Direction of Movement of Jasperoidizing Solution

By T. S. LOVERING

CONTRIBUTIONS TO ECONOMIC GEOLOGY

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Petrofabric analysis of asymmetric zonal overgrowths on quartz crystals in jasperoid shows direction mineralizing solutions moved—information of both theoretical and practical value

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DIRECTION OF MOVEMENT OF JASPEROIDIZING SOLUTION

By T. S. Lovering

ABSTRACT

Experimental work has shown that crystals nourished by moving solutions commonly grow asymmetrically with overgrowths facing upstream, toward the stoss direction. This feature suggests that hydrothermal jasperoids show zonation which indicates the direction of movement of the hydrothermal solutions. Petrographic examination of jasperoids from the Gilman district, Colorado, and the East Tintic district, Utah, showed that asymmetric zonal overgrowth perpendicular to the *c*-axis of quartz is common in the jasperoidized limestones and dolomites examined. A special type of petrofabric analysis was devised to determine the direction of asymmetric zonal growth perpendicular to the *c*-axes. Directions of overgrowth were plotted as unidirectional vectors on a lower hemisphere equal-area projection. Contoured concentrations of overgrowth vectors similar to the usual contoured petrofabric diagrams were made and compared with the significant structural conditions in the two areas sampled. The vectors were also analyzed mathematically to obtain resultants for all vectors and for selected groups of vectors. The resultant for the Gilman district, which has a relatively simple geologic setting, and the resultant for the Tintic Standard mine in the East Tintic district, which has a very complex structural setting, agree in indicating a statistically significant concentration of vectors pointing in the direction of the most probable source of hydrothermal solutions. Additional vector concentrations in the Gilman district suggest that the jasperoidizing solution deposited jasperoids where convective circulation took place in cells at right angles to the main direction of updip motion of the hydrothermal solutions. In the East Tintic district the resultant of all the vectors points downward from the jasperoid area directly toward the main ore body in the Tintic Standard mine, and thus could have been used as a guide to exploration. The jasperoid at the Tintic Standard mine is closely associated with ore, whereas that in Gilman has a much more tenuous association with the actual ore. The technique developed seems worthy of additional investigation both as an exploration tool and because its use can throw additional light on the genesis of jasperoid bodies themselves.

INTRODUCTION

The experimental work by Newhouse (1938, 1941) showed that crystals nourished by moving solutions in unobstructed channels grew most rapidly on the upstream, or stoss, faces. He noted that crystals close to and on the lee side of other obstructing crystals might receive more nourishment on the sides or on the downstream faces, and thus grow more rapidly on the lee sides. Asymmetric crystal growth is shown best by zonal structure that makes visible the asymmetric overgrowth; it also may be recorded in abnormal elongation parallel to certain crystallographic directions, by groups of crystals piled in oriented stacks, or by "hollow crystals" whose lee sides were undernourished.

Experimental work by the author, using copper sulfate solution, checked the results of Newhouse and added little that was new; it was found, however, that where crystal growth was rapid the zonal overgrowth was far less unidirectional and the crystals much smaller than where the growth was slower. The speed of the current was also an important factor; as the speed dropped below about 1 cm per minute the zonal overgrowths of chalcanthite tended to become more and more random. At higher current rates the overgrowths were more and more consistently directed upstream except for those on crystals in the lee of obstructions. In a current moving 5 cm per minute almost all the crystals showed overgrowth on the stoss sides. The degree of preferred orientation reflects the relative amount of nourishment received through physical transport of the solute as contrasted with that provided by diffusion; the speed of current required to produce a marked preferred orientation of stoss-side overgrowths depends on the concentration and kind of solute that was precipitating. The behavior of copper sulfate illustrates only the tendencies of crystal growth in an easily crystallized compound; the rates of movement of solution and degree of supersaturation of a solution depositing quartz would be entirely different, but crystal growth nevertheless would similarly reflect relative rates and precipitation gradients.

Petrographic study of jasperoids from the Gilman district, Colorado, and the East Tintic district, Utah, shows that zonal overgrowth perpendicular to the *c*-axis of quartz is common in the jasperoidized limestones examined (fig. 1) and that statistically significant concentrations of overgrowth directions can be found by detailed petrofabric study.

After the author had developed theory and petrofabric technique and applied them to the study of the Tintic Standard mine jasperoids, the petrofabrics were rechecked independently by Dr. Bronson Stringham when he was the author's assistant in 1945, and later the work on the Cave and Coolidge jasperoid was carried on by graduate students at the University of Michigan under the author's direct supervision. The data presented later in this paper thus are believed to be free from operator bias.

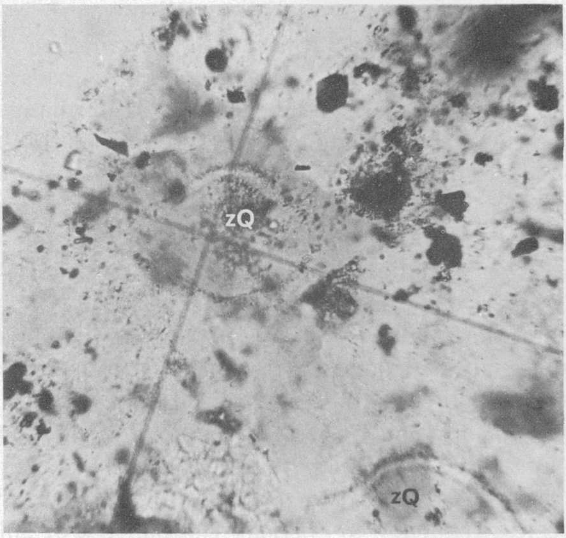


FIGURE 1.—Jasperoid from J stope, 900 level. Tintic Standard mine, showing asymmetrically zoned quartz crystals, zQ. Crossed nicols. × 285.

THEORETICAL CONSIDERATIONS

The conversion of large masses of rock to jasperoid probably involved the pervasive movement of substantial quantities of solution, but the small size of the openings available for the fluids suggests that the flow would be relatively slow even though a strong pressure differential existed. Solutions moving through the complex of minute interconnecting openings of the host rock might have an overall movement in a definite direction but still follow tortuous channels in detail. The pattern and the dimensions of the open spaces would determine the size of the block required to give a representative sample of the overall direction of flow in a given spot. In a thick bed made up of 1-mm spheres, the average direction of flow in a 2-cm cube might be expected to approximate closely that in the aggregate for several meters in any direction, but in an aggregate made up of 1-m spheres, the average direction of flow in a random 2-cm cube would have little meaning. To get the same relative sampling would require a cube 2,000 cm on a side.

The characteristics of replaceable rocks probably differ greatly from district to district, but some acceptable generalizations can be made. The more widely spaced the network of openings traversed by moving solutions, the less the chance of consistent directions of flow in small volumes of the mass chosen at random. Whatever their dimensions, irregular channels would not favor as high a degree of preferred orientation of zonal overgrowths as would straight parallel channels. If the solution movement were sufficiently slow or changed direction many times, a completely random orientation might result regardless of the space pattern of the channels.

Even under favorable conditions, overgrowths in many directions inevitablv would be present in jasperoidized rocks, but the concentration of overgrowth directions should be significantly greater on the stoss sides of the crystals than on other sides.

If the orientation of the *c*-axes of quartz seed crystals were completely random, slight deflections from the general current direction could nourish opposite sides of crystals with their *c*-axes nearly parallel to the direction of flow; such crystals would show the least agreement in *a*-axis overgrowth. Because quartz crystals grow most rapidly along the *c*-axis, the crystals whose *c*-axes are nearly parallel to the current have less tendency to obstruct the passage of solutions as a result of crystal growth than do the crystals disposed at right angles to the current. Thus the largest and best zoned crystals in the jasperoid might be those that show the smallest degree of asymmetric zonation. Conversely, the crystals whose *c*-axes lie perpendicular to the direction of solution movement would be expected to exhibit the most conspicuous asymmetric zonal overgrowth and the greatest degree of preferred orientation of *a*-axis elongation.

