THE EVOLUTION OF FRACTURE-RELATED PERMEABILITY
WITHIN THE RUBY STAR GRANODIORITE
SIERRITA PORPHYRY COPPER DEPOSIT, PIMA COUNTY, ARIZONA

by
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ABSTRACT

Quantitative data from the margins of the Sierrita porphyry copper deposit were derived by direct measurements from fractures in the field and fluid temperatures in the laboratory. These data constrain interpretations of the nature and extent of fracture permeability at different stages of cooling of the quartz monzonite porphyry which invaded the Ruby Star Granodiorite batholith at Sierrita.

Fracturing coeval with formation of the ore body extends into the granodiorite some 4.5 km away from the center of the hydrothermal system. Integrated fracture densities decrease from values of 0.2 to 0.3 cm⁻¹ near the system's center to a background value of 0.03 cm⁻¹ or less outside the system. Four mineralogically distinct vein types with a distinct paragenetic sequence are present. Distribution of vein types in the granodiorite indicates that the areal extent of fracturing associated with each type diminishes with time.

Vein-filling temperatures determined from fluid inclusions at two localities reveal a general decrease in the homogenization temperature of vein quartz of each vein type as the system evolved. Sulfide-bearing quartz veins collected at sites 1.8 and 2.9 km from the system's center showed similar temperatures of formation; however, secondary inclusions representing later events, present at the 1.8 km site, were absent at the 2.9 km site, suggesting that the late lower temperature event related to their formation was less widespread.

INTRODUCTION

Studies related to the origin and evolution of porphyry ore deposits indicate that large masses of fluids flow through extensively fractured host rocks and intrusive stocks to form the mineralization and alteration observed (Norton and Knight, 1977). Furthermore, studies of the fluid dynamics of such systems indicate that one of the variables which dictates fluid flow rates is the flow porosity or permeability (Norton and Knapp, 1977).

Norton and Knapp (1977, p. 915) define flow porosity as representing "those pores through which the dominant mode of fluid transport is by fluid flow." They suggest that rock permeability of a fractured plutonic rock may be approximated by a simple flow porosity model. Other forms of porosity, such as diffusion porosity (representing pores through which transport is by diffusion through the aqueous phase) and residual porosity (representing unconnected pores), do not augment rock permeability.

From Darcy's Law for fluid flow through a porous medium it can be shown that for fractured rocks permeability is a function of both the abundance of continuous fractures and the cube of the fracture aperture or width. The exact relationship, as derived by Snow (1970), is shown in Equation 1:

$$k = \frac{nd^3}{12} \quad (1)$$

where k is the permeability (cm^2), n is the fracture density¹ (cm^{-1}), and d is the fracture aperture (cm).

The only previous study to measure fracture densities and fracture apertures in an effort to quantitatively determine permeability within a hydrothermal system was conducted by Villas and Norton (1977) in a portion of the Mayflower stock, Park City, Utah. The permeabilities obtained from the Park City data are in reasonable agreement with reported values of permeabilities for fractured plutonic rocks (Brace, in press) suggesting that under some conditions permeability is indeed a measurable parameter. In another study, Titley (1978) measured fracture abundances and apertures in an oxidized and leached portion of a porphyry copper system in New Britain. There, apertures were easily determined because of the leaching which had taken place resulting in removal of vein material, as a result of modern geological processes.

This paper presents the results of a study in which relative permeabilities, as represented by fracture densities, were measured within the wall rocks of a porphyry copper system. Changes in fracture densities were determined with respect to: time of vein formation as interpreted from paragenetic relationships; space, as represented by the location of a fracture within the system; and temperature changes as the system evolved. In other words, this study seeks answers to the

1. The term fracture density used here is synonymous with fracture frequency used by Snow (1970) and other authors. The term density is preferred because it carries a spatial relationship, and does not carry the time connotation that frequency implies. It has been used elsewhere (Titley, 1978).

question: "How does fracture-related permeability in a porphyry copper system change with time and in space?"

The Duval Corporation, Sierrita porphyry copper deposit, located 40 km southwest of Tucson, was chosen for the study for several reasons. First, the comparatively isotropic character of one of the wall rock hosts, the Ruby Star Granodiorite, provided an ideal setting for a fracture-related study. Furthermore, the large area of good outcrop exposed within the granodiorite on the pediment surface to the north of the ore body allowed for a detailed study over a considerable area. Finally, the district's comparatively simple geology reduced complications arising from complex geologic situations related to structural and chemical anisotropy of wall rocks.

GENERAL GEOLOGY

The Sierrita porphyry copper deposit of the Duval Corporation is located at the southern end of the Pima mining district on the east flank of the Sierrita Mountains (Figure 1). The general geology of the Sierrita hydrothermal system, which includes the genetically-related Esperanza ore body, has been described in various levels of detail by Lacy (1959), Cooper (1960), Lynch (1966, 1968), Aiken and West (1978), and West and Aiken (in press), and is only summarized here.

Laramide age mineralization is hosted by pre-Laramide igneous rocks and by Laramide-aged intrusions. Pre-Laramide rocks present in the area consist of the Triassic-aged Ox Frame Volcanics, exposed on the south side of the ore body, and the Harris Ranch Quartz Monzonite of Jurassic age on the west. The andesite and rhyolite of the Ox Frame Volcanics are important hosts to mineralization in the Esperanza ore body, which lies southeast of the Sierrita pit; the Harris Ranch Quartz Monzonite (190 m.y. old; Cooper, 1973) is a host to some chalcopyrite and molybdenite mineralization in the south and west portions of the Sierrita pit (Figure 2).

Laramide intrusive activity commenced about 67 m.y. ago (Cooper, 1973) with emplacement and cooling of several quartz diorite stocks, two of which act as important hosts to sulfide mineralization, and culminated with the intrusion of the Ruby Star Granodiorite and its associated porphyries from about 58 to 53 m.y. ago (Damon and Mauger, 1966). The Ruby Star Granodiorite composes a batholithic body which extends

Figure 1. Location Map of the Sierrita Porphyry Copper Deposit and Other Nearby Mines.

Figure 2. Generalized Geological Map of the Sierrita-Esperanza Area Showing Pit Outlines and Study Area. -- Geology from Cooper (1960).

some 40 km northwestward from the Sierrita system. Two rock types have been recognized within the batholith by Lovering et al. (1970) and consist of an equigranular granodiorite and a porphyritic phase of similar mineralogy which is characterized by large (2-3 cm) phenocrysts of orthoclase in an equigranular holocrystalline groundmass. The porphyritic nature of that portion of the batholith exposed within the study area was examined in detail during this study. Criteria used included the number of orthoclase phenocrysts within a representative 10 cm square and the size of the largest phenocrysts found in that area. The analysis indicates a highly irregular and transitional contact between the two phases of granodiorite, strongly suggesting that the textural variation is a result of cooling processes within the granodiorite and is not a result of two separate intrusive events. With some noticeable irregularities, the porphyritic phase appears to occur along the central axis to the elongate north-northwest trending batholith (Figure 3).

A younger rock type, possibly a differentiate of the Ruby Star body, occurs at the southern edge of the batholith and is interpreted as the progenitor of the Sierrita-Esperanza porphyry copper system. This rock, a quartz monzonite porphyry, consists of a stock some 2 km in diameter, with Jurassic and Triassic wall rocks to the south and west and the younger intrusions to the north and east (Figure 2). As many as five different textural variants have been recognized (West and Aiken, in press) within the quartz monzonite porphyry stock. All rocks in contact with this porphyry and the porphyry itself contain copper-molybdenum ore; the emplacement of the porphyries is therefore considered the significant mineralizing event.

