

Fissural permeability in the Roşia Poieni copper deposit: Influence on ore repartition at the open pit scale

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Abstract Fracture permeability is a key parameter in fluid flow through the crust. In a hydrothermal system, fluid flow is dominated by the vein network. A quantification of paleopermeability has been performed at the scale of the hydrothermal system of Roşia Poieni, a Romanian porphyry copper. A suitable method for the quantification of permeability in this type of hydrothermal environment is used based on a discontinuous environment, which consists of the rock as a homogeneous medium (matrix) + N different elements (fractures) that can be described by structural analysis.

Paleopermeability heterogeneities have been observed: lower levels of the intrusion are characterized by higher paleopermeabilities generated by thick and clustered veins, whereas higher levels are characterized by a more pervasive paleopermeability with thin veins that have a homogeneous spatial repartition. At each level of the open pit, specific zones can be defined in relation to the density and spacing of veins, leading to variations in paleopermeability that are correlated with two types of mineral filling: (1) quartz-pyrite and (2) copper minerals.

Keywords: Porphyry copper, fissural permeability, fluid flow, mineralization

1. Introduction

Fracture permeability is a key parameter in the understanding of fluid flow through the crust. The fractures, which may present a great extent and width, act as preferential channels in rocks of low permeability and thus control both the intensity and the direction of the fluid flow. The high permeabilities described in hydrothermal systems are directly produced by a fracture permeability that is much greater than the low matrix permeability of the host rocks, which ranges from 10^{-4} to 10^{-17} darcy in crystalline rocks (Brace et al., 1968) and from 10^{-2} to 10^{-11} darcy in sedimentary rocks (Norton and Knight, 1977; Curewitz and Karson, 1997). Therefore, in a hydrothermal environment, permeability must be estimated by modeling an equivalent porous matrix crosscut by anisotropic 3D fractures that concentrate fluid flows.

Following Scheidegger (1974), the modeling of rock permeability can be performed using two main types of models:

Geometrical models use the concept of equivalent porous media and require the definition of a size parameter that is defined by an equivalent hydraulic radius (Walsh, 1981; Brace et al., 1968; Gangi, 1978; Brown, 1987). This approach requires the geometrical characterization of the main drains (extents and widths) and pore sizes. Each object, pore, and fracture is represented in the model and acts as an individual source of permeability.

Statistical Models are based on statistical laws that describe the geometrical characteristics of the pore and fracture networks. No direct or deterministic representations of pores and fractures are used (Guéguen and Dienes, 1989). When precise observations and measures are sufficient to describe the fracture network geometry, geometrical models are better suited

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for characterizing the permeability developed by a fracture network in a massive rock. Within these geometrical models, two types of porous media can be distinguished:

The first model offers a continuous approach, which maintains that the rock porosity is defined by a single homogeneous medium constituted by a matrix that is crosscut by dense fractures. A homogenous porous medium is defined by a mean porosity and permeability that integrate both the pore matrix and fracture hydraulic contributions (Snow, 1969; Oda, 1986; Ababou, 1991; Vuillod, 1995).

The second approach defines a discontinuous media and maintains that fractures are individual channels characterized by a specific porosity and permeability that differ from those of the fracture matrix. This approach requires a precise structural analysis and a deterministic characterization of the fracture network. The identification of discrete fractures in the rocks allows the assessment of the flow anisotropy and the definition of a permeability tensor. Permeability is related to the geometrical parameters of fractures, such as the direction, density, spacing, lengths and widths. Therefore, this approach is more appropriate for characterizing the paleopermeability of a vein system when its geometrical characteristics can be described by a field study or drillhole logging.

The fracture permeability can therefore be quantified using these geometrical parameters, and several different reports in the literature use a classical “cubic law” of width approach (Snow, 1969; Oda, 1986; Ababou, 1991; Vuillod, 1995). For example, equation 1 determines the conductivity C_m of the fracture set m and relates this conductivity to the mean spacing S_m and mean cubic width w_m of the fracture set, which is represented by k fractures. C_m (units of m/s) is the maximum conductivity because the fracture set is assumed to be infinite in this model.

$$C_m = \frac{g}{12 \cdot \nu} \cdot \frac{w_m^3}{S_m} \quad (1)$$

$$\text{with } S_m = \frac{1}{N_m} * \sum_{k=1}^{N_m} S_{m,k} \quad (2)$$

$$\text{and } w_m = \frac{1}{N_m} * \sum_{k=1}^{N_m} w_{m,k}^3 \quad (3)$$

where g : acceleration due to gravity [$m \cdot s^{-2}$]

ν : kinematic viscosity of the fluid [$m^2 \cdot s^{-1}$].

w_m : mean width of fracture set [m]

$w_{m,k}$: thickness of the k^{th} fracture [m].

S_m : mean spacing of the fracture set m [m]

$S_{m,k}$: spacing between fractures $k-1$ and $k+1$ [m]

N_m : number of fractures in the fracture set m

The fracture set conductivity C_m is related to the permeability K_m (m^2) by the following relation:

$$K_m = C_m \cdot \frac{\mu}{\rho \cdot g} \quad (4)$$

where μ is the fluid dynamic viscosity, ρ is the fluid density [kg/m^3] and g is the acceleration due to gravity [m/s^2]

The permeability quantification method is based on equation 1, which was proposed by Vuillod (1995). This method uses a cubic law of fracture width and the spacing parameter between fractures within a fracture set. Indeed, even if large and well-developed drains exist within the rock matrix, the final equivalent permeability of the rocks is not always important. This model uses the spacing parameter as a weight of the permeability values and then defines a hydraulic influence of each fracture of width w (Fig. 1).

This work will discuss the use of a geometrical model to characterize the paleopermeability in a hydrothermal system. The model has been applied on a porphyry copper deposit (Roşia Poieni, Romania), and this paper will discuss the correlation between the estimated permeability (and its variation at the open pit scale) and the spatial distribution of the copper mineralization.

2. Geological setting

The southern part of the Apuseni Mountains (West Romania) exhibits a variety of mineral occurrences (Cioflica et al., 1973; Ianovici et al., 1977; Borcos et al., 1983; Udubasa et al., 1992; Heinrich and Neubauer, 2002) that are related to Neogene volcanic activity (Lemne et al., 1983; Pécksay et al., 1995; Rosu et al., 1997; Alderton et al., 1998). The Roşia Poieni porphyry copper deposit, which is the largest such deposit in the Apuseni Mountains, belongs to the metallogenic district of Bucium-Baia de Arieş (Fig. 2). The basement consists of pre-Mesozoic metamorphic rocks intruded by magmatic bodies and covered by pyroclastics of variable composition (Fig. 2).