A statistical picture of the orientation of *c*-axes and *a*-axis elongations should be analyzed with these considerations constantly in mind. Porous jasperoids that formed from relatively fast moving solutions should provide a minimum of conflicting data; dense jasperoids formed by diffusion through nearly stagnant solutions might have completely random orientations of *c*-axes and *a*-axis overgrowth. Furthermore, investigations in regions of geothermal power potential show that in hyperthermal areas convection currents are commonly present and give rise to oppositely directed currents, which change position from time to time. Convection currents probably existed also in jasperoidizing solutions where thermal waters mingled with cooler ground waters. Here some opposing directions of overgrowth would be expected. Evaluation of a petrofabric analysis of such material requires that the overgrowths having a downward component be separated from those having an upward component, and that each group be interpreted with reference to the local geology. A plot of the directional vectors representing crystal overgrowths, together with contours showing their relative concentrations, is essential to a meaningful interpretation.

PETROGRAPHIC TECHNIQUE

With a Federov universal stage the direction in space of the *c*-axis of a quartz grain can be determined regardless of the grain's orientation, but limitations are imposed on the usable orientations of grains where the direction of zonal overgrowth and elongation parallel or approximately parallel to the *a*-axes is to be determined; these elements can be observed and measured accurately only when the *c*-axis of the crystal can be moved to a vertical position. The horizontal axes of the universal stage are limited to a rotation of 55° in either direction, and only those grains whose *c*-axis makes an angle of more than 35° with the plane of the thin section can be turned into position for measurement of asymmetric overgrowths parallel to the *a*-axes. It thus is necessary to study three mutually perpendicular sections of the jasperoid to include all possible orientations of *a*-axis overgrowth. If the three slides are a horizontal section, an east-west vertical section, and a north-south vertical section, the angles turned for complete coverage of all orientations must include the solid sections of a sphere included between the intersection of mutually perpendicular planes making angles of 45° with the x, y, and z axes of the sphere. In the horizontal section the angles sought would range from 45° in east-west and north-south directions through 50° in N. 35° W., N. 55° W., N. 35° E., and N. 55° E. directions to 55° in northeast and northwest directions. In the vertical sections corresponding angles would range from 45° for the horizontal and vertical directions to 55° for the intermediate 45° directions (p. F9; fig. 2).

The specimens of jasperoid chosen for such a study should be porous rather than dense, and the grain size of the quartz crystals should average not less than 75μ (0.075 mm). The orientation of the specimen must be noted in the field so that each of the three mutually perpendicular thin sections made from it can be properly marked with its orientation. Commonly, one section is made parallel to the bedding, if that useful reference plane is known, but the plotting of results is somewhat simpler if one section is cut parallel to the horizontal plane, another to the north-south vertical plane, and a third to the east-west vertical plane.

The technique of measuring the orientation of crystallographic directions in a thin section by using a universal stage was well explained by Ingerson (Knopf and Ingerson, 1938) and more recently by Turner and Weiss (1963). As some readers may not have access to published information, the method for obtaining the orientation of the *c-axis* of quartz is summarized below, together with an extension of the method to include the problem of asymmetric crystal overgrowth.

c-AXES OF QUARTZ

The following discussion assumes the measurements are made with a Federov universal stage and that the results are plotted in lower hemisphere projection on a Schmidt equal-area net. A stereographic net is almost as satisfactory.

The Federov universal stage has four axes of rotation—two vertical and two horizontal when all are in the 0° positions. The vertical axis of the inner ring is commonly designated the A_1, that of the outer ring the A_3, and that of the microscope stage on which the universal stage is mounted the A_5. The horizontal axis of the intermediate ring is the A_2 and the horizontal axis of the outer ring is the A_4.

A_3 need not be used in the jasperoid investigation and can be set and clamped with A_2 in the north-south position. Because of the limitations of movement of the universal stage two methods are used to determine the position of the *c*-axis lying at angles above and below 45°. If the *c*-axis makes an angle of less than 45° with the plane of the thin section the axis is turned to the horizontal and made parallel to A_4; if the *c*-axis is inclined at a steeper angle the axis is turned to a vertical position. It is usually difficult to judge whether the *c*-axis lies at an angle above or below 45°, and many grains may have to be tried by first one method and then the other.

If the *c*-axis is not steep, the measurement is made as follows: A_2 and A_4 are set at 0° and A_5 is clamped so that A_4 is in an east-west position, A_1 is then rotated to extinction and A_2 is turned; if extinction is not maintained the *c*-axis is in a north-south position and A_1 must be turned 90° at which position extinction will be maintained during rotation of A_2. The *c*-axis is now in an east-west position but not necessarily horizontal. A_2 is set at 0° and A_4 is rotated; if extinction is maintained the *c*-axis is horizontal. If extinction is not maintained, A_4 is tipped about 35° and A_2 is rotated until extinction is achieved. The *c*-axis is now horizontal and parallel to A_4 and the grain remains dark when A_4 is rotated.

A_1 and A_2 are read and recorded and the data plotted on transparent paper superimposed but free to turn on the Schmidt net. A mark is made on the paper at 0° and the sheet is then turned until this mark is at the A_1 reading. The A_2 reading is then plotted by placing a mark over the east-west line of the Schmidt net at the point corresponding to the number of degrees from the horizontal indicated by A_2, measured from the edge of the net on the same side that the A_2 reading was taken. When the oversheet is turned so that the zero mark is again at 0°, the point plotted indicates where the *c*-axis of the observed grain will fall when all axes of the stage are turned back to 0° and the section is horizontal.

If the *c*-axis is steep, the procedure differs somewhat. A_2 and A_4 are set at 0° and A_5 is clamped with A_4 in an east-west position. A_1

is turned until the grain is at extinction and A_2 is then rotated. If the grain remains at extinction the *c*-axis is in the desired east-west position, but if the extinction is relieved the *c*-axis is north-south and A_1 must be turned 90°. After the *c*-axis is placed in the east-west direction, A_5 is unclamped and the microscope stage is turned to 45° to obtain maximum birefringence and A_2 is then rotated until the grain becomes extinct. The *c*-axis is now vertical and A_1 and A_2 are read and recorded. These data are plotted by turning the plotting paper to the reading of A_1 as before and placing the point on the equator, but this time the degrees must be counted from the center of the net toward the opposite side from which the A_2 reading was made.

a-AXIS ELONGATION AND ZONAL OVERGROWTH

As stated on page F5, the directions of *a*-axis elongation and zonal overgrowth can be observed and measured only when the *c*-axis of the grain has been turned vertical. In this position the plane of the *a*-axis is parallel to the microscope stage, and zonal growth lines and differences in dimension can be most easily seen. For measurement of these elements after the *c-axis* has been made vertical, A_5 is turned until the greatest dimension of the grain is parallel to the east-west cross hair. The upper nicol is then removed and the zoning of the crystal observed. If the zones are wider on the right side, the apparent direction of solution flow indicated is from right to left. The actual direction, however, is from left to right because the microscope reverses the field. An arrow pointing to the right is drawn in the notes to indicate that the solutions feeding that particular grain were probably moving to the right.

Four notations should now be available: A_1 and A_2 which orient the *c*-axes to the vertical, A_5, and an arrow which gives the direction of zonal overgrowth

A_1 and A_2 are then plotted, according to the procedure just described for fixing the position of the *c*-axis when turned to the vertical. With the *c*-axis point over the equator of the net, the plane of the *a*-axes is marked on the net by a north-south great circle (meridian) 90° away from the *c*-axis. The direction of elongation lies in this plane; for plotting this direction, the A_5 reading is noted and without movement of the paper this value is counted off on the circumference of the net from the equator as the zero point, and measured clockwise if A_5 had been turned counterclockwise, and measured counterclockwise if A_5 had been turned clockwise. A straightedge is placed from this point to the center of the net. The point where the straightedge crosses the great circle made by the plane of the *a*-axes represents the direction of *a*-axis elongation. From this point, an arrow is then drawn parallel to the straightedge and pointing either right or left as recorded in the notes. This arrow indicates the direction of solution movement as shown by zonal overgrowth, and points either toward or away from the center of the hemisphere. An arrow pointing toward the center indicates a vector appropriate to rising solutions, and an arrow pointing away indicates a vector for descending solutions. These downward- and upward-directed vectors should be separated ultimately and plotted in separate hemispherical projections.

