Water-Rock Interaction 2001, Cidu (ed.), © 2001 Swets & Zeitlinger, Lisse, ISBN 90 2651 824 2

Scale versus detail in water-rock investigations 2: Field-scale models of fracture networks in mineral deposits

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ABSTRACT: Predicting spatial properties of heterogeneous, mineralized rocks is important for many applications. Because each mineral deposit is unique, any analytical framework for studying coupled, water-rock systems must be sufficiently robust to account for variability within and between areas. Rock-water interactions are difficult to model, but a helpful approach to modeling fracture-controlled flow networks in mineralized rocks is to evaluate mineralized fractures and structural geologic systematics in and around specific mineral-deposit types. We propose that the necessary coupling of deformation, chemical transport, and heat transfer in hydrothermal systems sets constraints on fault and fracture systematics that must occur, and these systematics vary according to mineral-deposit type. We propose a set of field-based systematics at different spatial scales for porphyry-style copper and molybdenum deposits and related veins that help in field sampling design and data analysis.

1 INTRODUCTION

Predicting ground- and surface-water chemistry in mineralized rocks is challenging because of heterogeneity in the spatial properties (Wanty et al. 2001). Such challenges lead to implicit assumptions in field studies about scale dependence or scale invariance in hydrologic phenomena. However, variance in lithologic and structural geologic characteristics frequently contribute to a lack of correspondence between predicted and measured properties in field studies. Sensitivity analyses show that hydraulic conductivities and recharge areas are frequently the sources of the greatest uncertainty in hydrologic and hydrogeochemical modeling (Hill 2000). Thus, the effects of geologic structures on ground water flow systems are of considerable importance.

The greatest heterogeneity in mineral deposits is at the microscopic and outcrop scales. At the larger scale of deposits and mining districts, the coupling of deformation, chemical transport, and heat transfer in hydrothermal systems set constraints on fault and fracture systematics that occur. The fracture systematics vary by mineral-deposit type, allowing for consistent field-scale fault/fracture models to be derived for a given type. This paper presents a fracture-network model of epizonal stockwork porphyry- and related vein-form deposits, and presents an example of a field study wherein this model is being tested.

2 FIELD-SCALE FRACTURE MODELS

Individual mineral deposits contain fracture networks that can vary from microscopic, short length-scale vein-filled fractures to meters wide, long length-scale veins. Fracture density and interconnectivity can be very high as in stockworks and breccias to relatively low as along long trace-length normal faults. To serve as an analog for field-scale fluid-flow models, mineral-deposit fracture-network models must describe the spatial distribution of fracture/fault systems within a specific mineral-deposit type.

Epizonal, hydrothermal mineral deposits are commonly found along strike-slip fault systems. The further development of fractures during mineralization follows a systematic pattern. Under regional tectonic compression, the strike-slip faults form typically at angles between 30-55° to the maximum principle far-field stress (σ_1). When échelon and parallel strike-slip faults mechanically interact, strain along them may be accommodated along linking extensional faults. Because these extensional faults are at low angles to σ_1, they should be hydraulically conductive. In fact, hydrothermal veins are often localized along such faults. Conversely, the presence of hydrothermal veins and alteration are direct evidence of hydraulic conductivity in the geologic past. The fracture networks that developed under past tectonic regimes still exist, and are often the dominant hydraulically conductive features in the present. Thus, an understanding of the development of fractures and the systematics of their spatial extent and orientation facilitates an understanding of present-day hydrology at several spatial scales.

Figure 1. Three spatial scales of fracturing in porphyry-style Mo-Cu deposit at Sierrita-Esperanza (S-E), Arizona USA. (a) Regional scale showing localization of deposit in releasing bend into right extensional stepover along right-lateral, strike-slip fault system. Contours are fracture density (cm^{-1}). (b) Deposit scale preferred northeast orientation of veins generally parallel to far-field extension direction. (c) Sketch of hand sample showing early-stage, interconnected curved-trace fractures crosscut by straight-trace fractures (at S-E short curved-trace network is generally absent). Data are in part after Cooper (1973) and Titley (1990).