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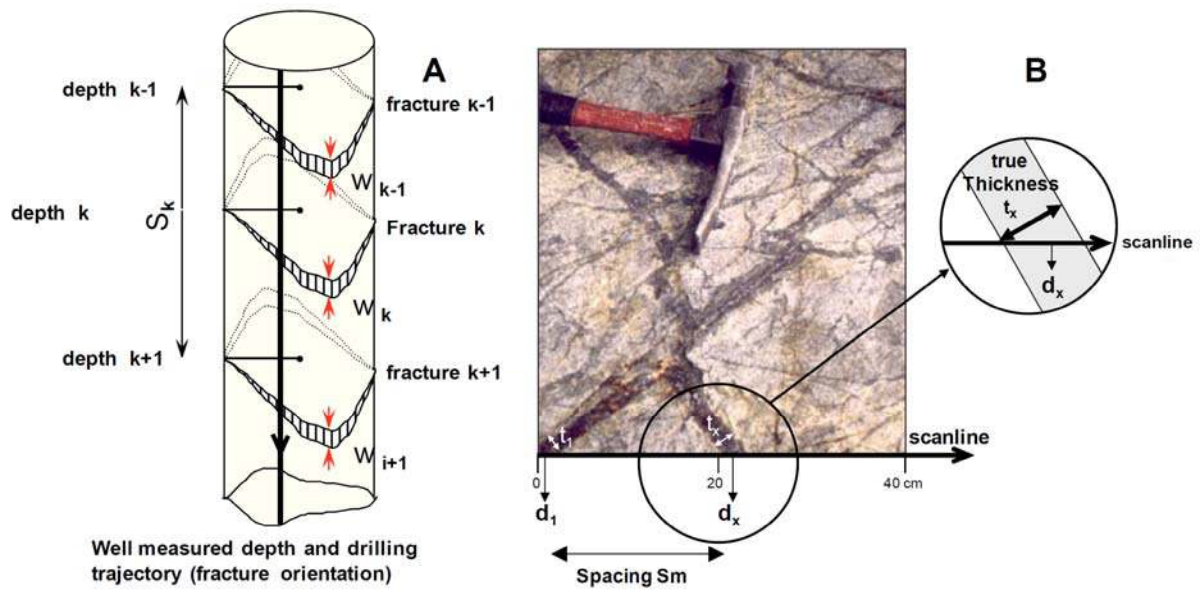


Fig. 1. A. Geometrical parameters describing a fracture set m that is determined by structural studies and that can be used for the quantification of the equivalent fracture conductivity (from Vuillod, 1995). S_k represents the mean spacing between fractures ($k-1$ and $k+1$) within the fracture set m . B. Stockwork organization and methodology of sampling along a scanline in an open pit: distance from the beginning of the scanline (D_1, \dots, D_x, \dots), true thickness (t_1, \dots, t_x, \dots), strike, dip and mineral assemblage of each vein are plotted.

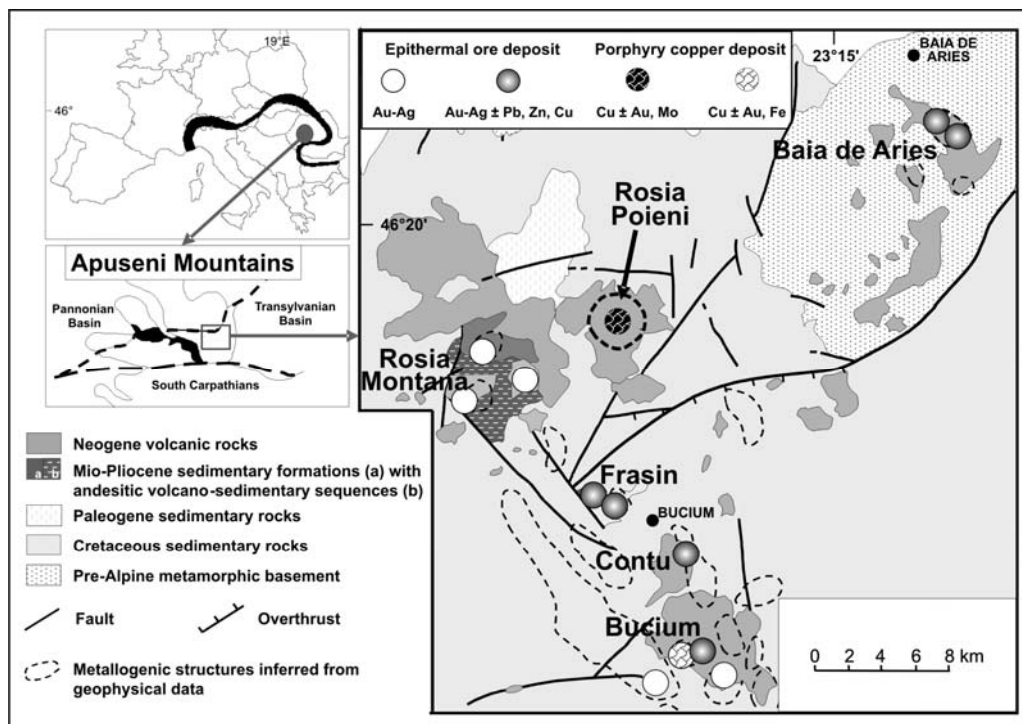


Fig. 2. Geological map of the Bucium-Baia de Arieş metallogenetic district and its location in the Apuseni Mountains, Romania (modified from Borcoş et al., 1983).