Figure 3. Generalized Map Showing Porphyritic Nature of Ruby Star Granodiorite in the Study Area.

Wide-scale fracturing of all rocks within the Sierrita porphyry system, as well as the bulk of sulfide mineralization, appear to be temporally as well as spatially related to this quartz monzonite porphyry and its intrusion at about 53 m.y. ago as dated by Damon and Mauger (1966). Younger quartz latite dikes, present within and north of the ore bodies, crosscut all rock types. Although of unknown age, their modes of occurrence, irregular distribution, and paragenetic relationship with host rocks suggest that they are unrelated to the dynamics of fracturing or to the mineralizing event. However, their orientations do mimic those of the mineralized structures in the district, changing from an east-northeast strike on the west to a northeast trend east of the ore body, and hence may follow older syn- or premineral structures.

NATURE AND PARAGENESIS OF ORE OCCURRENCES

The predominance of Sierrita-Esperanza ore mineralization occurs in veins and veinlets. Sulfide veins as wide as several centimeters and with several meters of mappable length are present but are rare. Much of the sulfide occurs in veins of millimeter width and a meter or less of persistence; a minor amount appears to occur as replacements of mafic minerals along or near microfractures (<0.1 mm wide). A number of different alteration mineral assemblages are present as vein and veinlet-wall selvages, and a distinct paragenesis of alteration has been recognized. This paragenesis, which is expressed by sequences of cross-cutting veins with different alteration assemblages, has been studied in detail (Smith, 1975; Beane, 1979; Preece and Beane, 1979; West and Aiken, in press). An important result of these studies has been the identification of times in the paragenetic sequence when different mineral assemblages were stable and of the temperatures at which they formed. Because there is a clear gradient of decreasing temperatures of deposition of these different sequences based on fluid inclusion studies, and because there are unequivocal crosscutting relationships between veins, an unequivocal interpretation can be made regarding at least one aspect of the hydrothermal process. Fracturing of the rocks persisted through much of the life of the hydrothermal process. A similar interpretation, based on field evidence, was advanced for some deposits of the southwestern Pacific (Titley, 1978; Titley, Fleming, and Neale, 1978).

Reconnaissance field work in the environs of the Sierrita and Esperanza ore bodies has revealed that the fracturing of porphyry and host rocks is not restricted to the volume of rock known to be ore. Persistent and consistent vein-veinlet sequences occur in some rock types for distances in excess of 5 km away from the center of the known ore. The Sierrita-Esperanza system is thus seen to contain economic mineralization in only a small fraction of the total volume of fractured and altered rock present. Consequently, in addition to the presence of fractures, another control of ore is that of the position of the porphyry bodies upon which the fracturing of porphyry and host rocks appears to be centered.

METHOD OF STUDY AND RESULTS

The study reported here was carried out in a wedge-shaped area which extends from the center of the mineralized part of the system, northward some 4 km to the limit of visible fractures in the host rocks. The sample area overlies the quartz monzonite porphyry of the deposit and the various phases of the Ruby Star Granodiorite. Its confinement to this area is deliberate and reflects an attempt to assess the evolution and habit of fractures in the Laramide batholith and porphyry only. The other rocks hosting mineralization in the district are presently under study by John White and Scott Manske at The University of Arizona.

Within the 6 sq km study area, over 200 sample sites were chosen which included locations within both the Sierrita and Esperanza ore bodies. At each site, five parameters were evaluated, two of which were independent. The independent variables were the distance of the sample site from the center of the system, designated by L , and the time of formation of a particular vein in the context of observable paragenesis, designated by t . Three other features, all dependent upon both L and t , were measured at each site and included fracture density, vein mineralogy, and vein orientation. A sixth feature, vein-filling temperatures, was measured from samples collected at two specially selected sites using fluid inclusions. Fluid salinities within these samples were also determined from fluid inclusions using the freezing point depression method.

Fracture Density

Fracture densities were determined in a fashion similar to that employed by Titley (1978). Areas of outcrop were assessed by eye, and representative areas, so determined, were studied in detail. Areas, generally 50 cm square, were isolated (Figure 4), and the cumulative length of all mineralized-altered fractures within the area was divided by the total sample area to yield fracture densities (n) with dimensions of cm^{-1} . The density so obtained is hereafter referred to as the integrated fracture density. Locations of the outcrops examined during the study and their respective integrated fracture densities are mapped on Figure 5 (in pocket).

In view of the fact that several different stages of fracturing are present in most of the exposures studied, the individual densities of groups of fractures exhibiting characteristic alteration assemblages were also measured as representative of fracture permeabilities existing at that time. Orientations of separate fracture groups were also determined at each site to allow evaluation of directional permeability. An example of the data collected at each site as reported in Appendix A is shown in Figure 6.

Sample measurements in this study represent only two dimensions of a block of rock. Fracture orientation studies conducted within the Sierrita pit reveal that vertical fractures are the dominant style (West and Aiken, in press) and that horizontal fractures are minor. Therefore, in order to incorporate the vast majority of fractures in the three-dimensional rock mass into the two-dimensional sampling method,

Figure 4. Representative 50 cm Square Area from Which Fracture Densities Were Measured.

ORIENTATIONS

<u>Qtz + Kspar</u>	<u>Qtz + Sulf (<1%)</u>
N54E,80S	N84E,80S
N54E,80S	N84E,80S
	N84E,80S
<u>Qtz + sulf (>1%)</u>	N12E,76E
N56E,80S	N23W,vert
	N81W,vert
<u>Kspar + Epid</u>	N81W,vert
N61E,75S	

Figure 6. Representative Sample of Data Collected at Each Sample Site.

horizontal sample areas exposed in streambeds and along ridgetops or slopes were used for fracture measurement, rather than vertical faces exposed on banks or cliffs. Nonetheless, some vertical faces were examined in the sample area in a continuous evaluation of the nature and distribution of fracture orientations. Such faces revealed that the tendency for fractures to be vertical extends outside the limits of the pit. Greater than 80% of all fractures measured during the study have dips greater than 60° . This figure fell to 55% when only fractures measured from vertical faces were included, and thus the general lack of horizontal or near-horizontal fractures is evident.

A plot of fracture density against the distance of the sample from the center of the quartz monzonite porphyry stock (Figure 7) reveals two important features. First, a central zone within the system, some 1.5 km wide, shows a remarkably uniform fracture density of about 0.2 cm^{-1} , a value about the same as that determined for ore-grade rocks within the Ruby Star Granodiorite within the Esperanza pit (Table 1). This zone of constant fracture density extends well beyond the known limit of ore-grade mineralization. Second, outside this inner zone, the fracture density values diminish rather regularly as a function of distance from the center, until a point about 4.5 km distant where fracturing related to the intrusion of the quartz monzonite porphyry disappears.

Vein Mineralogy

The presence of four distinguishable vein sets, with a distinct paragenetic sequence as observed by crosscutting relationships, allowed

Figure 7. Integrated Fracture Density versus Distance from the Quartz Monzonite Porphyry Center.

Table 1. Fracture Density Data Collected in the Esperanza Pit.