2.1 *Porphyry-style mineral deposits*

Porphyry-style wall-rock alteration and ore zones may vary from 100s to thousands of millions of tons of rock. Figure 1 illustrates three scales of fracturing in the vicinity of and within these deposits using the Sierrita-Esperanza Mo-Cu deposit, Arizona, as an example. At the regional scale, strike-slip faults are the primary displacement zones (PDZ) localizing the deposits (Fig. 1a). Most frequently, they are within releasing bends into extensional stepovers along PDZs. The deposits form in vertically elongated cylindrical, medium- to coarse-grained porphyritic intrusive complexes. At deposit scale, the ore-bearing fracture networks form an upward-tapering, conical zone around a less intensely fractured, lower grade core, all within the cylindrical intrusive center. The ores are generally along straight fractures that tend to be preferentially elongated in the direction of the extensional faults that make up the stepover (Fig. 1b). At the microscopic and outcrop scale, the fracture networks consist of an early-stage dense, interconnected network of millimeter to centimeter length-scale curved fractures and subsequent centimeters to meters-scale, straight fractures (Fig. 1c). Sulfide minerals are mostly along straight fractures.

2.2 *Vein-form mineral deposits*

Epizonal vein-form deposits frequently occur along tensile fractures. They may have strike lengths of kilometers and be up to tens of meters wide, and vary down to trace lengths of meters to hundreds of meters and widths of centimeters to a few meters. Associated alteration may affect many km^3 of rock, with ore zones consisting of from 100s of thousands to millions of tons within the spatially more extensive alteration.

Ore bodies are discrete entities within spatially more extensive vein networks. The ores are concentrated where the vein-controlling tensile fractures are segmented by synthetic or antithetic shear faults, producing a “tensile-shear mesh” (cf. Hill 1977) within an extensional stepover. Figure 2 shows a well-developed mesh at Mahd adh Dhahab, Saudi Arabia outlined by open stopes. Thus, vein ore bodies reflect the compartmentalization of hydrothermal fluid flow during mineralization.

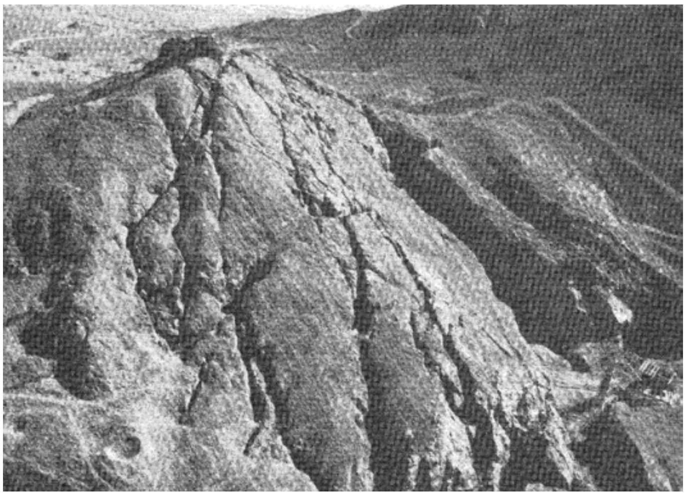

Figure 2. Aerial photograph of open stopes on Mine Hill, Mahd adh Dhahab epizonal vein deposit, Saudi Arabia (from Hilpert et al. 1984). The stopes outline a “tensile-shear” fault mesh within an extensional stepover between left-lateral strike-slip faults. Extensional faults strike towards the top of the photograph and are segmented by oblique, synthetic and antithetic shear faults. The segmentation imparts the observed zigzag pattern of the stopes.

3 FIELD APPLICATION

At many localities worldwide, porphyry-style deposits are associated with overlapping, overlying and/or lateral vein deposits. The example below is the porphyry-style molybdenum deposit and related veins located in Redwell Basin near Mount Emmons, Crested Butte, Colorado USA (Fig. 3).

3.1 *Geologic framework of Redwell Basin*

The Redwell Basin deposits occur in a sequence of Cretaceous marine, clastic sedimentary rocks consisting of silty sandstone, sandy limestone, and carbonaceous shale overlain by shale, thick bedded and massive sandstone, coal, and carbonaceous shale (Gaskill et al. 1967). The sedimentary rocks are intensely hornfelsed in the upper and lowermost reaches of Redwell Basin Creek due to intrusive activity.