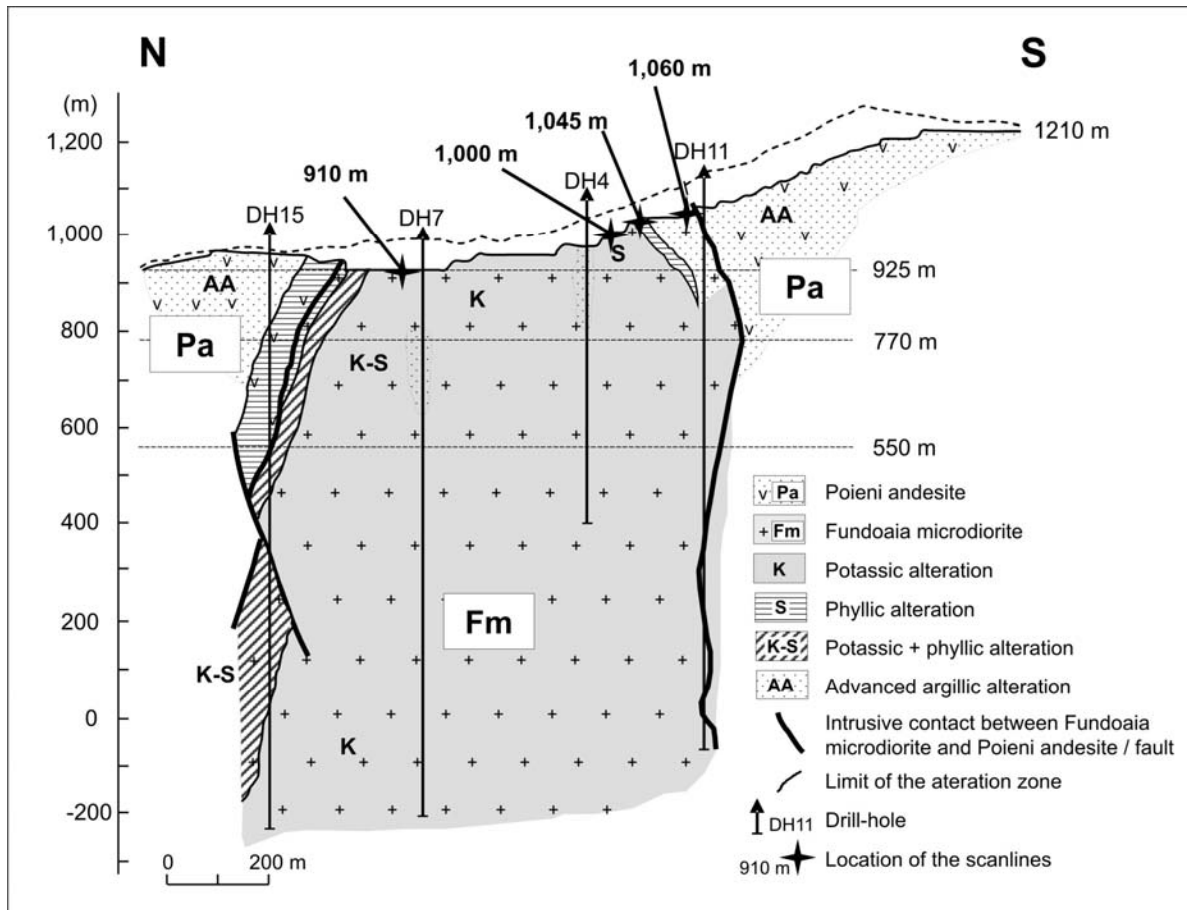


Fig. 3. North-south cross-section of the actual Roșia Poieni open pit (reconstructed from Ionescu, 1974 and Milu, 2004) showing the porphyritic intrusion and host rocks, alteration types and zones. The location of the four scanlines (900, 1,000, 1,045 and 1,060 m) is indicated with stars.

Two types of igneous rocks, both characterized by intense hydrothermal alteration, are exposed in the open pit. The host rocks (the Poieni andesite), are intruded by a subvolcanic body characterized by a porphyritic texture, the Fundoia microdiorite (Fig. 3). Ionescu (1974), Ionescu et al. (1975) and Boștinescu (1984) performed a mineralogical and petrographical study of the rocks from the Roșia Poieni area. They mentioned the disseminated character of the copper mineralization and a zoned pattern of. Recent studies (Milu, 1999; Milu et al., 2004) have shown that the Fundoia subvolcanic body and the Poieni host rocks are characterized by a strong hydrothermal alteration that is spatially related to the Fundoia intrusion.

Fig. 3 presents a schematic reconstruction of the Roșia Poieni volcanic structure and shows the concentric pattern of the hydrothermal alteration from the potassic core to a well-developed advanced argillic zone (Milu et al., 2004). The main high-grade zone (>0.6 % Cu) is located in

the central part of the intrusion (Milu et al., 2004). Outside the potassic zone, the copper grade decreases to 0.1 % Cu, except in zones where a phyllic alteration is superimposed on a potassic alteration (Fig. 2). The upper part of the Roșia Poieni structure displays an advanced argillic alteration and is barren (<0.05 % Cu). Gold occurrences greater than 0.02 ppm Au (lower limit of detection) are restricted to the potassic (\pm phyllic) zones and do not exceed a mean value of 0.5 g/t Au (Milu, 1999; 2004). The open pit is now on standby, but the reserves are estimated to be 350 Mt, with an ore grade of 0.36% Cu and 0.29 g/t Au and 0.02 g/t Mo (Borcos et al., 1998). The evolution of the geometrical characteristics of the mineralized stockwork has been described by André-Mayer and Sausse (2007).

The mineralization comprises pyrite, chalcopyrite, magnetite, hematite, molybdenite and bornite with subordinate tetrahedrite-tennantite, enargite and digenite and minor amounts of

pyrrhotite, sphalerite, galena, covellite and chalcocite. Chalcopyrite is the dominant hypogene copper mineral. The mineralization is pervasively disseminated within the altered rock, veins and fractures associated in a well-developed stockwork (Figs. 2 and 3) that is best developed in the potassic zone.

3. Data collection

The present vertical extent of the open pit exposure is 300 m (between altitudes of 910 and 1,210 m; Fig. 3). Four horizontal sampling lines were selected in the open pit at different altitudes (910, 1,000, 1,045 and 1,060 m, Fig. 3). In most mineral exploration situations (trenches, boreholes, drifts, etc.), only this type of 1D sampling is possible despite the 3D organization of both individual veins and networks (Park and West, 2002; Peacock et al.,

2003). Moreover, existing methods allowing a 2D data analysis are still immature, and there is currently no satisfactory method to analyze 3D spatial data (Gillespie et al., 1993; Pickering et al., 1995).

Three of the sampling lines are oriented in an E-W direction (altitudes 910, 1,000 and 1,060 m), whereas the fourth is oriented N-S (altitude 1,045 m, Fig. 3). The 1,060 m scanline is located close to the contact between the intrusive body of Fundoia and the host andesite of Poieni, which is marked by the onset of the argillic alteration (Fig. 3). For each scanline and each vein, the intersection distance between veins and the spacing between the vein sets and the scanline were measured, and information, such as the width, strike, dip and vein mineral assemblage, was collected (Fig. 1 and Table 1). Vein counts range from 146 to 725 over lines of lengths from 7.9 to 14.4 m, leading to a database of approximately 1,700 fractures (Table 1).

Table 1. Database acquired on the Roşia Poieni stockwork with indications of length, number of measurements, and vein density for each scanline. The 1,000 and 1,060 m scanlines are not continuous because of access difficulties, screes or strong weathering and are thus respectively divided in four and two sections.

Scanline	Section	Length (m)	Number of data		Density N/m (m ⁻¹)
910 m	-	12.7	353		27.5
1,000 m	1	11.3	213	725	18.8
	2	14.4	205		14.2
	3	10.2	219		21.5
	4	7.9	88		11.2
1,045 m	-	11.0	146		13.3
1,060 m	1	13.2	210	468	15.9
	2	8.1	258		31.7

4. Fracture permeability quantification

The study of the fracture permeability based on this type of 1D profile leads to an extrapolation problem because of the visual limitations of the true geometry of the fractures, excluding the reconstitution of the 3D fracture network. Therefore, to model the hydraulic behavior of the fractured media requires the use of equivalent porosity and permeability models cha-

racterizing the fractured rock matrix. The assumption of a negligible matrix, that is crosscutted by a permeable fracture, allows the quantification of local permeability that is directly related to the width of each fracture and to the spacing between fractures.

The permeabilities were first quantified by accounting for the totality of the fractures for a given profile. This method does not consider the chronology of the tectonic events (opening and

reopening of fractures) or the mineralogical filling of each vein, but it does allow the visualization of the evolution of the global permeability distributions at the open pit scale. For each profile, the equivalent hydraulic properties have been quantified using equations 1 to 3, as presented above.

4.1. Evolution of the permeability in the open pit

The mean values of individual directional conductivity distribution developed for each vein and quantified for each profile are shown in Fig. 4. These values are relatively high because the geometrical width measured for the open pit is generally higher than, but proportional to the real hydraulic width of the veins, which is entered as cubic input parameters in Equation 1.

We can observe that the mean permeability decreases from the deeper level (910 m) to the shallower levels (1060 m). The 910, 1045 and 1060 m levels are characterized by very heterogeneous permeabilities, whereas the 1000 m level exhibits much more homogeneous values (Fig. 4).

4.2. Evolution of the permeability at the scanline scale

Permeability heterogeneities have been observed at the open pit scale, considering that each profile is characterized by homogeneous characteristics. However, heterogeneity in the geometrical parameter distributions has been observed in each profile by André-Mayer (2000) and André-Mayer and Sausse (2007), and thus, potential heterogeneities of permeability at the scanline must be addressed.

