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Heterogeneities in fractured aquifers: Examples from outcrops and implications for fluid flow modeling

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Surface outcrops provide natural analogs for aquifers and they offer an opportunity to study the geometry of geologic heterogeneities in three dimensions over a range of scales.

We show photographs, maps, quantitative field data of rock fractures and sedimentary features in outcrops exposed in a unique collection of many different settings. These include small-scale sedimentary structures, carbonate nodules, faults, and other fractures as documented in outcrops of porous sandstone (Utah, USA and Italy), tight sandstones (Bolivia), dolomite (Northern Italy), and carbonates (Central Italy).

We simulate the geometries observed in outcrops with simple conceptual and numerical models of flow to show how important it is to recognize the appropriate attributes for the description and the process responsible for the formation of geologic heterogeneities. For example, knowing the type of structural heterogeneities (fault, joint, compaction band, stylolite, and vein) and their development mechanics helps to predict the distribution and preferential orientation of these features within an aquifer. This knowledge is particularly important for modeling of fluid flow where geophysical or borehole data are lacking.

Geologic heterogeneities of sedimentary, structural or diagenetic (chemical) nature influence the fluid flow properties in many aquifers and reservoirs at scales varying over several orders of magnitude and with a spatial variability ranging from mm to tens of meters. Heterogeneities may enhance or degrade porosity and permeability, they impart anisotropy to permeability and dispersion and affect mass transport-related processes in groundwater. Furthermore, aquifer heterogeneities control aquifer continuity and compartmentalization. In fractured aquifers, geologic and diagenetic heterogeneities may affect connectivity, aperture of the flow channels or the distribution of permeability buffers, barriers and seals. Also variations in layer thickness and lithology within a fractured aquifer influence fracture frequency as well as vertical and horizontal connectivity.

Structural heterogeneities, such as faults and fractures, are critical for flow in aquifers over a wide range of effective matrix porosities. Many parameters influence the potential for faults to be barriers or pathways for fluids. The displacement distribution of a fault determines the juxtaposition of permeable and non-permeable formations. The net-gross ratio of sand and clay together with the amount of displacement define their sealing or compartmentalization potential. The type, distribution, and petrophysical properties of the structures associated with the main fault affect the overall fluid-flow behavior in the fault zone. The linking and distribution of fault segments determine, in the end, how effective the faults are in sealing or channeling fluids.

Diagenetic or chemical heterogeneities represented by areas of preferential cement precipitation or dissolution may or may not be localized by sedimentary and/or structural heterogeneities adding another layer of complexity to the characterization of the effects that structures and sedimentary features have on fluid flow.