Composite igneous breccia pipes, consisting of rhyolite and rhyolitic intrusion breccia, crop out in the wall and floor of upper Redwell Basin and the porphyry-style mineralization is at depth beneath these pipes. Granodiorite porphyry dikes also crop out in the study area.

3.2 *Porphyry- and vein-controlling faults*

The stockwork-veined porphyry molybdenum deposit (Sharp 1978) is localized in a zone of predominantly N50°E-striking, left-lateral strike-slip faults in upper Redwell Basin where they intersect N30°W and north-south normal faults (Fig. 3). The north-south normal faults continue north to a parallel strike-slip fault zone implying the north-south faults are components of an extensional stepover between the northeast zones. Thus, the Redwell Mo deposit is in the releasing bend into the stepover. The Mo deposit-related breccia intrusion (b in Fig. 3) is elongated parallel to the stepover. Polymetallic Cu-Zn-Pb vein deposits occur to the southeast of the porphyry deposit and in the Daisy mine along the north-striking extensional faults (Fig. 3).

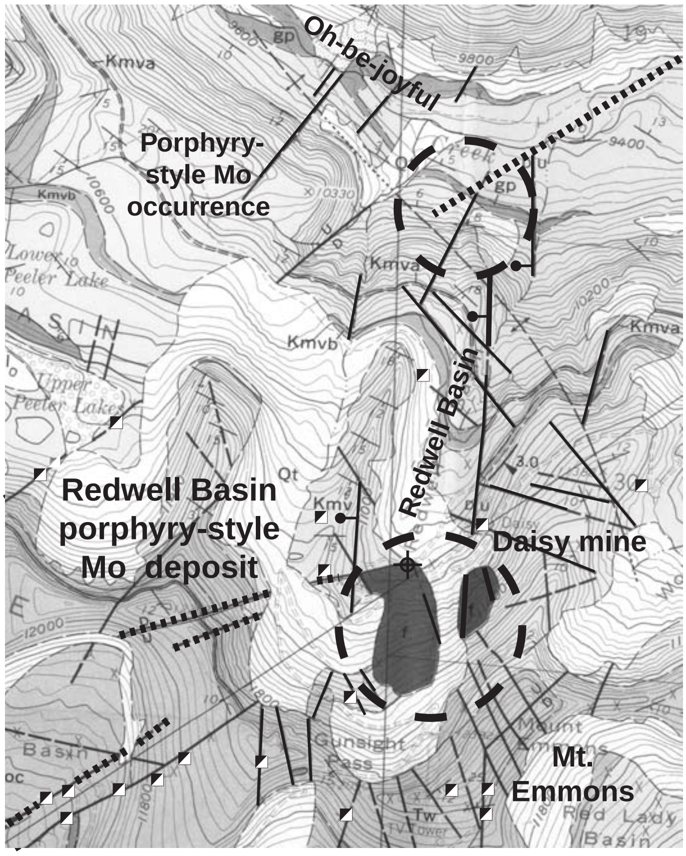

Figure 3. Geology of Redwell Basin, Colorado (from Gaskill et al. 1967). Redwell Basin Creek flows north from the cirque beneath Mt. Emmons. Porphyritic intrusions shown with letter b. Circular dashed lines show the location of Redwell Basin porphyry molybdenum deposit (A) in the uppermost part of the basin and zone of stockwork veining anomalous in molybdenum in the lowermost part of the basin. Angle drill hole location shown with crossed circle and mines as shaft symbol.

3.3 *Hydrogeology and hydrogeochemistry*

The Redwell basin is approximately 1 km wide and 2.5 km long. Surface water originates from several sources including springs and seeps, fracture systems feeding gaining stream reaches, mine workings, and artesian flow from a drill hole a few meters above Redwell Creek. The drill hole angles from the north to the south and penetrates the porphyry deposit.

The average gradient of the creek is 28%. At the time of sampling, discharge varied from approximately 20 L/min to 2000 L/min.