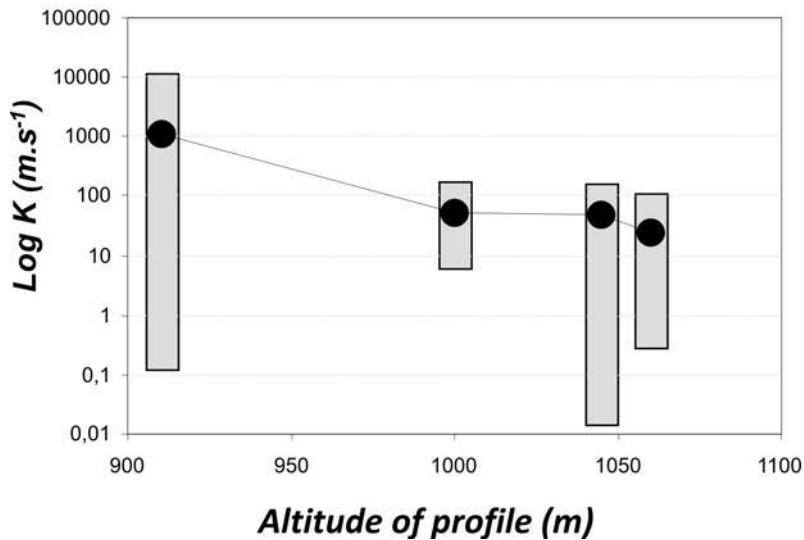


Fig. 4. Mean directional conductivities (black circles) developed by the veins constituting the fractured network in the levels 910, 1000, 1045 and 1060 m. Grey zones shown the extreme values (amplitude between minimum and maximum).

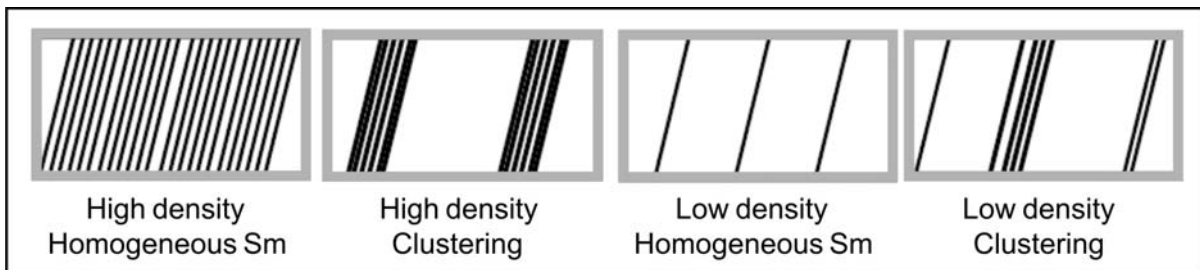


Fig. 5. Theoretical spatial geometries that could be observed along a scanline for different vein densities and spacing standard deviations (André-Mayer, 2000).

Geometrical heterogeneity of the vein network can be indicated using two main parameters: the density of the veins (d) and the interdistance between vein $k+1$ and $k-1$,

which defines the clustering between, veins (S_m). Fig. 5 shows the main geometrical repartition that can be described using the d and S_m parameters.

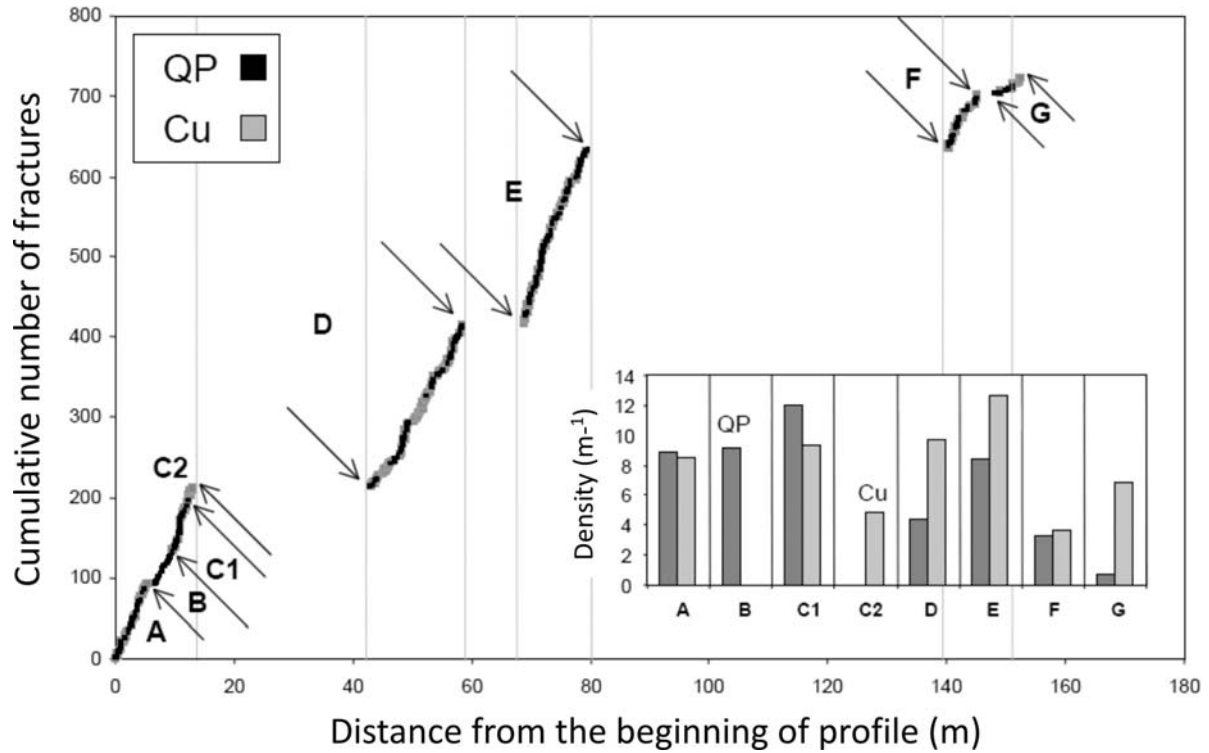


Fig. 6. Discrimination of the 8 zones in the 1000m profile in relation with mineralogical vein fillings or/and vein density differences. B and C2 zones are, for example, characterized respectively by lack of Cu and QP veins.

Table 2. Description of the different zones identified in the three EW profiles. The mean value of spacing S_m and vein thickness w_m and their standard deviations σ_w and σ_s are presented for each zone.

