and breccias of Arrastre Basin, which since have been classified as latites by Cross. Although no reasons why the massive facies of the flows were considered less favorable were stated, the nature of the fissuring observed at the surface in these massive beds suggests that they tended to become fractured more intimately by diagonal sets of fracture planes, and the open spaces were consequently distributed through a great width of lode. Under the conditions at the Silver Lake mines the diagonal fractures on the footwall side were, on the other hand, most favorable, and the ore was confined to a few large fissures.

Why diagonal fissuring under certain conditions produces favorable lodes and under other conditions less favorable lodes is apparently dependent on physical laws governing the spacing of fissures. Becker[34] developed on a purely mathematical and physical basis a partial theory of the spacing of fissures, in which he showed that under ideal conditions the division of bodies by sets of fissures results in blocks whose faces are parallelograms. The ratio of the long and short sides of these faces and the inclination of the planes of fissuring to each other and to the faces of the slabs of rock being deformed are dependent on the physical properties of the material and the inclination of the applied pressure. The fissuring planes to which Becker had reference are those of maximum shearing stress resulting from compression and it might be supposed that the fractures which have been described in this paper as tension fractures would scarcely show such regularity. In the description of the Silver Lake fissuring it was shown, however, that the so-called tension fractures are in reality the result of combined shearing and tensional stresses; therefore they might be expected to follow certain rough rules of spacing. It is apparent also from inspection of these fissures in the field that some law of spacing was actually operative. Where the principal planes of movement were closely spaced the diagonal fissuring is likewise closely spaced, and where the planes of movement were widely spaced, as near Silver Lake, the diagonal fissures are widely spaced and correspondingly increased in size.

In applying this generalization to the conditions in Dives Basin it is necessary also to consider the reactions of the dif-

[34]Becker, G. F., Finite homogeneous strain, flow and rupture of rocks: Geol. Soc. America Bull. vol. 4, pp. 57-68, 1893.

ferent rocks, because from observation it is apparent that some of them have less tendency to become divided by sets of diagonal fissures. Becker's theory also accords with such facts, as he stated:[35]

"The results derivable from this theory of division certainly accord with some well-known facts. Thus, if a tough mass is acted upon by a shearing tool, it is a matter of daily experience that the mass undergoes a single cut. For this case viscosity comes into play, and by the theory only one set of fissures will be developed, which means that only one fissure will intersect the mass. Again, if one attempts to cut a brittle substance like glass with a shearing engine, the mass, according to experience, shatters instead of simply dividing. In theory, as in practice, only masses capable of considerable deformation under the system of external stresses can be divided by a single cut."

In Dives Basin the tough rocks, represented by the fluidal facies of the Burns flows, and the more plastic rocks, represented by certain of the breccia beds interbedded with these flows, were those most capable of distributed deformation or strain under shearing stress. The brittle or massive rocks, represented by the massive facies of the Burns flows and by the pyroxene andesites, were, on the other hand, incapable of deforming in this manner and were consequently shattered, much as glass is shattered by a shearing engine. The basal tuff-breccia of the Burns formation, which appears to be somewhat intermediate in its physical properties, lies beneath these rocks in depth and is not exposed, so that its actual reaction to these shearing stresses could not be observed.

On the east side of Arrastre Basin layers of the fluidal facies of the Burns flows commonly rest upon the basal tuff-breccia and are in turn overlain by thin layers of the massive latite such as rims the outlet of Silver Lake. Above them there is a considerable thickness of the fluidal facies and breccia beds, with the massive beds becoming prominent again only nearer to the top of Little Giant Mountain. The arrangement of the rocks, however (pp. 148-150), is very irregular and varies greatly from place to place. For this reason it was found impracticable to map these layers throughout the district, as would be desirable. In Dives Basin, across the ridge, the general arrangement of the rocks is in alternating layers of brittle and more easily deformable rocks. The floor of Dives

[35]Becker, G. F., op. cit., p. 60.

Basin lies upon a series of massive flows and thinner layers of less massive rocks, which results in the cliffy steplike entrance to the basin. The difference in reaction of these layers to the fissuring stresses probably becomes more pronounced at higher altitude because of the preponderance of softer rocks in the middle part of the section, between the floor of the basin and the crest of Little Giant Mountain.