The data for the vertical sections should ultimately be transposed to the horizontal and a composite of all three sections made for the final step in the study. This transposition to the horizontal requires rotating all points and arrows 90° and tracing these points on the horizontal projection. The rotation is accomplished by turning the oversheet, on which the data from a vertical section are plotted, until the desired axis of rotation is parallel with the north-south line of the net and shifting all point 90° on parallels. Particular care should be given to the arrows when transferring them from the vertical to the horizontal section, for not only should they be properly placed but their direction either upward or downward must be correctly plotted. It should be remembered that although all arrows pointing outward on the horizontal projection are descending directions, similarly pointing arrows on the vertical projections may point either upward or downward; all outward-pointing arrows in the lower half represent descending directions, but in the upper half they are ascending directions.

PROCEDURE AND INTERPRETATION

A preliminary step in the study of a jasperoid is to measure and plot from the horizontal thin section the *c*-axis of 150–300 grains selected at random and without regard for the angle the axis makes with the section. Both methods of *c*-axis determination, as previously outlined, should be employed so that any orientation may be measured. Figures 2 and 3 illustrate how the relative concentration is accented by contouring. The pattern of the contours should determine whether a preferred orientation or a random one is present.

A small circle superimposed on an equal-area net represents a conical angle. The magnitude of this angle can be approximated by measuring its diameter in degrees, according to the degree scale on the equal-area net. The size of the circle may be changed according to the number of axes plotted (Turner and Weiss, 1963, pp. 61–64). A 16° circle enclosing 1 percent of the net is a satisfactory size for bringing out the pattern of concentration when 100 points or more are plotted. The circle is placed above the paper containing the plotted points over a high concentration of them and then moved until all the space in which contiguous or overlapping groups containing the same number is covered; contours are drawn to include these groups, using the center of the circle to limit the distance of the contour from the points at the outside of the group being contoured. Alternatively, the circumference of the circle can be used to give a coarser pattern, and all overlapping circles be joined to form contours. Several areas may show similar concentrations and contours are drawn around them. Decreasing concentrations are then sought in increments of 1 or 2 percent. These areas commonly are adjacent to the larger concentration areas, but some may be in independent positions. A preferred orientation commonly causes a girdle or spot pattern.

The plot of the *c*-axes can be used in selecting grains in the three mutually perpendicular sections to be measured for *a*-axis elongation and zonal overgrowth. If random orientation is apparent no selection is necessary, but if preferred orientation is evident the grains for *a*-axis elongation and zonal overgrowth measurement should be selected so that their *c*-axis pattern approximates that obtained in the general *c*-axis sampling. This selection requires an analysis of the proportion of *c*-axes that lie in the visibility zones of each of the three perpendicular sections to be studied.

Since only those grains inclined more than 35° to the section will now be used, the net containing the plotted *c*-axes is divided into reference segments and used as a guide in the selection of zoned crystals for study (see fig. 2). Thin solid lines are drawn through the center of the net in the same direction as the vertical thin sections. These lines will be termed "section lines." Light dashed lines are then drawn through the center at 45° angles to the section lines. These represent two limits for *c*-axis observation in each vertical thin section. The traces of four intersecting planes (2 north-south and 2 east-west) that dip at 45° are then plotted on the net (fig. 2), and the area that they enclose is shown by heavy solid lines having a slight outward curvature between the 45° light dashed lines; heavy dashed lines are drawn from the circumference of the net to the points along the light dashed lines where the planes intersect on the hemisphere. If for the moment we consider the net as a projection of a complete sphere, the heavy solid lines then divide the sphere into three double and slightly distorted complementary solid cones whose cross sections approach a circle but are rudely tetragonal in outline.

The *a*-axes overgrowth of crystals, the *c*-axes of which plot as points within the central area of figure 2, may be measured in the horizontal thin section; for *c*-axes falling in the outer areas the overgrowth can be measured in the vertical sections represented by the appropriate section line (fig. 2). The section lines together with the periphery of the net divide each "cone" into quadrants. The percentage of points lying within each quadrant is calculated and used as a guide in further sampling. In the final composite of the three sections, the

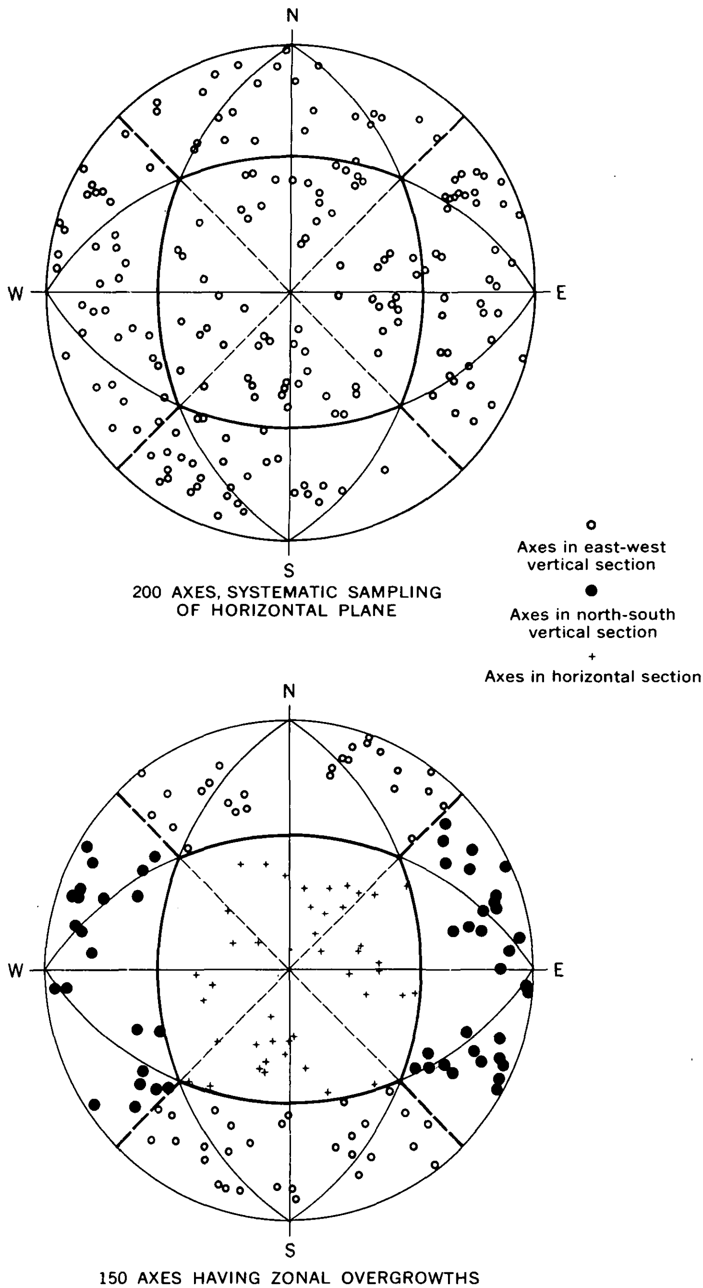


FIGURE 2.—*c*-axes of quartz in samples from the Cave and Coolidge prospect, Gilman, Colo. Schmidt net projection, lower hemisphere, showing two north-south and two east-west planes at 45° to vertical axis. Heavy lines outline the area enclosed by these planes. Light dashed lines represent limits of *c*-axis observation in north-south and east-west vertical planes. Heavy dashed lines lead from circumference of net to points where the 45° planes intersect the hemisphere.

percentages of plotted *c*-axes should agree with the percentages found in the preliminary measurements. Attention therefore must be given to every measurement to make sure that the proper number of *c*-axes fall within the appropriate quadrants. Contours drawn on these points, though showing some divergence from those drawn on the original *c*-axis plot, should have the same general pattern (fig. 3).