Vein Mineralogy	HR-qm ¹	RS-qmp ²	bqd ³
Biotite	0.12 cm ⁻¹		
Quartz-Orthoclase	0.05 cm ⁻¹	0.08 cm ⁻¹	0.08 cm ⁻¹
Quartz-Orthoclase- Muscovite-Chalcopyrite	0.15 cm ⁻¹	0.05 cm ⁻¹	0.09 cm ⁻¹
Quartz-Sericite- Pyrite	0.08 cm ⁻¹	0.05 cm ⁻¹	0.02 cm ⁻¹
Quartz-Monzonite- Chalcopyrite-Pyrite	0.07 cm ⁻¹		
Quartz-Orthoclase- Epidote	0.05 cm ⁻¹	0.02 cm ⁻¹	0.08 cm ⁻¹ (Cpy) ⁴
Epidote	<u>0.08 cm⁻¹</u>	<u>0.02 cm⁻¹</u>	<u>0.05 cm⁻¹</u> (Cpy)
Integrated Fracture Density	0.60 cm ⁻¹	0.22 cm ⁻¹	0.32 cm ⁻¹

¹Harris Ranch quartz monzonite.²Ruby Star (quartz monzonite porphyry phase).³Biotite quartz diorite.⁴Chalcopyrite.

the integrated fracture densities to be separated in time on a mineralogic basis. It should be noted here that the interpretation of vein and alteration mineralogy in and adjacent to the Sierrita pit is facilitated by three important characteristics of the system. First, even within the higher grade hypogene ore, the sulfide content (which occurs chiefly in veins) is relatively low (2-3% by volume) compared with many other deposits in the region. Second, the Sierrita ore body and rocks to the north lack the texturally destructive and paragenetically late fracture-guided quartz-sericite-pyrite alteration developed in other deposits of this region. Consequently, the Sierrita deposit has not been strongly secondarily enriched and supergene processes have not resulted in further obliteration of primary features. Third, alteration mineralogy changes distinguishably with time as solution chemistry and temperature vary during the life of the hydrothermal system.

The vein sequence recognizable in the distal portion of the Sierrita system is delineated in Figure 8. The earliest vein type observed consists of quartz + orthoclase $\pm$ magnetite. The orthoclase usually occurs as a vein selvage of variable width to a centrally located quartz vein; magnetite, where present, occurs both as stringers and as discrete grains within the quartz, and less commonly within the orthoclase. These veins are crosscut by quartz veins with low (<1%) sulfide in the vein walls as evidenced by the presence of minor goethite as the lone oxidation product. There follows development of quartz veins with higher sulfide content in which either sulfides are still present or jarosite occurs. These veins, sometimes up to 2 cm in width,

Figure 8. Paragenesis of Principal Vein-filling Minerals.

originally contained >1% sulfides among their alteration products. Although some sulfide-bearing veins transitional between these two types do occur, for the most part there appears to be a distinct and recognizable difference between the two sulfide vein sets. The youngest recognizable vein type is that of orthoclase + epidote $\pm$ chlorite $\pm$ quartz $\pm$ trace sulfides. In this type, as well, the orthoclase commonly occurs as a vein selvage, often a few centimeters in width.

Fracture type can be related to its abundance and position with respect to the center of mineralization by consideration of these vein types and their separate fracture densities. Figure 9 shows the relationships and suggests two additional characteristics of fracture evolution. First, each successive vein set that develops is more restricted to the porphyry center. The early quartz-orthoclase veins extend virtually to the limit of fractured rocks, approximately 4.5 km from the porphyry center. The two quartz-sulfide vein types (grouped together here) extend to a distance of just over 3.5 km from the porphyry center and, finally, the late orthoclase-epidote veins are not found beyond a distance of about 3 km from the center. Second, by far the greatest amount of fracturing occurred during the time of the quartz-sulfide stages or, in terms of paragenetic time, midway in the hydrothermal evolution of the system.

Vein Orientations

As fractures evolved during the lifetime of the hydrothermal system, their orientations changed. For all four mineralogical types observed, the dominant trend is northeast, a trend similar to that

Figure 9. Fracture Density by Mineralogy versus Distance from the Quartz Monzonite Porphyry Center.

observed by Rehrig and Heidrick (1972) for some porphyry systems of the region. However, the dominant strike direction of the features associated with each mineralogically separable event changed (Figure 10).

Relatively early quartz-orthoclase veins have a dominant northeast trend which shifted to veins with a more east-northeast trend and which contain low total sulfide content. However, the generally wider, high total sulfide veins appear to return to the northeast direction, and the paragenetically late orthoclase-epidote veins again strike predominantly east-northeast.

Homogenization Temperatures

Samples were taken from two locations for study of fluid inclusions. These locations, 1.8 and 2.9 km from the porphyry center, provided samples of crosscutting veins in the Ruby Star Granodiorite. Both primary fluid inclusions, trapped during crystal growth, and secondary fluid inclusions, created by subsequent filling of microcracks, were observed in vein quartz from these sites. They were studied using standard techniques described by Roedder (1967). All inclusions observed homogenized to a liquid upon heating and none contained daughter salts. Figure 11 presents some of the results of this work. Note that the temperatures recorded are homogenization temperatures and are not pressure corrected.

Temperatures shown are those from three veins at the 1.8 km site. Techniques described by Preece and Beane (in preparation) involving the study and interpretation of secondary inclusions were employed. Vein 1, from the early quartz-orthoclase type, shows temperatures of

Figure 10. Rose Diagrams Plotting Orientations for Each Vein Set.

Figure 11. Histograms of Primary and Secondary Fluid Inclusions from Three Distinct Vein Types at a Sample Site 1.8 km from the System's Center.

homogenization ranging up to 380°C with an important peak at $340\text{--}360^{\circ}\text{C}$. A wide range of lower homogenization temperatures from secondary inclusions is also present. The second histogram combines data from two quartz-sulfide veins which crosscut the earlier quartz-orthoclase vein. It is apparent that although the low-temperature measurements of secondary fluid inclusions in earlier quartz-orthoclase veins are present and repeated, in the later quartz-sulfide veins the $340\text{--}360^{\circ}\text{C}$ peak observed in the quartz-orthoclase type is absent. The same pattern is repeated in the inclusions from the orthoclase-epidote veins which crosscut the sulfide veins. Low-temperature peaks reoccur, but the higher temperature exhibited by primary inclusions observed in the two older types are missing.

Thus, there is a progression of temperatures, represented by specific peaks characterizing temperatures of hydrothermal solutions associated with specific alteration assemblages. Fluid inclusions with homogenization temperatures of $340\text{--}360^{\circ}\text{C}$ accompanied early quartz-orthoclase veins; temperatures of $240\text{--}320^{\circ}\text{C}$ were observed in intermediate quartz-sulfide veins; and fluid inclusions associated with orthoclase-epidote veins homogenized at $170\text{--}230^{\circ}\text{C}$. Although some quartz growth in the early quartz-orthoclase veins occurred at slightly lower temperatures, as evidenced by the presence of primary inclusions in the range $250\text{--}320^{\circ}\text{C}$ (Figure 11), paragenetic relationships within the quartz suggest that this later low-temperature quartz growth was minor when compared to that formed at about 350°C . The presence of more than one primary peak within the same vein was also observed by Preece (1979)

who reported cooling through time during filling in each of the veins he studied from the Sierrita pit.