Applying the empiric and theoretic principles to the fracturing of these layers gives the conditions diagramatically represented by figure 4, which shows the change in character of a rupture passing from one kind of rock to another. The change would not of course be as abrupt as indicated, and in constructing the section the movement is assumed to have been solely horizontal and only slightly more than sufficient to develop primary types of rupturing in all the rocks. The actual displacements of the walls may have involved vertical as well as horizontal components during initial rupturing, and furthermore the initial rupturing would not occur simultaneously in all the different beds. According to theory the more brittle beds would rupture first, while the other rocks were still undergoing elastic or plastic deformation.

It is known that movement along the shear zone from the North Star to and beyond the Dives was greatly in excess of the amount that could have been caused by initial rupturing at all horizons. These excess (or supplementary) displacements involved both horizontal shifting and down-faulting of the hanging wall and resulted at the North Star in further fracturing and rotation of the shattered blocks of brittle latite. Where the walls of the principal planes of movement were close together this action would finally reduce the blocks between the walls to a rubble, such as was found in parts of the Royal Tiger mine. Also at places along the Shenandoah-Dives (Mayflower) dike similar rubbles were produced where the shearing planes were confined within or near the dike walls. This supplementary movement along such shear planes, even where no dike is present, is similar in its action to movements along dike walls, as the action is controlled in part by preexisting surfaces of rupture. Its effect upon openings where the primary rupturing was of a simple character would be like that already described and would be controlled by changes in strike and dip of the initial fracture plane. Where the primary rupturing was complex, as at the North Star, its effect would be unpredictable but would probably result in further rotation and confused fracturing of the blocks.

The most complex vein structure, found on the higher slopes of Little Giant Mountain, accords with such an interpretation. Similar complex fissuring might be found at greater depths, where there are considerable thicknesses of the more brittle rocks. However, fissures of simple pattern are found in the lower levels of the Dives mine, extending northwest beneath the slopes of the peak, and it appears from the mine maps that along these lower levels the ore-bearing veins largely occupied fissures parallel to the main shear zone, but that at places these fissures tail out and are overlapped en echelon by other fissures that likewise turn and parallel the main shear. This simplification of the fissure system may indicate either that the rocks at this depth are not brittle or that the dike is present along the vein fissure or that the dike is not far beneath these workings. The principle of this type of rupturing is illustrated in figure 3, A (C and D). These dominant ruptures are, however, connected by subordinate fissures that have resulted from minor movements supplementary to the movements that caused the primary rupturing.

As this excess supplementary movement along the main fault evidently became less intense toward the southeast, because of gradual dissipation of the fissuring energy along diverging fractures, the ore bodies along the shear zone should become more dependent on the nature of primary rupturing, and owing to the feathering of the fissure systems they would very likely become individually smaller. Only a few of the diverging fissure systems away from the main shear appear to have been opened sufficiently to enclose bodies of ore, but possibly the ore shoot on the Mountaineer claim of the Highland Mary Mining Co. represents such a fracture plane diverging toward the west from the main line of shear. As no detailed work was done on this area this suggestion cannot be supported by evidence. However, as the fissuring energy along the shear zone became weaker and its divergence more pronounced, it is to be expected that diverging fracture planes, like those of the Silver Lake footwall system, would be opened to greater width than those paralleling the main shear.

Beneath Dives Basin at depths corresponding to the Eureka rhyolite the nature of the fissuring is evidently dependent on the presence or absence of the dike beneath the basin, and, if the dike is present, on the depth at which it occurs. If the dike fails to extend beneath the basin or extends at so great a depth that it fails to cut the Eureka rhyolite, the fissuring in the rhyolite is probably tighter and less favorable than that already found by the deep workings from Arrastre Gulch. The physical properties of the rhyolites and of the breccias interbedded with them suggest that the zone of shearing would be comparatively simple rather than complex. Supplementary movements would be more likely than initial rupturing to produce large openings, and hence openings along the main shear zone might be expected to become gradually smaller toward the southeast.

If, however, the dike extends beneath the basin and cuts the Eureka rhyolite, the greater part of the shearing movement would be concentrated along the dike walls, with the result that less of the fissuring energy would be expended in producing distributive deformation in the rhyolites and breccias. Under these conditions openings of favorable size might be expected to continue much farther southeast than under the conditions mentioned above.