Greater accuracy can be achieved by dividing the quadrants into octants for better guidance in the selection of crystals to be measured, but in the author's work division into quadrants was found to be satisfactory.

The completed composite plot of the c-axis elongations and of the zonal overgrowths parallel to the *a*-axes results in three separate hemispherical projections, two of which correspond to the unidirectional vectors and either have dots representing the upward-directed vectors in one plot and downward-directed vectors in another, or show arrows in the net pointing toward or away from the center. The vector concentrations are then contoured in the same way as for the *c*-axes (figs. 4, 7).

The pattern of the contoured vectors must first be studied to ascertain randomness or possible anisotropy; if anisotropic, any localized high concentrations of vectors should be interpreted in relation to geologic factors such as bedding, joints, and fractures. The technique described was applied to analysis of jasperoid samples from two contrasting geologic environments: one, a relatively simple geologic environment—the Cave and Coolidge prospect in the Gilman district, Colorado—and the other, a highly complex structural setting—the Tintic Standard mine in the East Tintic district, Utah.

MATHEMATICAL ANALYSIS OF VECTORS

In addition to the graphic representation of a vector population described and interpreted above, a mathematical statistical analysis of the geological vectors is possible (Fischer, 1955; Steinmetz, 1962; Watson, 1956). The essence of this type of attack is the computation of a vector that represents the most probable angle and direction of the best resultant of the group of vectors plotted. This group can include all the vectors, or the vectors may be considered in various groups as dictated by the logic of the problem or the bias of the operator. For each resultant a "circle of confidence" can be computed, which is a circle that represents the area on the hemisphere where the probability that the true resultant direction falls outside it is less than some specified amount, usually taken as less than 5 percent (95 percent confidence) or less than 10 percent (90 percent confidence). The sines and cosines of both the azimuth and the plunge of the vectors

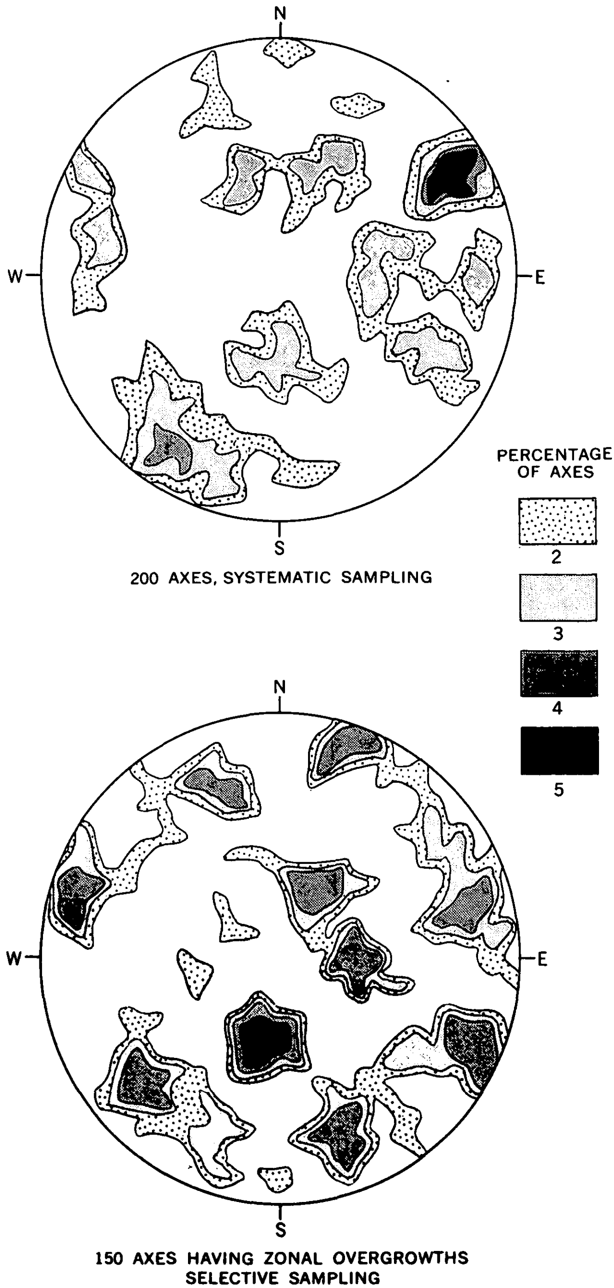


FIGURE 3.—Composite contour diagrams of quartz *c*-axes from Cave and Coolidge prospect plotted on lower hemisphere. Contours show percentage of axes per 1 percent of the area.

are obtained and are then manipulated mathematically so as to give the azimuth and plunge of the resultant of the vectors used.

The formulas used and illustrative data from the Cave and Coolidge prospect are shown on a typical work sheet in table 1.

TABLE 1.—*Calculation of resultant of ascending vectors (in lower hemisphere) within ±15° of bedding plane, Cave and Coolidge prospect*

N=number of samples

A=azimuth of movement vectors

A_r=azimuth of resultant vector

D=inclination of movement vectors

D_r=inclination of resultant vector

$a=\cos D \times \sin A$; $b=\cos D \times \cos A$; $c=\sin D$

$a_r=\cos D_r \times \sin A_r$; $b_r=\cos D_r \times \cos A_r$; $c_r=\sin D_r$

$R=[(\Sigma a)^2+(\Sigma b)^2+(\Sigma c)^2]^{1/2}$

Sample	A (azimuth of dip)	D (inclination of dip)	sin A	cos A	cos D	cos $D\times$ cos A (b)	cos $D\times$ sin A (a)	sin D (c)	Checked [1]
1	343°	07°	−0.2924	+0.9563	0.9925	+0.9491	−0.2902	0.1219	✓
2	352°45′	09°30′	−.1262	+.9920	.9863	+.9784	−.1245	.1650	✓
3	0°	17°	0	+1.0000	.9563	+.9563	0	.2924	✓
4	18°30′	12°30′	+.3173	+.9483	.9763	+.9258	+.3098	.2164	✓
5	19°45′	16°	+.3379	+.9412	.9613	+.9048	+.3248	.2756	✓
6	21°15′	16°	+.3624	+.9320	.9613	+.8959	+.3484	.2756	✓
7	24°30′	23°30′	+.4147	+.9100	.9171	+.8346	+.3803	.3987	✓
8	29°30′	12°	+.4924	+.8703	.9781	+.8513	+.4816	.2079	✓
9	37°45′	21°	+.6122	+.7907	.9336	+.7382	+.5715	.3584	✓
10	49°30′	21°	+.7604	+.6494	.9336	+.6063	+.7099	.3584	✓
11	54°45′	13°	+.8166	+.5771	.9744	+.5623	+.7957	.2250	✓
12	56°	11°	+.8290	+.5592	.9816	+.5489	+.8737	.1908	✓
13	67°45′	11°	+.9255	+.3786	.9816	+.3717	+.9085	.1908	✓
14	73°15′	10°	+.9576	+.2882	.9848	+.2838	+.9430	.1736	✓
15	82°15′	04°	+.9909	+.1348	.9976	+.1345	+.9885	.0698	✓
16	94°	11°	+.9976	−.0698	.9816	−.0685	+.9792	.1908	✓
17	121°30′	02°	+.8526	−.5225	.9994	−.5222	+.8521	.0349	✓
18	125°45′	01°	+.8116	−.5842	.9998	−.5841	+.8114	.0174	✓
19	317°15′	0°	−.6788	+.7343	1.0000	+.7343	−.6788	0	✓
Total			+9.3813	+10.4859	17.9862	+11.2697	+9.1249	3.7634	
Total (squared)			88.0088	109.9541	323.5034	127.0039	83.2638	14.1632	

[1] Check $b^2+c^2+a^2=1.000\pm0.003$.