Profile 910 m					Profile 1000 m					Profile 1060 m				
zones	S_m (m)	σ_s (m)	w_m (mm)	σ_w (mm)	zones	S_m (m)	σ_s (m)	w_m (mm)	σ_w (mm)	zones	S_m (m)	σ_s (m)	w_m (mm)	σ_w (mm)
A	0,05	0,05	2,90	3,56	A	0,12	0,07	4,70	4,54	K	0,0593	0,0659	8,72	21,69
B	0,07	0,06	5,90	7,99	B	0,16	0,07	4,90	6,20	J	0,0922	0,0614	5,67	8,14
C	0,06	0,04	4,82	11,43	C1	0,08	0,07	4,20	8,3	I	0,083	0,0866	3,23	3,34
E	0,08	0,05	4,21	4,67	C2	0,09	0,03	11,20	19,25	H	0,32	0,1681	3,25	1,83
F	0,07	0,05	3,45	2,59	D	0,15	0,14	4,39	5,38	G	0,0642	0,0638	3,12	1,55
G	0,04	0,03	2,42	2,43	E	0,10	0,09	3,43	4,84	F	0,0634	0,0474	4,25	10,44
H	0,07	0,07	18,75	25,95	F	0,17	0,18	5,81	9,80	E	0,111	0,088	2,18	2,24
I	0,11	0,06	2,31	0,94	G	0,28	0,25	4,75	2,66	D	0,0929	0,0906	4,4	0,55
J	0,04	0,03	3,80	1,81						C	0,1639	0,1512	3,86	2,27
K	0,04	0,03	1,68	0,81						B	0,0668	0,0486	1,83	0,78
										A	0,0843	0,1234	2,78	1,42

Plotting of cumulative number of fractures in relation to both distance from the profile beginning and mineralogical filling of the fractures (Fig. 6) involves the discrimination of specific zones. For example on the 1000 m profile, 8 zones (named A to G) have been identified in relation to the vein density and the

presence or lack of quartz/pyrite. Table 2 summarizes the obtained zones with this method for each profile, with the mean value of spacing S_m and vein thickness w_m and their standard deviations σ_w and σ_S . Ten, eight and eleven zones were identified for the 910 m, 1060 m and 1060 m profiles, respectively.

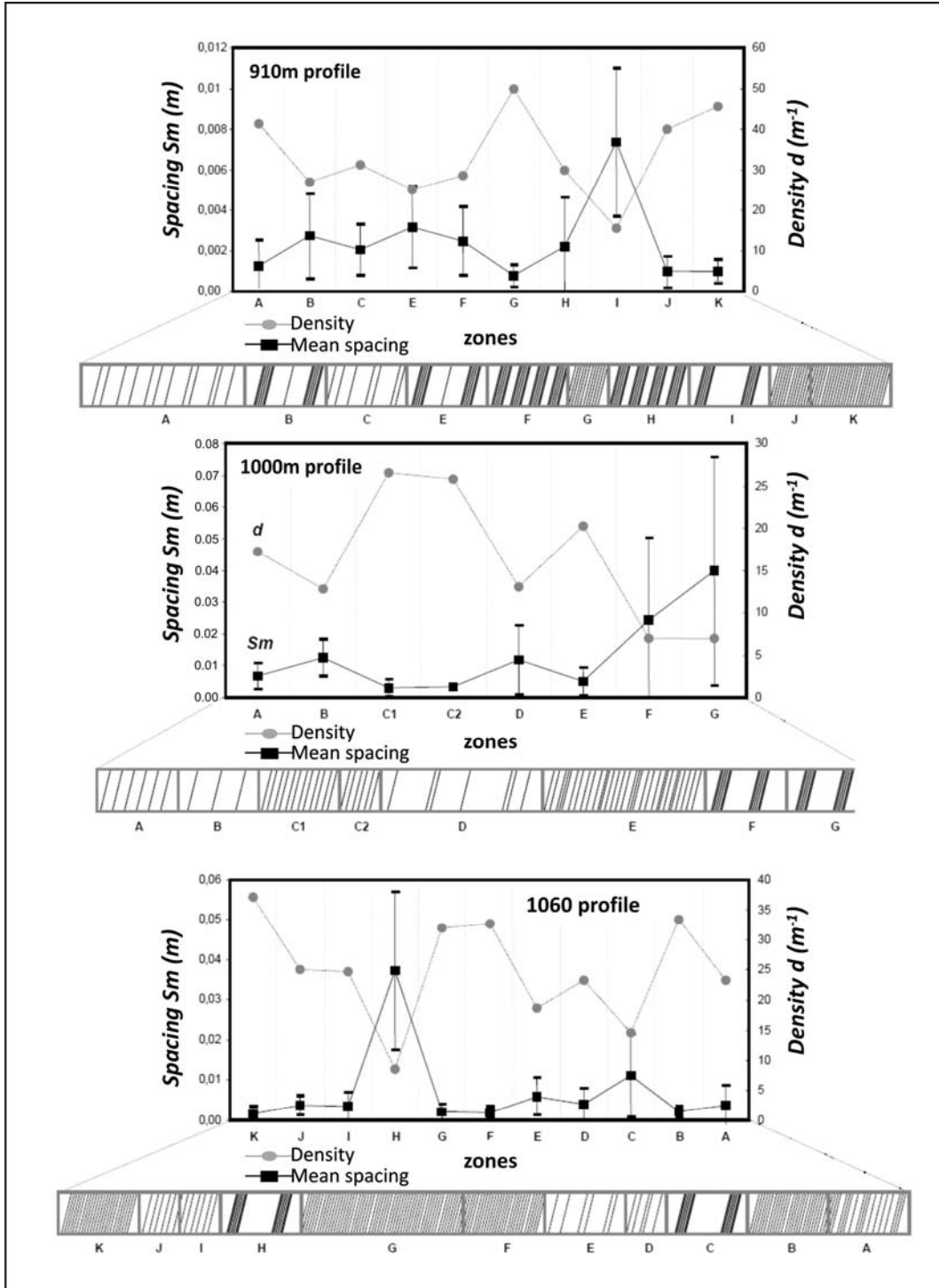


Fig. 7. Diagram showing the mean spacing values S_m (spacing between $k-1$ and $k+1$ vein) with their standard deviation and vein density identified for each zone for the 910 m, 1000 m and 1060 m profiles. A schematic representation of the spatial organization of the veins in each zone is proposed following the description in Fig.5.

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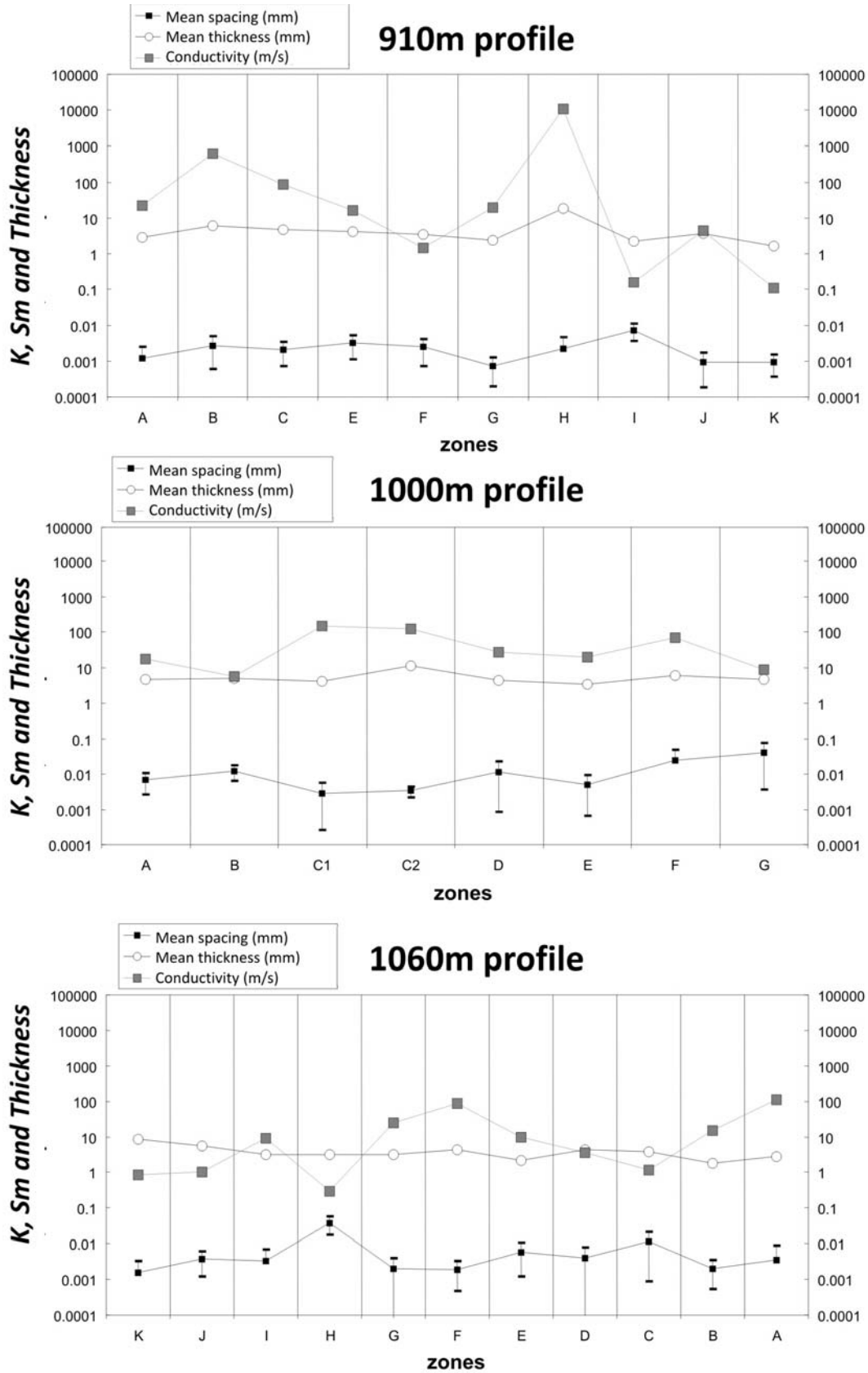


