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# Observations of reactive transport through fractures in outcrop: A methodology to define the spatial and time scales of fluid flow

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We constrained the spatial and time scales of fluid flow in a low-porosity sandstone unit exposed in the Northern Apennines (Monte Venere Fm.) by a quantitative analysis of alteration halos around fractures in outcrop. Alteration halos are often associated with preferential fluid flow through discontinuities. So-called redox fronts (reactive fronts) form and propagate where dissolved-oxygen-rich-water flows through a fracture and interacts with reduced sandstone matrix. The alteration halos exposed in the studied outcrop have the two following characteristics: (1) they are symmetrical around the joints; (2) they have similar width where observed on the same bedding surface regardless of which joint set they belong to. The alteration halos observed suggest that all joints of different sets and most small faults are conductive to meteoric water at shallow depth. On the other hand, veins are local barriers to mass transport by diffusion. The fundamental research questions that we address in this work are: (1) Do outcrop characteristics of alteration halos associated with fractures match the predictions of theoretical diffusion models and can they be used to infer the spatial and time scales of flow in a fractured rock? (2) Do alteration halos provide information on the connectivity and barrier properties of a fracture network in a low-porosity sandstone? Answering these questions is relevant to understand pollutant transport in fractured rocks, the effective sealing of nuclear waste repositories, landslides triggering, and evaluate the recharge rates of aquifers in low-porosity rocks. By using petrologic and petrophysical data, analytical modeling, and the width of the alteration halos, it was possible to estimate when the fracture network was open to fluid flow. The inferred time span for fluid flow and diffusion through the fracture network is sensitive to the porosity n of the rock matrix used in the analytical solutions: 2200 $\pm$ 500 years with n = 0.08, 4600 $\pm$ 900 years with n = 0.05, and 16000 $\pm$ 4000 with n = 0.02. The second and third age determinations are consistent with the landscape evolution of the area since the end of the last Wűrmian ice age and with the timing required to fill the fractures observed in outcrop. An important finding is that at shallow depth, all joints, regardless of their orientation are conductive to meteoric water infiltrating from the topographic surface. On the other hand, fractures filled with calcite cement (veins) are not conductive to fluid flow and function as a barrier to diffusion and the development of alteration halos. The characteristics of the alteration halos point out that fluid flow was mostly concentrated in the joint network. The characteristics of the alteration halos also suggest that most of the advective transport occurred in the joint network whereas dissolved oxygen transport by diffusion occurred from the joint walls into the rock matrix. Furthermore, reduced iron moves by diffusion from the rock matrix toward the joint opening.