Direction cosines of resultant: $b_r=+0.7522$; $a_r=+0.6099$; $c_r=+0.2512$.

Resultant of movement vectors:

$N=19$ $R=14.9810$

$c_r=\sin D_r=0.2512$ $\quad \sin A_r=\dfrac{a_r}{\cos D_r}=0.6293$

$D_r=14°33'$ $\quad A_r=39°$

Circle of confidence:

$(N-R)=4.0190$ $\quad \theta$=spherical radius $\quad \cos\theta=c$

$X=\left(\frac{1}{p}\right)^{1/18}-1$ where p is deviation factor, arbitrarily picked as 0.05 or 0.1

$$c=1-\frac{(N-R)\ (X)}{R}$$

for $p=0.1$,

$X=(10)-1=1.1365-1$

$X=0.1365$

$$c=1-\frac{(4.0190)\ (0.1365)}{14.9810}$$

$c=0.9634$ $\quad \theta=15°27'$

If the population of vectors is to be divided into groups that, for one reason or another, seem more significant than the totality, it is apparent that many choices as to grouping are possible. The contoured patterns for the two hemispheres are used as a guide in making such a choice.

The value of using analytical methods to obtain precise figures for azimuths and slopes of resultants of several groups of vectors for solution movements is questionable. The interpretation of the directions of movements becomes progressively less confident as more vector clusters are tested for separate resultants. The resultant for all of the vectors gives the direction and slope with the least subjective bias, but it entirely ignores the geologic setting. It should, however, indicate a general direction of flow within the "circle of confidence" calculated.

CAVE AND COOLIDGE PROSPECT, GILMAN DISTRICT, COLORADO

Five specimens of jasperoid were obtained from the Cave and Coolidge prospect in the Gilman district, Colorado, through the courtesy of Mr. Frank Meloit, General Manager, Empire Zinc Co. at Gilman. The jasperoid is a replacement of hydrothermally dolomitized Leadville Limestone about half a mile northwest of the No. 1 ore body of the Eagle mine at Gilman. The Leadville Limestone throughout this area has a regional northeasterly dip of about 15° with only minor local deviations in strike and dip. Although the rocks in the Cave and Coolidge prospect are inadequately exposed, the structural control of alteration and ore deposition in the Eagle mine, where geologic relations are similar, was well shown on washed walls underground and was carefully studied during the 1930's in the No. 1 ore body and the nearby area by the author and Mr. Ogden Tweto of the U. S. Geological Survey. The sequence of hydrothermal events includes several periods of hydrothermal dolomitization followed by the introduction of jasperoid, and, later, of the manganosiderite and sulfide ores exploited in the mine. Both the altered zones and the ore bodies show a pronounced structural control, chiefly by joints and bedding. The most prominent trends in the No. 1 ore zone are controlled by joints striking N. 70°–75° E., N. 20°–35° E., and N. 60°–70° W., and by minor faults striking N. 55° E. Altered rock and preore solution channels follow the joints, especially the intersections of northeast-trending joints and bedding planes.

Hydrothermal dolomite, jasperoid, and ore are largely confined to the Leadville Limestone, but ore has been found also in older rocks. Mineralized northeasterly faults are common in the Precambrian rocks and in the Paleozoic rocks between the Precambrian and the Mississippian Leadville.

Three thin sections of each of the five jasperoid specimens from the

Cave and Coolidge prospect were studied, and the composite of fifteen sections is shown in figures 2–5. The pattern of the long or c-axes of the quartz shows little anisotropy but instead is fairly random (fig. 3). The pattern of the a-axes, on the contrary, shows a marked anisotropy. The pattern of the upward-pointing vectors in figure 4 corresponding to upward-moving solutions or downward-pointing overgrowths is contoured to show concentrations of 3, 4, or 5 percent within unit areas (16° circles) of the hemisphere; the strike and dip of the beds and some prominent joint systems in the Eagle mine are also plotted on the hemispherical projection. The concentration of upward-directed vectors subparallel to the bedding is as notable as the absence of downward vectors in this part of the companion projection. Such a coincidence is unlikely to be fortuitous and suggests a major hydrothermal current moving updip parallel to the bedding. The greatest concentration of upward vectors in the bedding centers around a vector directed 15° upward at about S. 25° W.

The greatest concentration of upward vectors apart from the bedding is bimodal. The heaviest concentration corresponds approximately to a vector directed upward N. 25° E. at an angle of 75°, the other is directed upward S. 75° E. at about 10°. When these three maxima are considered relative to the joint systems that obviously control the movement of hydrothermal solutions in the nearby Eagle mine, it is apparent that all three could represent solution movement along intersections of joint systems and the bedding plane or along the joint systems themselves.

The downward-directed vectors also have an anisotropic pattern which, however, is less apparent than that of the upward-directed vectors. They too show a trimodal distribution of maxima, the heaviest concentration clustering around an axis directed S. 70° E., downward at 45°; the two other maxima comprise one sloping N. 60° W. downward at 55° and another one directed N. 85° W. downward at 10°. These downward vectors could be controlled by joint systems but not by bedding. The high concentration near the western edge of the hemispheres for both the ascending and descending vectors is of special interest because of the opposite directions indicated for the ascending and descending solutions. This opposition of directions may reflect the mixing of rising and descending solutions. Ascending and descending vectors in the same area could also be explained as asymmetric overgrowths on crystals parallel to the general direction of movement of a silica-saturated solution. Lack of a girdle pattern perpendicular to the general direction of updip solution movement, however, suggests a different explanation, such as periodic changes in direction of a convective circulation that was at right angles to the general updip movement of the hydrothermal solution (fig. 5).

The contoured vector patterns seem best explained by hydrothermal solutions that rose southwesterly along bedding planes, especially along intersections of bedding planes with the northeasterly joint system. Locally and from time to time, however, the solutions apparently moved almost vertically upward along the intersections of northeast and west-northwest joints which dip steeply south; cooler water apparently moved down along the intersection of nearly vertical west-northwest joints and N. 60° E. joints to mix with water rising to the southwest along bedding planes. This mixing presumably produced local convection cells which changed position and direction from time to time (figs. 5, 6).