Fig. 8. Mean values of the permeability (grey squares developed by the veins in the 3 profiles with the discrimination of each specific zone. The mean values of spacing (black squares) and thickness (white circles) are also indicated.

Variations in the vein density and spacing for each zone are presented in Fig. 7. In this figure, the spacing values have been normalized to the density for each zone to enable comparison. A schematic representation of the veins' spatial organization is proposed for each profile. Des-

pite a high density, the veins in the 910 m profile have a more clustered distribution than those of the 1000 m and 1060 m levels (Fig. 7).

The mean fissural permeability has been estimated for each zone of each profile using the geometrical characteristics presented above.

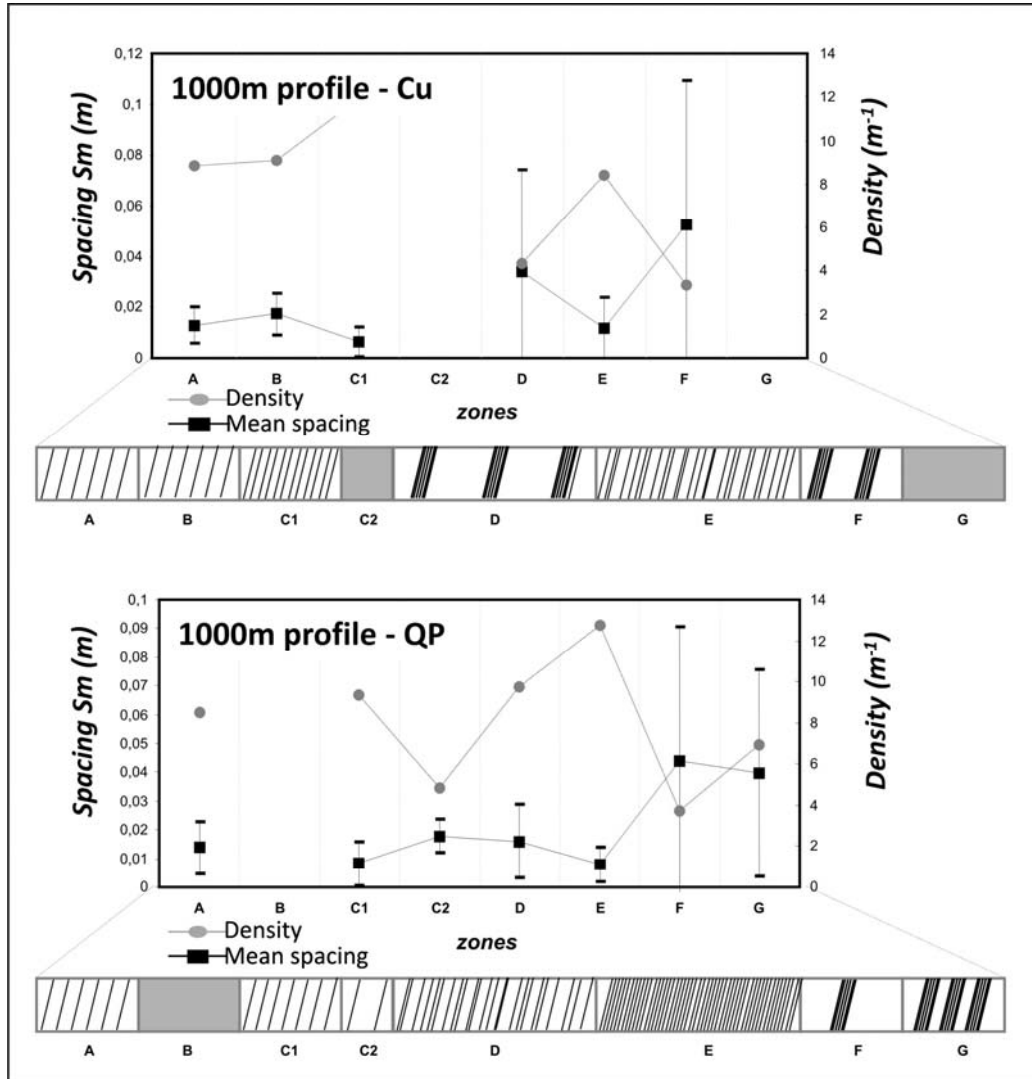


Fig. 9. S_m values, spacing between vein $k-1$ and $k+1$ with the standard deviation (blacks squares) and density (grey circles) of Cu and QP veins for each discriminated zones of the 1000m profile. A schematic representation of the spatial organization is given following the parameters presented in Fig. 5.

The following results are shown in Fig. 8:
 - For the 910 m profile, conductivities are very heterogeneous despite the constant vein thickness. The observed variation in the permeability thus seems not to be linked to variations in the vein thickness (perhaps with the exception of the H zone). The highest permeability seems to be related to a high

density of fractures correlated with a cluster organization. The J and K zones, with high vein densities but not clustering, induce low permeability.
 For the 1000 m profile, the estimated permeability seems very homogeneous at first glance. However, this constant value is linked to different parameters: high vein density for specific

zones (C1, C2, E, Fig. 8) or a cluster organization in zones F and G despite low vein density. - For the 1060 m profile, the permeability values are the lowest and relatively heterogeneous. In this profile, zones with a clustered organization develop the lowest

permeability values, which should be related to the low vein thickness observed in this profile (Table 1). Thick veins seem to be important for the development of high permeability, even if the veins have a clustered organization.