The wide range of temperatures less than the homogenization temperatures observed in the first two veins, as represented by secondary inclusions, suggests that as each set of fractures was developed, older fractures were reopened and solutions at cooler temperatures passed through and were responsible for the development of planes of secondary inclusions. It is my interpretation that these small-aperture secondary planes lack the size and continuity for fluid flow. Transport is therefore interpreted to be by diffusion in the aqueous phase. Such transport is not a part of the rock's flow porosity or permeability. Further evidence supporting this interpretation lies in the fact that although fractures were filled with the secondary fluid they did not alter the original vein mineralogy to that of the new assemblage.

A comparison of observed homogenization temperatures within the quartz-sulfide vein types from each of the two sample locations (Figure 12) shows similar temperatures of homogenization from primary inclusions. The temperature range 210-330°C is equally represented at each site. However, in the more distant sample locality (2.9 km), the lower peak at 190°C ascribed to the late orthoclase-epidote event does not exist. The absence of orthoclase-epidote veins past 3.0 km, and the absence of low-temperature secondary fluid inclusions indicates that the late low-temperature event was less extensive than the other earlier events.

Figure 12. Histograms of Primary and Secondary Fluid Inclusions from Quartz + Sulfide Veins at Sites 1.8 and 2.9 km from the System's Center.

Salinities

The salinities of fluids circulating in the distal portions of the Sierrita system were determined using fluid inclusions. Since no daughter salts were observed during the study, freezing point depression methods (Roedder, 1962; Preece, 1979) were necessitated. Freezing temperatures so determined were then converted to NaCl equivalent salinities from equations regressed on experimentally determined freezing point depression curves for aqueous NaCl solutions (Potter, Clyne, and Brown, 1978).

Efforts to determine freezing point temperatures were greatly inhibited by the small size of the majority of the inclusions (typical inclusions averaged between 5-10 μ in diameter). Difficulties in nucleating ice within the inclusions (Roedder, 1962), coupled with the optical problems inherent with the inclusions' small sizes, greatly reduced the number of inclusions suitable for freezing point determinations. In total, salinities were calculated for only 16 inclusions, prohibiting any delineation of the changes in fluid composition during the life of the system.

Despite the limited data (Table 2), one observation can be made. All fluids observed in the distal portion of the Sierrita system have salinities below 3 molal NaCl equivalent and the majority have salinities in the range 1-2 molal. Preece (1979), working in the center of the Sierrita system, observed two compositionally distinct fluids: a high-salinity, 9-12 molal solution present during early "potassic" veining, and a lower salinity, 1-3 molal solution, present at a later time.

Table 2. Freezing Temperatures and Corresponding Salinities
Collected from Sixteen Fluid Inclusions.

(Mineralogy)	Freezing Temperatures (°C)	Concentration (Molal NaCl Equivalent)
Quartz + Orthoclase	-2.0	.6
Quartz + Orthoclase	-3.2	1.1
Quartz + Orthoclase	-2.4	.7
Quartz + Orthoclase	-4.6	1.5
Quartz + Orthoclase	-3.5	1.2
Quartz + Sulfide	-4.5	1.5
Quartz + Sulfide	-6.7	2.2
Quartz + Sulfide	-3.7	1.3
Quartz + Sulfide	-2.1	.6
Quartz + Sulfide	-1.7	.5
Quartz + Sulfide	-4.3	1.4
Quartz + Sulfide	-4.7	1.5
Quartz + Sulfide	-5.0	1.6
Quartz + Sulfide	-3.7	1.3
Orthoclase + Epidote	-3.1	1.1
Orthoclase + Epidote	-3.8	1.3

No evidence of the early high-salinity fluids was observed in fluid inclusions from vein-filling quartz in the distal portions of the system.

Formation Temperatures

Assuming a relatively constant pressure during the lifetime of the Sierrita hydrothermal system, the uniform salinities measured from fluid inclusions in the three vein types indicate that differences in homogenization temperatures do reflect differences in formation temperatures. Furthermore, co-existing liquid- and vapor-rich fluid inclusions within veins in the center of the Sierrita pit observed by Preece (1979) allow for reasonable approximations of formation pressures. Preece estimated a pressure of 330 bars for the Sierrita system.

Using this pressure value and the salinities observed in this study, the measured homogenization temperatures can be corrected for pressure with the data of Potter (1977). The resulting formation temperatures for the three vein types are 360-380°C for quartz-orthoclase veins, 270-350°C for quartz-sulfide veins, and 180-240°C for orthoclase-epidote veins.

SUMMARY AND DISCUSSION

The results of these studies have provided information on the evolution of fracture permeability in the Ruby Star Granodiorite. The data provide an insight into the manner in which the thermal, mechanical, and chemical states of large geothermal systems evolve and also provide a basis for interpreting the relationships among solution temperatures, vein mineralogies, and fracture densities and orientations. The most significant results of the study are summarized as follows:

1. At the level observed, the lateral extent of fracturing of rocks away from the porphyry center decreases with evolving time. The earliest-formed fractures extend to the limit of the hydrothermal system. At Sierrita the oldest fractures (characterized by quartz-orthoclase alteration selvages) are present throughout rock studied up to 4.5 km from the center. Successively younger vein types evolved in fractures progressively closer to the porphyry center.
2. At any location in the Ruby Star Granodiorite within the system, for example at 1.8 km (Figure 13), the fracture density starts out at low values (.03), increases to a maximum (.12), and then diminishes (.02). Coincident with this change is the progression in vein-related alteration mineralogy from quartz-orthoclase to quartz-sulfide to orthoclase-epidote assemblages.
3. At Sierrita, fracture density is greatest in a northeast to east-northeast direction, although the direction of maximum

Figure 13. Fracture Densities by Mineralogy versus Distance from the System's Center with Homogenization Temperatures at 1.8 km.

fluctuates between the two orientations during the system's history.

4. Temperature of fluids in fractures drops with time: from a maximum of 360-380°C (early quartz-orthoclase) to 270-350°C (quartz-sulfide) and finally to 180-240°C (orthoclase-epidote).
5. The range and overlap of primary and secondary fluid inclusion homogenization temperatures suggest a monotonic decline in temperatures of solutions which flowed through the fractures. Although a continuum of temperatures is indicated, rock fracture in the system is clearly episodic. Three separate episodes of wide-scale fracturing are recognizable in the periphery of the Sierrita system; each episode is characterized by a distinctive alteration mineralogy, temperature, and crosscutting relationship with fractures of other episodes.
6. Comparison of the data derived from the sample site at 1.8 km with other sites in the area indicates that at that location, maximum fracture permeability occurred when the fluid temperatures were in the range 270-350°C. It is further noteworthy that the quartz-sulfide assemblage in these fractures is that of the principal ore-bearing stage of the Sierrita ore body.
7. Fluids associated with quartz deposition in the distal portion of the Sierrita system have salinities less than 3 molal NaCl equivalent. The great majority have salinities between 1 and 2 molal.

It can be inferred from the preceding observations that wide-scale fracturing of plutons and their host rocks is not by itself sufficient for the ore-grade concentration of sulfides. This fracturing may be required to occur at the proper time in the evolution of the system such that the temperature at that time is amenable to the deposition of sulfides. This apparent coincidence may or may not be forced by processes inherent in the evolution of a metallized porphyry system, but nonetheless it is clearly evident in the history of the hydrothermal process in the Sierrita system.