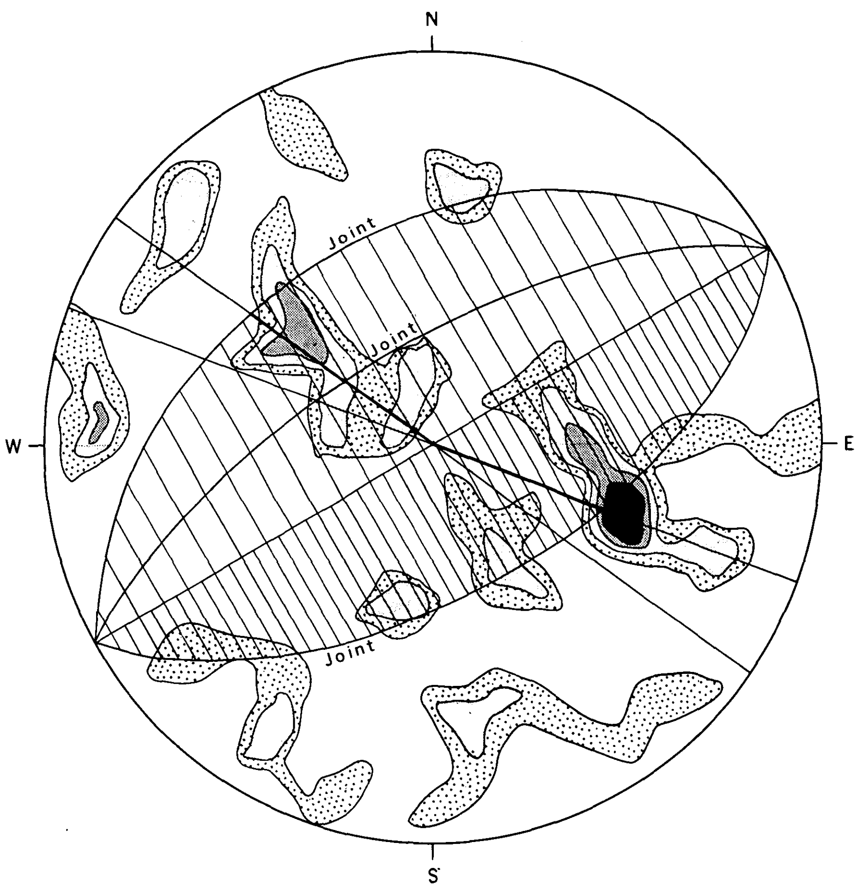
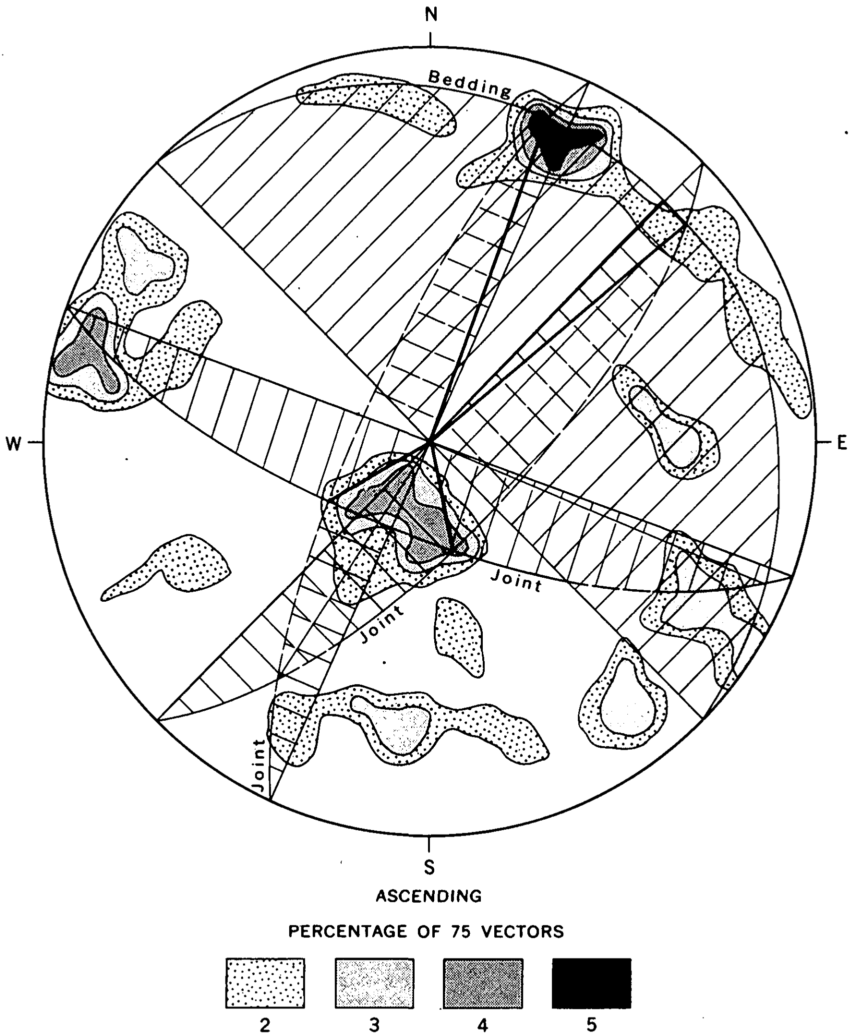


Figure 4 (above and right).—Solution movement vectors plotted on lower hemisphere, Cave and Coolidge prospect, Gilman, Colo. Contours show percentage of vectors per 1 percent of area. Joint planes and bedding shown by hachured areas; intersections by heavy lines.

The general technique dévised by Fischer (1955) and modified by Steinmetz (1962) as described earlier in this paper was used on the Cave and Coolidge prospect data, which have been analyzed in various ways so that the advantages and limitations of the mathematical method are illustrated.

A mathematical analysis shows that the resultant of all the vectors in both hemispheres is directed upward at only 1° with an azimuth of 213° (S. 33° W.). But the fact that the circles of 95 percent and of 90 percent confidence have radii of 45° and 39°, respectively, indicates that the resultant of a much larger number of vectors could be tens of degrees different in both azimuth and slope. If the geologist



is satisfied with a 90 percent "circle of confidence," the chances are 9 out of 10 that regardless of how many vectors were plotted, for the Cave and Coolidge jasperoid the ultimate resultant of the entire population would be less than 40° away from the S. 33° W. resultant sloping up at 1°; this limitation would allow for an angle of inclination parallel to the dip of the bed (to agree with the geological bias of the author) pointing in an updip direction and would indicate that the jasperoid was formed by rising dominantly hydrothermal solutions.

Figure 4 suggests that the downward-directed vectors have a bimodal distribution separated by a line having an azimuth of N. 55° E. (fig. 5). The resultants in the two areas are calculated to be downward-directed vectors N. 44° W. at 42° and S. 38° E. at 45°. The obvious choice for a bimodal division for the ascending vectors would be along a line parallel to the strike of the bedding, namely N. 45° W., and here we find that the resultant of the vectors in the northeast half slopes S. 50° W. upward at 33° and the resultant of the vectors in the southwest half slopes N. 51° E. upward at 50°.

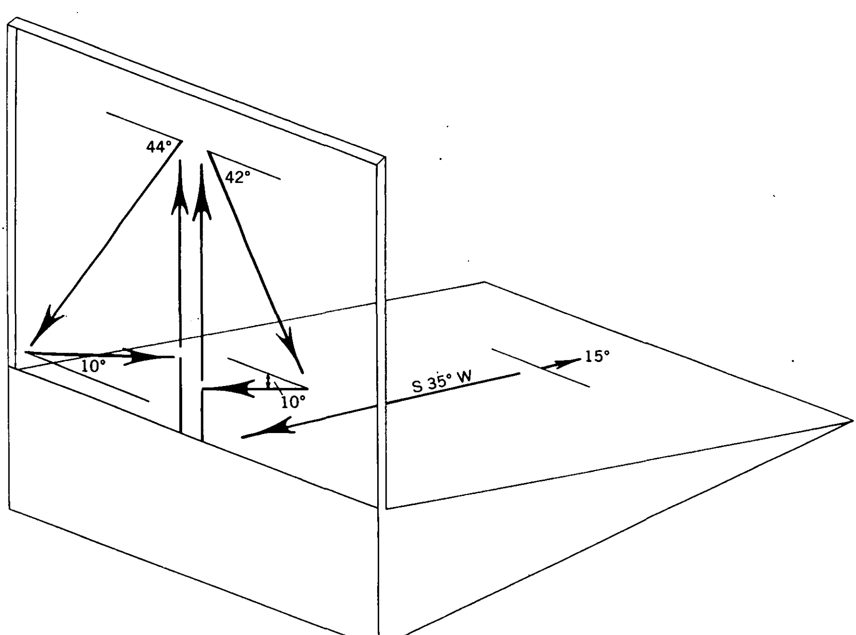


FIGURE 5.—Resultants of various vector groups plotted on lower hemisphere, Cave and Coolidge prospect, Gilman, Colo. Resultants for halves of hemispheres shown by dashed arrows; resultants for indicated concentration clusters by solid arrows.