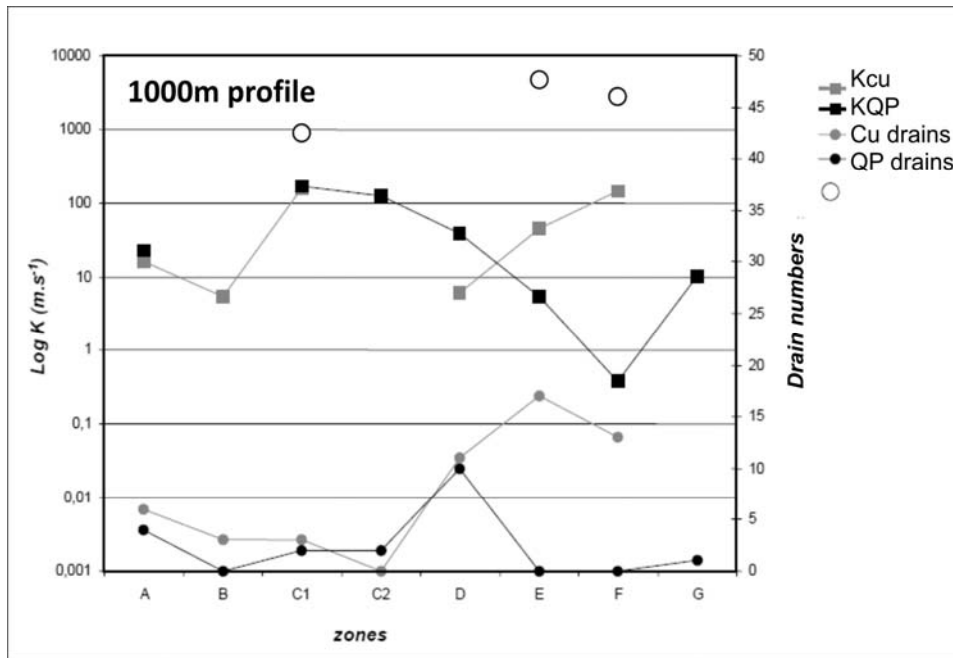


Fig. 10. Comparison of developed permeability of the Cu (grey squares) and QP (black squares) veins.

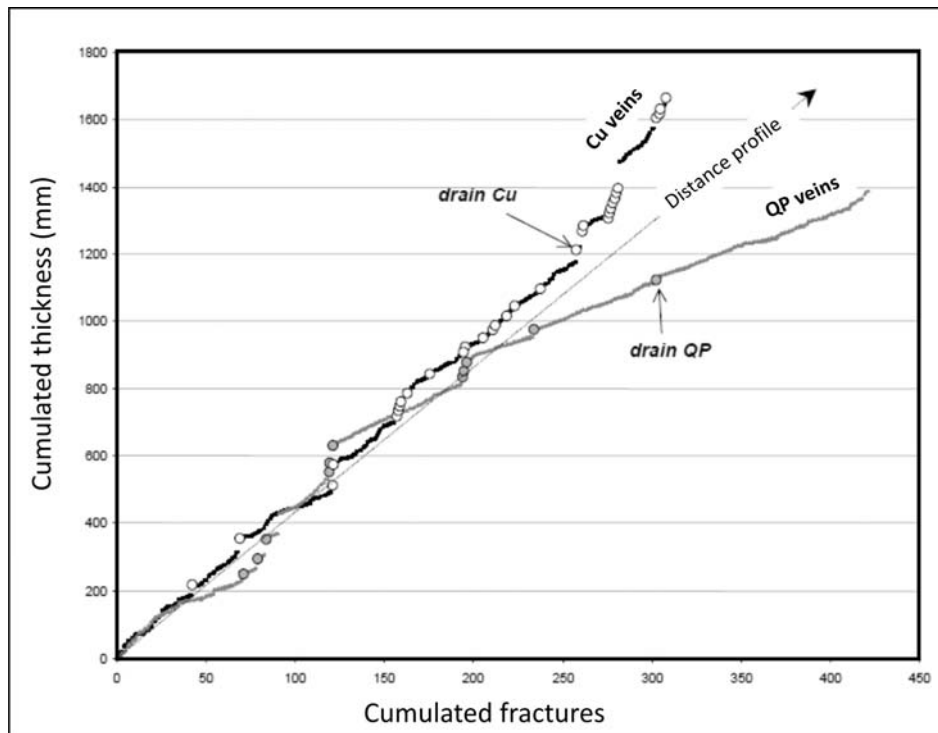


Fig. 11. Cumulated fracture number in function of cumulated thickness.

5. Relation between the fracture permeability and mineralization: the 1000 m level

At the 1000 m level, vein discrimination was achieved using the mineralogical composition of their filling: copper sulfides (Cu) vs. quartz-pyrite (QP). The spatial organization of these two types of veins has been compared to identify the major differences in their hydraulic

behavior. These two types of veins express the same variation, with the end of the profile exhibiting a more clustered repartition of fractures than the beginning. The estimated permeabilities of QP and Cu veins differ along the 1000 m profile (Fig. 10). The Cu vein permeability increases from the D to the F zones, whereas that of the QP vein decreases.