Fracture Permeability

The foregoing discussions have considered and have been based upon an evaluation of fracture densities. Because permeability is a function of both the fracture density and the fracture aperture, it is necessary that aperture values be determined in order to quantify rock permeability. At the present time, no thoroughly adequate method of quantifying the original aperture width of a crack is known. In the fractures of the Sierrita system, virtually no measurable open space remains. The alteration minerals are all or mostly products of replacement reaction and there is little or no evidence of open-space filling textures. Thus, although wide (2-5 cm) alteration envelopes as well as narrow (1 mm) ones exist, it is not possible, at the present time, to quantitatively determine original fracture apertures. Notwithstanding this difficulty, it is clear that fractures were the major conduits of fluid movement and hence it is clear that the openings along these fractures were the major contributors to the permeability of the system.

Villas and Norton (1977, p. 1476) assumed that present-day openings would provide "reasonable initial estimates" of paleoaperture values. Fracture aperture values measured in this manner in the Mayflower stock of their study revealed some variations; however, no systematic changes in aperture width with depth or with lateral extent were observed. Therefore, until some method of measuring the original aperture width and the changes in that width through the alteration process can be discovered, it is reasonable to assume that effective fracture apertures are constant or near constant during the dynamic history of a porphyry copper system. It seems reasonable to also suggest that the values of fracture density provide a valid approximation of relative flow porosity for the fracture types measured in the Sierrita system.

If such assumptions are incorporated into the conclusions previously stated, it would follow then that at Sierrita: (a) lateral extent of permeability decreased with time; (b) at any point in the system, initial permeabilities were low, they increased to a maximum during the sulfide deposition stage, and then diminished; and (c) the maximum permeability existed when fluid temperatures were in the range of 250-320°C.

Origin of the Fractures

The values of measured fracture densities in the Ruby Star Granodiorite and the fact that greatest densities are found near the porphyry intrusion center suggest that the porphyry intrusion was a source of fracture-forming forces. If a centrally located pressure source derived from the emplacement and cooling of the quartz monzonite porphyry were solely responsible for the fracturing of the porphyry and the Ruby Star

Granodiorite, the following relationship would be valid: as the area over which the pressure was exerted increased, fracture densities would diminish as a function of the inverse square of the distance from that center. Integrated densities in the Sierrita system decrease laterally at a much slower rate. This suggests that forces other than, or in addition to, magma pressure (Knapp and Norton, in press; Knapp and Knight, 1977) were responsible for the development of the observed fracture densities. Further, quartz-orthoclase and orthoclase-epidote filled veins show no change in density over a long distance away from the intrusion center (Figure 13). However, the distribution of fracture densities of the quartz-sulfide veins appears to approximate a function related to the square of the distance from the quartz monzonite porphyry.

CONCLUSIONS

It is evident from this study at Sierrita that the relationships among the various dependent variables operating within the system--permeability, alteration mineralogy, vein orientation, and temperature--and, in turn, their relationships to both time and space within the system, appear to be extremely complex. However, it is equally apparent from the results of this study that detailed analysis of these parameters in the field and in the laboratory can provide valuable insights into defining these interrelationships, which in turn can provide valuable constraints for theories regarding the evolution of geothermal systems and porphyry ore genesis.

From the standpoint of ore search, results of this study underscore the importance of detailed evaluation of fracture characteristics and alteration. At Sierrita, a hydrothermal center might have been located solely on the basis of detailed fracture measurement in the distal portion of the system. Furthermore, fluid inclusion data gathered from a single outcrop, indicating temperatures of formation of quartz-orthoclase and quartz-sulfide veins as high as 300-350°C would have suggested the presence of a high-temperature hydrothermal system somewhere in the Pima district. Structural and geochemical data such as this, augmented by an understanding of the geology and alteration paragenesis, can become important tools in delineating the nature and extent of some hydrothermal systems.

APPENDIX A

FRACTURE DENSITY DATA

The first step in measuring fracture densities in the Ruby Star Granodiorite was to locate outcrops that would yield representative values for the immediate area surrounding the site. To do so, the exposed outcrop was visually scanned and an effort was made to avoid outcrops that clearly contained either more fractures or fewer fractures than the average for the rock exposed. Except in areas where the pediment surface was covered by gravels and soils, every effort was made to select such outcrops at approximately 200-300 ft intervals.

Once a suitable outcrop was located, the following procedure was followed. A 50 cm square area was outlined on the rock surface with a magic marker. A detailed diagram of the veins visible in the square was then drawn--careful attention was paid to distinguishing vein mineralogies and paragenetic relationships. Such a diagram is shown in Figure 6 accompanied by the density and orientation measurements that followed.

After the outcrop had been drawn and all of the veins located and properly classified by mineralogy, the fracture length of each recognized vein type was measured from the outcrop. Such data yielded fracture densities for each vein type and, when added together, an integrated density for the entire square area. Orientations, both strike and dip, were also measured for each vein within the area and were also separated by vein mineralogy.

The fracture density data for each site are reproduced in Table A-1 and the location of each site is mapped on Figure 5 (in pocket).

Table A-1. Fracture Density Data (cm^{-1}).

Site	MINERALOGY				Integ. Frac. Dens. ⁵	ORIENTATION						
	Q+K ¹	Q+S ²	Q+S ³	K+E ⁴		NNE ⁶	NE ⁷	ENE ⁸	WNW ⁹	NW ¹⁰	NNW ¹¹	
1R	.10	.03	.03	-	.16	.05	-	.09	.02	-	-	
2R	.02	.09	.04	-	.15	-	-	.06	.03	.06	-	
3R	.03	.07	.02	-	.12	-	-	.09	.03	-	-	
4R	.01	.03	.01	-	.05	-	.02	-	.03	-	-	
5R	.01	.09	.01	-	.11	-	-	-	.11	-	-	
6R	-	.08	.01	.02	.11	-	-	.06	.02	-	.03	
7R	.01	.05	-	.03	.09	-	-	.05	.04	-	-	
8R	no density calculated											
9R	.02	.07	-	.02	.12	-	.02	.10	-	-	-	
10R	-	.08	.02	-	.10	-	-	.10	-	-	-	
11R	.03	.07	.02	-	.12	-	-	.02	.10	-	-	
12R	no density calculated											
13R	-	.08	-	.03	.12	.02	-	.07	.03	-	-	
14R	.01	.08	.02	.01	.12	-	-	.07	.03	-	.02	
15R	.02	.05	-	.04	.11	.03	-	.06	.02	-	-	
16R	-	.10	-	.04	.15	-	-	.12	.03	-	-	
17R	.01	.07	-	-	.08	-	-	.05	-	-	.03	
18R	.08	.02	-	-	.10	-	.07	.03	-	-	-	
19R	.06	.04	.02	-	.12	-	.06	-	-	-	.06	
20R	-	.16	.02	-	.18	-	.14	.04	-	-	-	
21R	.02	.10	-	-	.12	-	-	.12	-	-	-	
22R	-	.12	-	.03	.18	.02	-	.14	.02	-	-	
23R	.02	.08	-	-	.11	-	.11	-	-	-	-	
24R	-	.06	.02	-	.08	.02	.06	-	-	-	-	
25R	-	.12	.03	.01	.16	-	.09	.03	-	-	.04	
26R	.01	.10	.02	-	.14	.01	.11	.02	-	-	-	
27R	-	.09	-	-	.10	-	.04	.03	-	.03	-	
28R	-	.15	.02	-	.17	.05	.07	-	.05	-	-	
29R	-	.14	-	-	.14	-	-	.06	-	-	.08	
30R	-	.14	-	.03	.17	.02	.13	.02	-	-	-	
31R	-	.10	-	.02	.12	.01	.07	-	.04	-	-	
32R	.01	.11	-	.01	.13	-	.04	.04	.05	-	-	
33R	.02	.09	.02	-	.13	-	.02	.05	-	.06	-	
34R	-	.14	-	-	.15	-	-	.04	-	.07	.05	
35R	-	.11	.01	-	.12	-	.02	-	.05	-	.05	
36R	-	.16	.02	-	.18	-	.02	.04	-	.03	.09	
37R	.02	.04	-	-	.10	-	-	.04	.02	-	.04	
38R	-	.26	-	-	.26	.09	-	.12	-	-	.05	
39R	-	.10	-	-	.12	.02	-	.02	.06	.02	-	
40R	-	.12	-	-	.12	-	-	.04	.02	.06	-	
41R	.04	.04	-	-	.08	-	-	.03	.04	-	.01	
42R	no density calculated											
43R	.02	.04	-	-	.06	-	.02	-	.02	-	.02	
44R	.04	.09	-	-	.13	.06	-	.07	-	-	-	
45R	-	.09	-	-	.09	-	-	.07	-	-	.02	