Because many asymmetric overgrowths are definitely random and caused by chance factors not directly related to the major directions of solution movement, the use of only those vectors that cluster in statistically or geologically significant areas can be justified. If calculations of ascending vectors in the northeast half of the hemisphere are restricted to the wedge that is within 15° of the bedding plane, a resultant is found that slopes upward at 15° in a S. 39° W. direction, which is parallel to the bedding. (See table 1 for calculation.) If we next consider resultants for groups of vectors containing more than 3 percent concentrations per unit area, three resultants can be calculated for the southeast half of the hemisphere: S. 70° E. up at 10°, N. 40° W. up at 18°, and N. 20° E. up at 73° (fig. 5).

The direction of the resultant calculated for all the vectors, together with the pattern of crystal overgrowths, shows such a striking relation to the geologic factors that the overgrowths obviously reflect an overall updip movement of jasperoidizing solutions toward the southwest. If the source of the jasperoidizing solutions were to be sought by exploration, it would be expected to lie N. 35°–40° E. of the Cave and Coolidge prospect, and to be a mineralizing center separate from that which gave rise to the zinc mantos exploited by the New Jersey Zinc Co.

The multimodal concentration pattern of quartz overgrowths may have a bearing on the genesis of the jasperoids. Such a pattern suggests that locally and from time to time both steep- and low-angle lateral currents influenced crystal growth, and this inference, in turn, suggests that jasperoid was deposited where convection currents formed as rising silica-bearing hydrothermal solutions mingled with

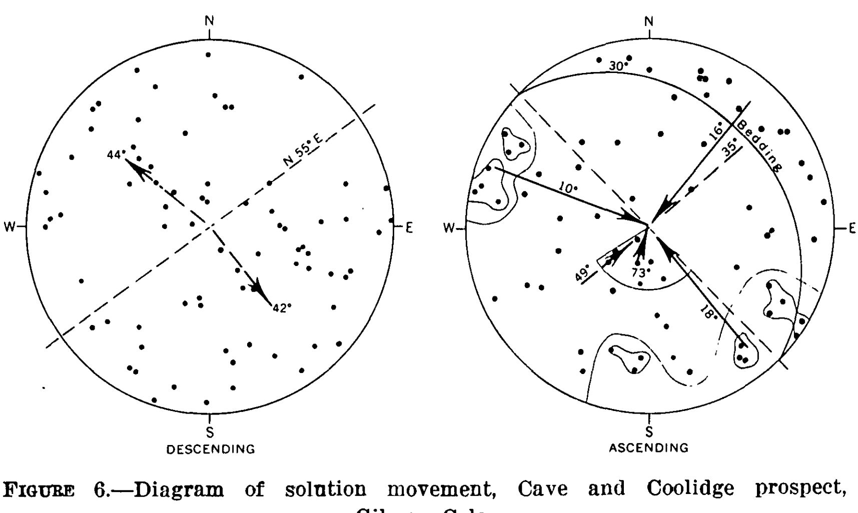


Figure 6.—Diagram of solution movement, Cave and Coolidge prospect, Gilman, Colo.

descending cooler ground water (fig. 6). Many of the asymmetric overgrowths, however, undoubtedly represent chance interference caused by local irregularities in the changing crystal mesh, and many more specimens will have to be analyzed before this hypothesis can be satisfactorily evaluated.

TINTIC STANDARD MINE, EAST TINTIC DISTRICT, UTAH

The East Tintic district, Utah, is about 60 miles south of Salt Lake City, and in contrast to the Gilman mining district, it has an extremely complex geologic setting. The three specimens of jasperoid examined were collected from the J stope area of the 900 level of the Tintic Standard mine, which exploited a large lead-zinc ore body in highly altered, faulted Cambrian limestone and shale adjacent to a steeply folded contact with the underlying Cambrian quartzite. The southernmost specimen was taken about a yard from the quartzite and jasperoid contact which here strikes N. 60° E. and dips about 45° N. A few yards farther east, however, the contact turns due north and dips 35° W.; about 35 feet farther north it turns abruptly west-southwest and dips about 40° S. Two other specimens were taken at 10 and 15 feet respectively south of the west-southwest part of the contact and 10 and 40 feet respectively west of the north-trending part. There is thus a gentle southwesterly dipping trough in the quartzite footwall below one of the specimens, and the other two were taken on the northwest and southeast sides of the trough.

The J stope ore body plunges southwest subparallel with the footwall trough for some distance, but the major ore body is northwest of the J slope area. The limestone was much fractured, before jasperoidization, by both steep- and low-angle faults, but only the main directions of the nearby quartzite-footwall contact with the jasperoid are indicated in figure 7. This figure also shows the contoured pattern of solution-movement vectors as interpreted from quartz overgrowths in nine oriented thin sections of the three specimens noted. The pattern shows a strong bimodal concentration for ascending-solution vectors; one maximum is virtually parallel to the trough between the north-trending and west-southwest-trending footwall contact, and the other slants S. 35° E. up at 45°, almost directly parallel to the dip of the N. 60° E. contact adjacent to the southernmost sample locality. This latter maximum is of special interest, because the opposite direction, which presumably should point down toward the source of the solution, points downward toward the main ore body of the mine.

The mathematical resultant computed for the entire sphere of projection points even more specifically to this large ore body as the source area for the jasperoidizing solution and has an azimuth of 112°29′ slanting upward at 31°43′; the reverse direction and slope angle (N. 68° W. down at 32°) would intersect the major ore body of the Tintic Standard mine about 200 feet below. The ascending and descending vectors for the J stope jasperoid are unevenly distributed: 88 slant downward and 114 slant upward. There are thus 30 percent more crystals showing overgrowths indicating upward movement than downward movement. The pattern of the downward vectors could result largely from chance growths on crystals that were parallel to the direction of flow or so related to obstructions and to solution-carrying interstices as to favor growth in random directions. The pattern slightly resembles a girdle arrangement normal to the two directions of flow indicated by the major concentration of vectors and their resultants in the lower hemisphere, but the pattern is also suggestive of solution movement along north-northeast fractures dipping about 50° E. No such fractures were mapped, although premineralization fractures that strike N. 10°–20° E. and dip 65°–70° are not uncommon. Resultants for various vector groups were also calculated (fig. 8); those for descending vectors are almost symmetrically distributed about the vertical axis and those representing rising solutions suggest the configuration shown in figure 7. The calculated resultant of all the vectors, however, seems much more relevant than resultants of the arbitrarily chosen groups.

Although the investigation of the jasperoids was made after the J stope and main ore bodies were found, it is of interest to note that exploration toward the sources of jasperoidizing solutions as indicated by this petrofabric study would have led into ore bodies; exploration to the southwest parallel to the trough vector maximum would have disclosed an excellent moderate-sized ore body whereas exploration west-northwest, parallel to the resultants calculated from all the overgrowth vectors and also subparallel to the source indicated by the second concentration maxima in the northwestern quadrant (fig. 7), would have led into the major ore body of the mine.