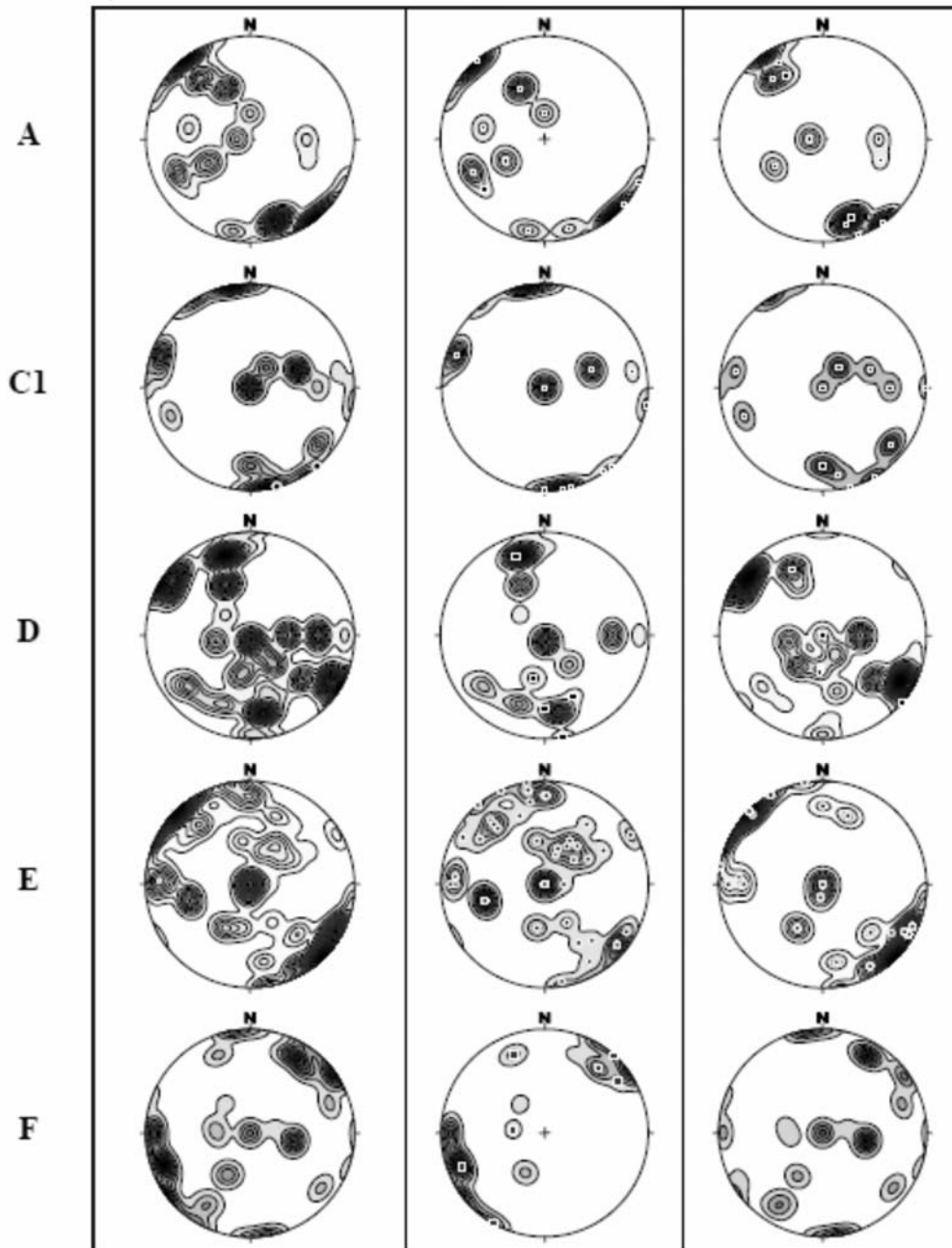


Fig. 12. Stockwork geometry of the 1000m profile in zones A-F, for the entire vein network (left), for the Cu veins (middle) and for the QP veins (right). Small squares express the orientation and dip of vein having thickness greater than 10 mm.

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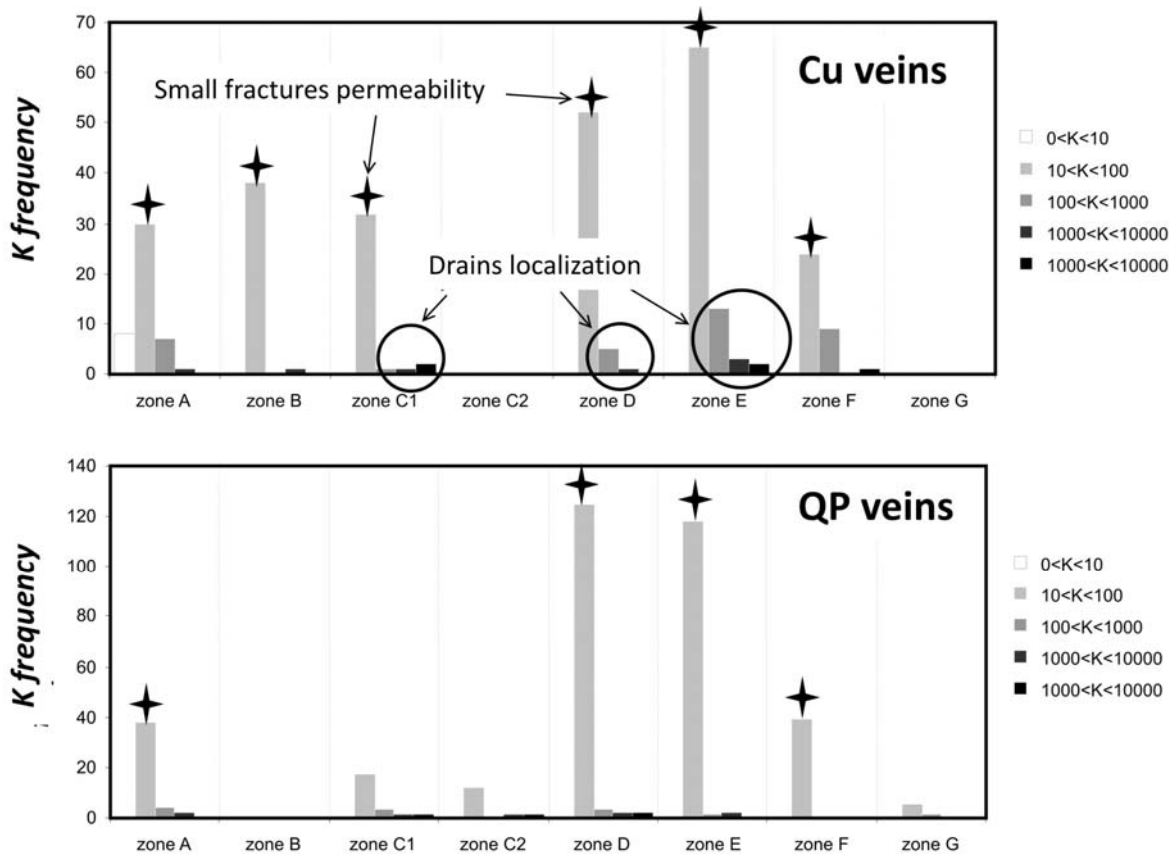


Fig. 13. Frequency of permeability in function of each specific zones.

This different behavior is directly linked to the geometric characteristics of the Cu and QP vein networks:

The cumulated vein thickness related to the cumulated fracture number (Fig. 11) shows the difference in the thickness evolution from the D zone. White and gray circles show the Cu and QP major veins with thicknesses greater than 10 mm, respectively. The higher values are more numerous for Cu veins than for QP veins.

The geometry of the vein network indicates pronounced differences between the QP and Cu veins.

Fig. 12 expresses the stockwork geometry of the 1000 m profile in each zone for the total network (left), the Cu veins (middle) and the QP veins (right). Small squares express the orientation and dip of veins thicker than 10 mm.

These thick veins show much more variable orientations for Cu veins, thus having an increased probability of connection between veins, whereas the orientations of the QP veins are much less variable for both thin and thick veins

Fig. 13 expresses the importance of drains in specific zones of the profile for the Cu veins.

The permeability of Cu veins evolves from a fissural permeability to a “drain permeability,” whereas the QP veins’ permeability is dominated in all the profiles by a fissural permeability without any drain.

Thus, the 1000 m profile, which at first seems to have a homogeneous permeability when the entire vein network is considered, is actually heterogeneous, as shown by the distinct consideration of the mineralogical filling of the veins.

6. Conclusions

Several conclusions can be drawn from this study:

1. The more suitable method for the quantification of permeability in a hydrothermal environment is based on a discontinuous media that treats the rock as a homogeneous media (matrix) + N different elements (fractures), which can be described by a structural analysis. This method uses the cubic law of fracture width and the spacing parameters between fractures within a fracture set. This study indicates the im-

portance of considering S_m in the permeability estimation. A simple cubic law of thickness may yield false homogeneous permeability at the profile scale if the spatial vein organization is not used.

2. The quantification of the permeability expresses the heterogeneity in the hydraulic behavior at the open pit scale: high permeabilities, observed in the lower levels of this hydrothermal system, must be related to major fractures and a clustered organization, whereas permeability becomes more pervasive in the upper level of the system, with thin fractures with relatively homogeneous repartition.
3. The distinction of the QP and Cu veins expresses the differences in their permeability, and a chronological study should be undertaken to understand the correlation between these two vein networks.
4. The systematic relationship between the clustered organization of the vein network and the copper content shows the potential in using the geometrical properties of the mineralized stockwork for exploration.

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