Speculation upon fracturing likely to occur within the pre-Cambrian and other basement rocks is scarcely warranted, as little is known about the reactions of these rocks to fissuring forces. It is evident, however, that they are sufficiently rigid and tough to transmit the fissuring energies much greater distances than the more easily deformable rhyolites and breccias. Ransome[36] has called attention to the fact that fissuring in the pre-Cambrian rocks tends to be simpler and narrower than in the shallower volcanic formations, but this

[36]Ransome, F. L., op. cit. (Bull. 182), pp. 53-55.

comparison is evidently made with the more favorable kinds of volcanic rocks.

Vein systems of Little Giant Basin

The vein systems of Little Giant Basin will not be described specifically except to point out that the general nature of the fissuring is similar to that in Dives Basin and near Silver Lake. The fissure zone extending about S. 45° E. from the vicinity of Gold Lake is the result of shearing forces like those that produced the southeasterly extensions of the Shenandoah-Dives and Silver Lake systems. The diagonal fissuring represented by fissures and veins striking from north-south to N. 15° W. was evidently produced by a combination of shearing and tensional stresses such as produced the footwall fissures of the Shenandoah-Dives and Silver Lake faults. A few of these such as the Potomac and North Star Extension, have been prospected, and some ore has been mined from shallow workings. It is probable that these ore shoots and channels would be narrower in the underlying Eureka rhyolite. Other veins lying in the hanging wall of the Black Prince and Gold Lake veins such as the Big Giant and Peerless, may perhaps fill sympathetic fractures developed at the same time as the main fault, which they essentially parallel. There is a noticeable tendency for the fissuring in Little Giant Basin to be deflected first by one and then by the other of the two principal planes of fracturing, and some of the larger shoots of ore are found where this deflection occurred. This relation is evidently illustrated by the ore shoot on the Potomac claim. At other places the shoots appear to be less dependent on such deflections, but the shoot on the Big Giant is near the crossing of two principal trends of fracturing, though chiefly confined to the N. 45° W. fissure. (See pl. I.)

Summary and Possible Application of Different Geologic Methods

The application of geologic principles in the search for and development of ore shoots and ore channels has been illustrated by examples given in the preceding text. Methods to be used during mining development of an ore shoot will of course depend on local conditions. If a vein is comparatively simple in structure, exacting geologic study and control of headings and stopes may seem and probably are at times unnecessary for efficient mining; yet careful study of the habits of fracturing will furnish knowledge that may later assist in search for or development of other shoots. Such methods are constantly applied by miners and prospectors in their work, but the results are rarely recorded in permanent form. The fracture systems of Arrastre Basin show that the same comparatively simple principles of fracturing have controlled different forms of ore localization. Although the large productive footwall veins of the Silver Lake system may seem a far cry from the smaller-scale diagonal fractures characteristic of other types of lodes, the differences lie chiefly in the magnitude of the fracture systems. Changes from one kind of lode to another are commonly gradual, and the study of details as mining progresses may aid in adapting the methods of mining to an increasing complexity of the lode structure. Such a simple procedure as exploring both walls of a dike that has localized fissuring may be easily overlooked, owing to local alteration that may obscure evidence of the dike's existence. The possible use of diamond drilling to determine the width and general nature of fissure zones, the thickness and depth of different geologic formations, and the position of the dikes is self-evident.

Application of geophysical methods in ore finding or in supplementing geologic data would seem to rest chiefly in the possibilities of determining the physical properties of different geologic formations, or in measuring the depths to different horizons. Certain elastic properties of the rocks can be determined by the transmission of elastic waves through the formations, as is commonly done by seismic methods. However, the strength and reactions of the different formations to stresses exceeding the elastic limits of the rocks can be determined only by field observations or by laboratory studies of their failure under controlled conditions. Such laboratory studies might well be used in conjunction with field observations on actual rupturing and would perhaps lead to a better foundation upon which to base speculations on the type of fracturing and width of openings in depth. As but little research work has been done on this subject, the possibility of success or of very definite results is conjectural. Measurement of the depths to certain geologic horizons by recording the reflection of artificially producted seismic waves is receiving rapid development in oil-field exploration. Although as yet such methods are perhaps impracticable in extremely rugged mountains, they would be applicable under favorable conditions.

The mineralogy and change of mineralization in depth, which have been mentioned only briefly in this paper, are to be given further study. There is evidence, however, that such studies may lead to more definite data on the distribution of different facies of mineralization and their zoning, and may therefore be helpful in predicting the value of ore in unexplored places.