Table A-1. Fracture Density Data (cm^{-1}), Continued.

Site	MINERALOGY				Integ. Frac. Dens. ⁵	ORIENTATION					
	Q+K ¹	Q+S ²	Q+S ³	K+E ⁴		NNE ⁶	NE ⁷	ENE ⁸	WNW ⁹	NW ¹⁰	NNW ¹¹
46R	.02	.08	-	-	.10	.04	-	.04	.02	-	-
47R	.07	-	-	-	.07	-	.04	-	.03	-	-
48R	.09	-	-	-	.09	-	.02	.04	-	-	.03
49R	.03	-	-	-	.03	-	-	-	-	-	.03
50R	-	.04	-	-	.04	-	-	.03	.01	-	-
51R	-	.04	-	-	.04	-	-	.04	-	-	-
52R	.04	.03	-	-	.07	-	.04	-	-	-	.03
53R	.03	.06	.03	-	.12	.05	.02	.01	.02	.02	-
54R	.15	-	-	-	.15	-	-	.12	-	-	.03
55R	.13	-	-	-	.13	-	-	.10	-	-	.03
56R	.04	.08	-	-	.12	.02	.01	.05	.02	-	.02
57R	.01	-	.06	-	.08	-	-	-	.08	-	-
58R	-	.06	.02	-	.08	-	-	-	.08	-	-
59R	-	.06	-	-	.08	-	-	-	.04	.04	-
60R	.02	-	-	-	.02	-	-	.02	-	-	-
61R	.10	-	-	-	.10	.07	-	.03	-	-	-
62R	-	.07	-	-	.07	.02	.03	.02	-	-	-
63R	-	.03	-	-	.03	-	-	.01	.01	.01	-
64R	-	.08	-	-	.08	.02	.02	-	.04	-	-
65R	-	.14	-	-	.14	-	.12	-	.02	-	-
66R	-	.11	-	-	.11	-	.03	.03	-	-	.05
67R	.08	.07	-	-	.15	.04	-	.08	.03	-	-
68R	-	.11	-	-	.11	.06	-	.03	.02	-	-
69R	.02	.09	-	-	.11	-	-	.06	-	-	.05
70R	.03	.06	-	-	.09	.03	-	-	.03	.03	-
71R	-	.08	-	-	.08	-	-	-	.06	.02	-
72R	no density calculated										
73R	.05	-	-	-	.10	-	.02	-	.08	-	-
74R	-	.12	.02	-	.14	-	-	.11	-	-	.03
75R	-	.14	-	-	.14	.05	-	.09	-	-	-
76R	.12	-	-	-	.12	.05	-	.07	-	-	-
77R	.07	-	-	-	.07	-	.02	.05	-	-	-
78R	.11	-	-	-	.11	-	.03	.05	-	.02	.01
79R	.09	-	-	-	.09	-	.02	.03	.02	-	.02
80R	.03	.03	-	-	.06	.03	-	.03	-	-	-
81R	.09	-	-	-	.09	-	.04	.04	-	.01	-
82R	.08	-	-	-	.08	-	-	.05	-	.03	-
83R	.06	.08	.01	-	.15	.06	-	.04	.02	-	.03
84R	.08	-	-	.08	.16	-	.06	.10	-	-	-
85R	.10	.06	.02	.02	.20	.06	.06	.02	.02	.04	-
86R	.02	.14	-	-	.16	.04	-	.07	-	-	.05
87R	-	.12	.02	-	.16	-	.02	.02	.04	.03	.05
88R	no density calculated										
89R	.06	.04	-	-	.10	.04	-	.04	-	.02	-
90R	no density calculated										

Table A-1. Fracture Density Data (cm^{-1}), Continued.

Site	MINERALOGY				Integ. Frac. Dens. ⁵	ORIENTATION					
	Q+K ¹	Q+S ²	Q+S ³	K+E ⁴		NNE ⁶	NE ⁷	ENE ⁸	WNW ⁹	NW ¹⁰	NNW ¹¹
91R	.07	.04	-	-	.11	.04	-	.02	.03	-	.02
92R	.06	.10	.02	-	.18	-	.08	.04	.06	-	-
93R	.02	.14	.04	-	.18	-	.03	.07	.03	-	.05
94R	.02	.18	.04	-	.22	.12	-	.06	-	.06	-
95R	no density calculated										
96R	.08	.07	-	.02	.17	.04	.04	.02	-	-	.07
97R	.02	-	.08	.02	.12	-	.06	-	-	.06	-
98R	.06	.10	-	-	.16	-	.08	.04	-	-	.04
99R	.15	.01	.06	-	.22	-	.05	.05	.05	.02	.05
100R	.03	.15	.04	-	.22	-	.10	.02	-	-	.10
101R	.02	.02	.12	.06	.22	-	.09	.08	-	.02	.03
102R	-	.09	.08	-	.17	.02	.06	.06	-	-	.03
103R	-	.04	.10	.01	.15	-	.08	.02	-	-	.05
104R	-	.10	-	.01	.11	-	.06	.05	-	-	-
105R	.02	.12	.06	-	.20	-	.10	.05	-	.02	.03
106R	-	.15	-	-	.15	.04	.14	.02	-	.02	-
107R	-	.12	.06	-	.18	-	.09	.05	-	.02	.02
108R	-	.09	-	.02	.11	-	.09	.02	-	-	-
109R	.12	.02	-	.02	.16	-	.04	.10	-	.02	-
110R	-	.09	.07	-	.16	-	.12	-	-	-	.04
111R	-	.08	.14	.02	.24	.06	.07	.11	-	-	-
112RA	-	.06	.14	.02	.22	.06	.07	.07	-	.02	-
112RB	.01	.12	.13	-	.26	.04	.10	.07	.03	-	.02
113R	-	.02	.16	-	.18	-	.09	.03	-	.04	.02
114R	-	.10	.05	.01	.16	-	.10	.06	-	-	-
115R	.02	-	-	.12	.14	-	.02	.12	-	-	-
116R	-	.04	.13	-	.17	-	.07	.04	-	-	.06
117R	-	.06	.10	-	.16	-	.08	.03	.03	-.02	-
118R	-	.06	.13	.01	.20	-	.17	-	-	-	.03
119R	.04	-	.14	.02	.20	-	.10	.02	-	.06	.02
120R	-	.06	.08	.02	.16	-	.10	.02	-	-	.04
121R	-	.15	-	-	.15	.04	.11	-	-	-	-
122R	-	.06	.09	-	.15	.02	.10	-	.03	-	-
123R	-	.02	.12	.01	.15	.06	.05	.01	-	-	.03
124R	-	.02	.13	.02	.17	.05	.08	-	-	-	.04
125R	-	.03	.10	.01	.14	-	.07	-	.03	-	.04
126R	.04	.06	.04	.01	.15	.03	.06	-	.03	-	.03
127R	-	.10	.02	-	.12	-	.08	-	-	.02	.02
128R	-	.13	-	-	.13	-	.08	-	-	-	.05
129R	-	.08	.04	.02	.14	.06	.04	-	-	-	.04
130R	.04	.05	-	.02	.11	-	.05	.06	-	-	-
131R	.05	.03	-	-	.08	-	.04	.02	-	.02	-
132R	.02	.07	.02	.02	.13	.03	-	.10	-	-	-
133R	-	.11	.02	.02	.15	-	.06	.02	-	.05	.02
134R	-	.11	-	.02	.13	-	.07	.06	-	-	-