3.3.1 *Fracture-controlled flow*

Induration and metamorphism of the sedimentary host rocks precludes significant intergranular ground-water flow except over extremely long time periods, so the observed flow must be predominantly along fractures. This is corroborated by the ground-water chemistry that demonstrates compartmentalization and isolation of chemically distinct “packages” of water (Tuttle et al. 2000). For example, a natural spring in the bottom of the basin just west of the Daisy mine that occurs along north-south fractures north of the molybdenum deposit (Fig. 3) has a pH of 3.6 and conductivity of 200 μS and is actively precipitating ferricrete. A few meters to the south-southeast, a spring along a northwest-striking fracture system has a pH of 7.2 and conductivity of 40 μS and appears to discharge water from the unmineralized sedimentary rocks in the western wall of the canyon.

To predict the current hydraulic conductivity, we estimate the present-day far-field stresses acting on the region using data in Zoback and Zoback (1989). Our estimate implies that northeast-striking, north-south, and northwest fractures should be hydraulically conductive. The inferred conductivities can be integrated with expected hydraulic gradients and the porphyry/vein fracture models to interpret and model the hydrogeochemistry of Redwell Basin. Mineralization in the upper reaches of the drainage should affect ground- and surface-water chemistry in the cirque area because of the elongation of stockworks and fault-veins to the north. In the intermediate and lower reaches of the basin, northwest-striking fractures in the basin sidewalls should provide ground waters dominated by fracture flow from unmineralized sedimentary rocks to the northeast of the porphyry and vein deposits.

3.3.2 *Porphyry deposit-related waters*

Fluorine and chlorine in the mineralized porphyries together with sulfur isotopes allow distinction of mineralized ground-water sources from unmineralized sources. Fluorine is present in such minerals as fluorite and topaz in the porphyry-style mineralization, and upon leaching results in molar F^-/Cl^- ratios greater than 2 to as high as 9.5 in waters from mineralized rocks.

Porphyry water has high concentrations of iron. Zinc accounts for 80% of the ore-metal load with Cu and Pb each accounting for 10%. $\delta^{34}S_{SO4}$ in the water is +2.7‰; sulfur in molybdenite in the deposit is +3.7 to +4.6‰ (Stein and Hannah 1985).

3.3.3 *Vein-related waters*

Mine drainages were sampled to characterize vein waters. Sulfate sulfur in mine workings ranges from +1.0 to –0.5‰. Mass balance calculations using sulfur isotopes indicate that mineralized waters in the upper reaches of Redwell Basin consist of 70% "porphyry water" and 30% other.

3.4 *Interpretation using field-scale model*

As predicted by the porphyry-style deposit fracture model developed from the analysis of deposit data worldwide (B.R. Berger, unpublished data) and summarized in Section 2.1, the Redwell porphyry-style system is localized in the releasing bend into an extensional stepover and elongated in a northerly direction. Further, the vein model presented in Section 2.2 predicts that vein mineralization should occur in the Redwell Basin along extensional faults segmented by northwest and northeast shear faults.

When considered in light of predicted present-day hydraulic conductivities and hydraulic gradients, the fracture networks in mineralized rocks imply that ground and surface waters in the upper southern and southeastern parts of Redwell Basin should be dominated by fracture flow through mineralized rocks. These relations were corroborated by the hydrochemical data. Further, the hydrogeochemical data show that ground waters in the study area are compartmentalized and predominantly "porphyry waters," "vein waters," and "unmineralized rock waters" can be distinguished.

Progressively downstream from the cirque, there is a continual input of depleted ^{34}S water and values approach those of waters from the vein mines. This implies that vein waters mix along north-striking normal faults and northwest-striking segmentation faults with the porphyry waters. Yet farther downstream, where northwest-striking fractures conducting water from unmineralized rocks intersect the stream, the conductivity of the stream waters steadily decreases and sedimentary sulfur is introduced.

4 CONCLUSIONS

In mineralized rocks, fracture flow dominates the ground-water regime. The combinations of field-scale fracture models of specific mineral-deposit types with predictions of local hydraulic heads and regional flow patterns provide a framework within which to predict ground-water flow patterns and interpret hydrochemical data. In the instance of Redwell Basin, Colorado, the use of molar concentration ratios such as F:Cl in conjunction with sulfur isotope ratios in different styles of mineralization and unmineralized rocks provides a comprehensive model of ground water flow and an understanding of the natural geochemical state of the local area. Further, there is a basis for modeling of potential environmental effects from future mining within the basin.

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