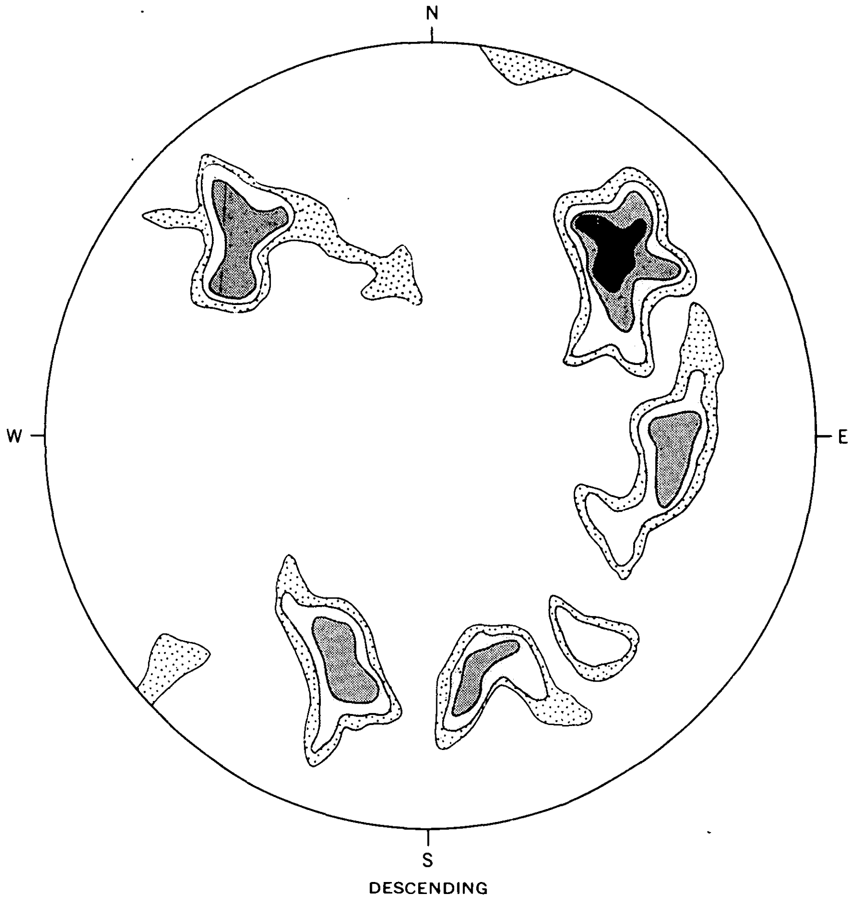
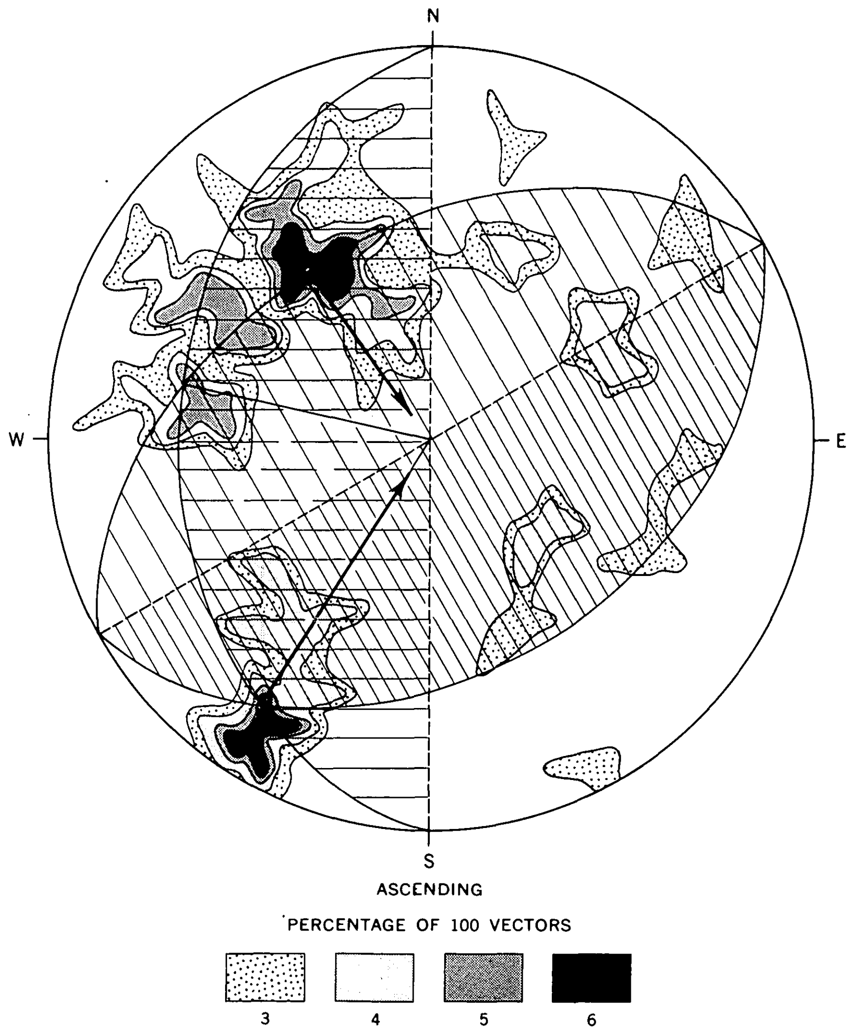


FIGURE 7 (above and right).—Solution movement vectors plotted on lower hemisphere, J stope jasperoid, 900 level, Tintic Standard mine, East Tintic district, Utah. Contours show percentage of vectors per 1 percent of area. Contact surfaces between jasperoid and quartzite shown by a hachured area; intersections by light solid lines; movement vectors by heavy arrows.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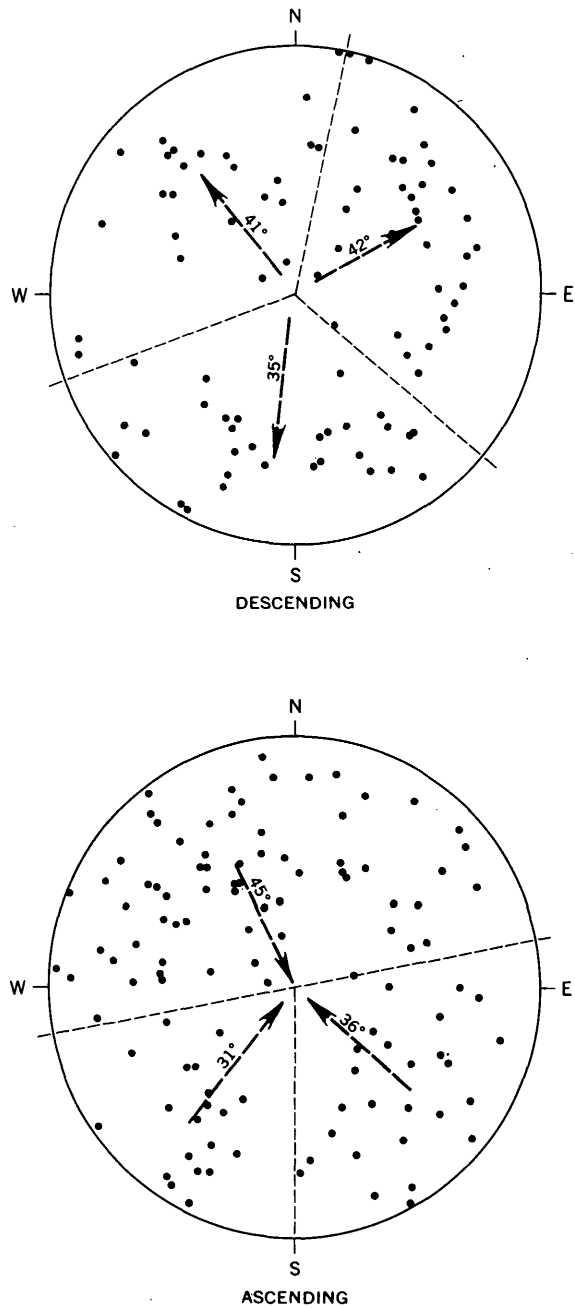

FIGURE 8.—Calculated resultants of various solution movement vector groups, J stope jasperoid, 900 level, Tintic Standard mine.

CONCLUSIONS

Studies by petrofabric methods of jasperoid overgrowths in specimens from two very different geologic environments led to unexpectedly significant results. In both instances the general direction of flow indicated by the petrofabric diagrams and by the resultant of all overgrowths is surprisingly compatible with the geologic interpretation of the probable source of the jasperoidizing solution. At the Tintic Standard mine such a petrofabric analysis could have been used as a guide to exploration for ore deposits. At the Cave and Coolidge prospect, the area downdip from the jasperoids has been little explored, but the relation of jasperoids to ore is less intimate than in the Tintic district. Nevertheless this technique has sufficient merit to warrant its use in other areas where jasperoid is of the "productive type" and likely to be an updip expression of ore deposits (Lovering and Hamilton, 1962), especially in much fractured or permeable beds where a hydrothermal current could be expected to maintain a generally uniform direction for some distance.

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