Table A-1. Fracture Density Data (cm^{-1}), Continued.

Site	MINERALOGY				Integ. Frac. Dens. ⁵	ORIENTATION					
	Q+K ¹	Q+S ²	Q+S ³	K+E ⁴		NNE ⁶	NE ⁷	ENE ⁸	WNW ⁹	NW ¹⁰	NNW ¹¹
135R	-	.10	.05	-	.15	.04	.07	.04	-	-	-
136R	-	.14	-	-	.14	-	.06	.06	-	-	.02
137R	-	.12	-	-	.12	-	.02	.08	-	.02	-
138R	-	.05	.02	-	.07	-	.04	.03	-	-	-
139R	.04	.06	-	-	.10	.03	-	.02	-	.03	.02
140R	-	.05	.03	-	.08	.03	-	.05	-	-	-
141R	-	.09	-	-	.09	-	.04	.03	-	-	.02
142R	-	.08	.09	-	.17	-	.03	.08	-	-	.06
143R	-	.12	-	.03	.15	.04	.11	-	-	-	-
144R	-	.11	.02	.02	.15	-	.12	-	-	-	.03
145R	.02	.11	.02	-	.15	.04	.09	-	-	.02	-
146R	.04	.13	.02	.02	.21	.02	.05	.08	.04	-	.02
147R	-	.15	.05	-	.20	.02	-	.14	-	.02	.02
148R	-	.08	.06	-	.14	.03	.08	.02	.01	-	-
149R	-	.11	.03	.02	.16	.08	.04	.02	-	.02	-
150R	-	.16	.06	-	.11	.03	.12	-	.02	-	.05
151R	.02	.14	-	-	.16	-	-	.09	.07	-	-
152R	-	.16	.04	-	.20	-	-	.16	-	-	.04
153R	-	.09	.06	.02	.17	.06	-	.07	.04	-	-
154R	-	.18	-	.02	.20	-	-	.11	.03	-	.06
155R	-	.22	-	.03	.25	-	.09	.12	-	-	.04
156R	-	.18	.03	-	.21	.03	.06	.09	-	-	.03
157R	-	.14	.03	.02	.19	.02	.05	.09	-	-	.03
158R	.02	.15	-	.02	.19	-	.03	.10	-	.02	.02
159R	-	.11	.02	-	.15	.02	.02	.07	.04	-	-
160R	-	.13	.03	-	.16	.06	-	.02	-	.06	.02
161R	-	.14	.04	-	.18	.12	.02	.04	-	-	-
162R	.07	.10	-	-	.17	.06	.08	.03	-	-	-
163R	-	.09	.04	-	.14	-	.08	.04	-	-	.04
164R	-	.12	.07	-	.19	-	.11	-	.06	-	.02
165R	.02	.10	-	-	.12	-	.03	.07	-	-	.02
166R	.04	.11	.02	-	.17	.05	.05	-	.07	-	-
167R	.02	.16	-	-	.18	.01	.04	.13	-	-	-
168R	-	.02	-	-	.02	-	.02	-	-	-	-
169R	.03	-	-	-	.03	-	-	.03	-	-	-
170R	.07	-	-	-	.07	-	.05	.02	-	-	-
171R	.04	-	-	-	.04	-	-	.04	-	-	-
172R	.03	-	-	-	.03	-	.01	.02	-	-	-
173R	.01	-	-	-	.01	-	-	.01	-	-	-
174R	.04	-	-	-	.04	-	-	.03	.01	-	-
175R	-	.12	.03	.02	.17	-	.09	.08	-	-	-
176R	-	.16	.02	.03	.21	-	.05	.14	-	-	.02
177R	.02	.14	.02	-	.18	-	.02	.10	-	.02	.04
178R	.04	.13	-	-	.17	-	-	.13	-	-	.04
179R	-	.17	.03	-	.20	-	.20	-	-	-	-

Table A-1. Fracture Density Data (cm^{-1}), Continued.

Site	MINERALOGY				Integ. Frac. Dens. ⁵	ORIENTATION					
	Q+K ¹	Q+S ²	Q+S ³	K+E ⁴		NNE ⁶	NE ⁷	ENE ⁸	WNW ⁹	NW ¹⁰	NNW ¹¹
180R	-	.15	.03	-	.18	.02	.06	-	-	.06	-
181R	.02	.15	-	.04	.21	-	.10	.06	-	-	.05
182R	-	.16	.04	-	.20	-	.14	.03	-	-	.03
183R	.02	.11	.06	.02	.21	.02	.04	.08	.04	-	.03
184R	.06	.10	.03	-	.19	.02	.06	.06	-	.05	-
185R	.07	.13	.05	-	.25	.03	.10	-	-	.12	-
186R	.04	.18	-	-	.22	.05	.09	.03	-	.05	-
187R	.05	.15	.03	-	.23	-	.10	.10	-	-	.03
188R	.03	.11	-	.01	.18	.06	-	.08	-	-	.02
189R	.02	.14	.02	-	.18	.03	.04	.06	-	-	.05
190R	.09	.11	.02	-	.22	.04	.02	.04	-	-	.12
191R	.02	.16	.02	-	.20	.04	.04	.09	-	.01	.02
192R	.02	.16	.03	-	.21	.03	-	-	.08	-	.10
193R	-	.12	.05	.02	.19	-	.14	.05	-	-	-
194R	.06	.07	.03	-	.16	-	-	.02	-	.08	.06
195R	.06	.04	.07	.01	.18	.06	.08	-	-	.04	-
196R	-	.16	.03	-	.19	.05	-	.06	-	.08	-
197RA	-	.07	.07	-	.14	-	.05	.03	-	-	.06
197RB	-	.17	.04	-	.21	-	.06	.09	-	.08	-
197RC	-	.18	.04	-	.22	-	.11	.03	-	-	.08
198R	.03	.15	.05	-	.23	-	.07	.09	-	.07	-
199R	-	.19	.03	-	.22	-	.12	.06	-	-	.04
200R	.06	.13	-	.03	.22	.04	.07	.03	-	.05	.03
201R	.02	.11	.03	.02	.19	-	.02	.12	-	-	.05
202R	.09	.08	.02	-	.19	-	.05	-	.07	.02	.05

¹Quartz + Orthoclase²Quartz + Sulfide (<1%)³Quartz + Sulfide (>1%)⁴Orthoclase + Epidote⁵Integrated Fracture Density⁶NS-N30°E⁷N30°E-N60°E⁸N60°E-EW⁹N60°W-EW¹⁰N30°W-N60°W¹¹NS-N30°W

LIST OF REFERENCES

- Aiken, D. M. and West, R. J., 1978, Some geologic aspects of the Sierrita-Esperanza copper-molybdenite deposit, Pima County, Arizona: Arizona Geol. Soc. Dig., v. 11, p. 117-128.
- Beane, R. E., 1979, Studies of mineralization and alteration at the Sierrita porphyry copper deposit, Arizona: II. wallrock influence on alteration and mineral deposition (abs.): 108th A.I.M.E. Mtg., New Orleans, Abstracts with Programs, p. 76.
- Brace, W. F., in press, Permeability of crystalline and argillaceous rocks: status and problems: Int. Jour. Rock Mech. Min. Sci.
- Cooper, J. R., 1960, Some geologic features of the Pima mining district, Pima County, Arizona: Geol. Surv. Bull. 112-C.
- _____, 1973, Geologic map of the Twin Buttes quadrangle, southwest of Tucson, Pima County, Arizona: U. S. Geol. Surv. Misc. Geol. Inv. Map I-745.
- Damon, P. E. and Mauger, R. L., 1966, Epeirogeny-orogeny viewed from the Basin and Range Province: Soc. Min. Eng. Trans., v. 235, no. 1, p. 99-112.
- Knapp, R. B. and Knight, J. E., 1977, Differential thermal expansion of pore fluids: fracture propagation and microearthquake production in hot pluton environments: Jour. Geophys. Res., v. 82, no. 17, p. 2515-2522.
- Knapp, R. B. and Norton, D., in press, Preliminary numerical analysis of processes related to magma crystallization and stress evolution in cooling pluton environments: Am. Jour. Sci.
- Lacy, W. C., 1959, Structure and ore deposits of the east side of the Sierrita Mountains: Arizona Geol. Soc. Dig., v. 2, p. 185.
- Lovering, T. G., Cooper, J. R., Drewes, H., and Cone, G. C., 1970, Copper in biotite from igneous rocks in southern Arizona as an ore indicator: U. S. Geol. Surv. Prof. Paper 700-B, p. B1-B8.
- Lynch, D. W., 1966, The economic geology of the Esperanza Mine and vicinity, in Titley, S. R. and Hicks, C. L. (eds.), Geology of the Porphyry Copper Deposits in the Southwestern United States: Tucson, The University of Arizona Press, p. 267-279.

- Lynch, D. W., 1968, The geology of the Esperanza Mine, Arizona: Arizona Geol. Soc. Guidebook III, Tucson, p. 125-136.
- Norton, D. and Knapp, R., 1977, Transport phenomena in hydrothermal systems: the nature of porosity: Am. Jour. Sci., v. 277, p. 913-936.
- Norton, D. and Knight, J., 1977, Transport phenomena in hydrothermal systems: cooling plutons: Am. Jour. Sci., p. 937-981.
- Potter, R. W., Jr., 1977, Pressure corrections for fluid-inclusion homogenization temperatures based on the volumetric properties of the system NaCl-H₂O: U. S. Geol. Surv. Jour. Res., v. 5, no. 3, p. 389-395.
- Potter, R. W., Jr., Clyne, M. A., and Brown, D. L., 1978, Freezing point depression of aqueous sodium chloride solutions: Econ. Geol., v. 73, p. 284-285.
- Preece, R. K., 1979, Paragenesis, geochemistry, and temperatures of formation of alteration assemblages at the Sierrita deposit, Pima County, Arizona: M. S. Thesis, The University of Arizona, Tucson, 106 p.
- Preece, R. K. and Beane, R. E., in preparation, Contrasting evolutions of hydrothermal alteration in quartz monzonite and quartz diorite at the Sierrita porphyry copper deposit, Arizona: The University of Arizona.
- _____, 1979, Studies of mineralization and alteration at the Sierrita porphyry copper deposits, Arizona: I. paragenetic relations and associated fluid characteristics (abs.): 108th A.I.M.E. Mtg., New Orleans, Abstracts with Program, p. 76.
- Rehrig, W. A. and Heidrick, T. L., 1972, Regional fracturing in Laramide stocks of Arizona and its relationship to porphyry copper mineralization: Econ. Geol., v. 67, p. 198-213.
- Roedder, E., 1962, Studies of fluid inclusions: I. low-temperature application of a dual purpose freezing and heating stage: Econ. Geol., v. 57, p. 1045-1061.
- _____, 1967, Fluid inclusions as samples of ore fluids, in Barnes, H. L. (ed.), Geochemistry of Hydrothermal Ore Deposits: Holt, Rinehart, and Winston, Inc., New York, p. 515-574.
- Smith, V. L., 1975, Hypogene alteration at the Esperanza Mine, Pima County, Arizona: M. S. Thesis, The University of Arizona, Tucson, 161 p.

- Snow, D. T., 1970, The frequency and aperture of fractures in rocks: Jour. Rock Mech., v. 7, p. 23-40.
- Titley, S. R., 1978, Geologic history, hypogene features, and processes of secondary enrichment at the Plesyumi copper prospect, New Britain, Papua New Guinea: Econ. Geol., v. 73, p. 768-784.
- Titley, S. R., Fleming, A. W., and Neale, T. I., 1978, Tectonic evolution of the porphyry copper system at Yandera, Papua New Guinea: Econ. Geol., v. 73, p. 810-828.
- Villas, R. N. and Norton, D., 1977, Irreversible mass transfer between circulating hydrothermal fluids and the Mayflower stock: Econ. Geol., v. 72, p. 1471-1504.
- West, R. J. and Aiken, M. A., in press, Geology of the Sierrita-Esperanza deposit, Pima County, Arizona, in Advances in the Geology of the Porphyry Copper Deposits of Southwestern North America, Titley, S. R. (ed.): The University of Arizona Press.

Shaw, R. T., 1970. The frequency and severity of insecticide resistance in cotton. *Ann. Entomol. Soc. Am.* 63: 12-20.

Thayer, L. W., 1975. Genetic history, systematic relationships, and taxonomy of *Phaenocarpa* as determined by the allozyme method. *Ann. Entomol. Soc. Am.* 68: 104-124.

Thayer, L. W., 1976. A. W. and Jones, T. L., 1976. Taxonomic revision of the genus *Phaenocarpa* (Diptera: Tephritidae). *Ann. Entomol. Soc. Am.* 69: 419-426.

Thayer, L. W. and Jones, T. L., 1977. Taxonomic revision of the genus *Phaenocarpa* (Diptera: Tephritidae). *Ann. Entomol. Soc. Am.* 70: 1271-1282.

Ward, R. J. and Jones, T. L., in press. Biology of the *Phaenocarpa* group (Diptera: Tephritidae). In: *Handbook of the Biology of the Tephritidae*, ed. by R. J. Ward and T. L. Jones. *Ann. Entomol. Soc. Am.* 70: 1-10.

FIGURE 5
SAMPLE LOCATIONS WITHIN THE RUBY STAR GRANODIORITE,
SIERRITA PORPHYRY COPPER DEPOSIT

E9791
1980
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