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FLOW IN FAULTS AND FRACTURES

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ABSTRACT

A survey is given of recent research into gas and liquid flow characteristics in fractured and faulted porous media, exemplified most commonly by rock formations. With a dense network of fractures, spatial averages can be taken over scales larger then the fracture spacing, and the medium regarded as a dual continuum as shown by Barenblatt et al. (1960), with separate permeabilities and pososities and with exchanges between them. In steady conditions, the net exchanges vanish , and the transport is largely along the low-porosity fracture network. Faults, on the other hand represent genuine physical discontinuities in the flow field, whose influence is indexed by the Fault Flow number, defined below. When this parameter is small, the fault has little influence on the pattern of flow, but if it is large, the fault acts freely as a flow conduit, venting gas flow to (or from) the atmosphere and, below the water table, concentrating and greatly speeding liquid flow. Jogs or offsets are frequently associated with faults, and these often serve as gas chimneys or as the source of liquid springs.

These flow patterns, with the interstitial fluid a liquid, produce patterns of mineral reaction, dissolution and precipitation, often concentrated in jogs and, to a lesser extent, along fault planes and their general characteristics are discussed briefly. A second example involves interstitial gas circulation around a heated waste repository which leads to a pattern of evaporation below, and condensation above the heat source; in time, the latter will reflux downwards, possibly threatening the longevity of the repository.

FRACTURE-MATRIX SYSTEMS

Many rock formations contain fracture networks that can provide barriers or pathways to fluid migration. Characteristically, the overall permeability of the fracture network is greater, often by orders of magnitude, than that of the rock itself, while its porosity (mean connected pore volume per unit volume of matrix) is much less. For example, the Topopah Spring welded tuff (an old volcanic rock from Yucca Mountain, the site of a proposed nuclear waste repository) is described (Buscheck et al., 1991) as having a very low matrix premeability (about $10^{-18}\ m^2$), a lowish matrix porosity (about 0.1) and a high density of fractures (more than 10 per meter). The fracture network, averaged over scales of order meters, has a permeability of 10^{-12} to $10^{-10} m^2$, at least six orders of magnitude larger than that of the matrix, while the porosity of the network is about (1.3 to 6)$\times 10^{-3}$, averaging 3% of that of the matrix.When the matrix is water-saturated, the fractures as well as the interstices in the permeable rock are liquid-filled, so that the fractures provide pathways for liquid flow while the matrix blocks provide the reservoirs. The mean interstitial fluid velocity is larger by a factor (porosity)$^{-1}$ than the transport velocity, which is the volume of fluid crossing unit area of the medium per unit time. On the other hand, when the matrix is unsatirated (the voids containing both gas and liquid, usually water), liquid water is drawn by capillary action into the finer interstices of the matrix blocks so that the fracture gaps are largely air-filled except at the edges of contact areas. Liquid water is virtually immobile, while gas and water vapour migrate through the fracture network, whose permeability controls the flow rates and patterns. Virtually the only role that the matrix permeability plays (in conjunction with the capillary or mafic suction) is in the process of imbibition of liquid water, infiltrate or condensate, into the matrix blocks.

Liquid flow along the fracture network often leads to dissolution or chemical alteration, generally on a small (mm. or cm.) scale. Although the basic principles involved are the same as they are on the small scale, many major mineral deposits formed from aqueous solutions are associated with faults and jogs, since the flow rates here can be so much larger.

THE FAULT FLOW NUMBER

Flow in a generally plane fault can be analysed using approximations similar to those in lubrication theory, and if the gap is of order δ and the length scale along the fault (e.g. the characteristic distance between contact areas) is λ, then provided the Reynolds number is well smaller than λ/δ (which is large), and subject to the usual caveats about averaging and heterogeneity, one expects a linear relationship between the volume flux in the fault q and the pressure gradient along it, divided by the fluid viscosity. The constant of proportionality k_f, of order $(10^{-1} - 10^{-2})\delta^3$ is called the fault permeability or transmissivity with dimension [L^3].

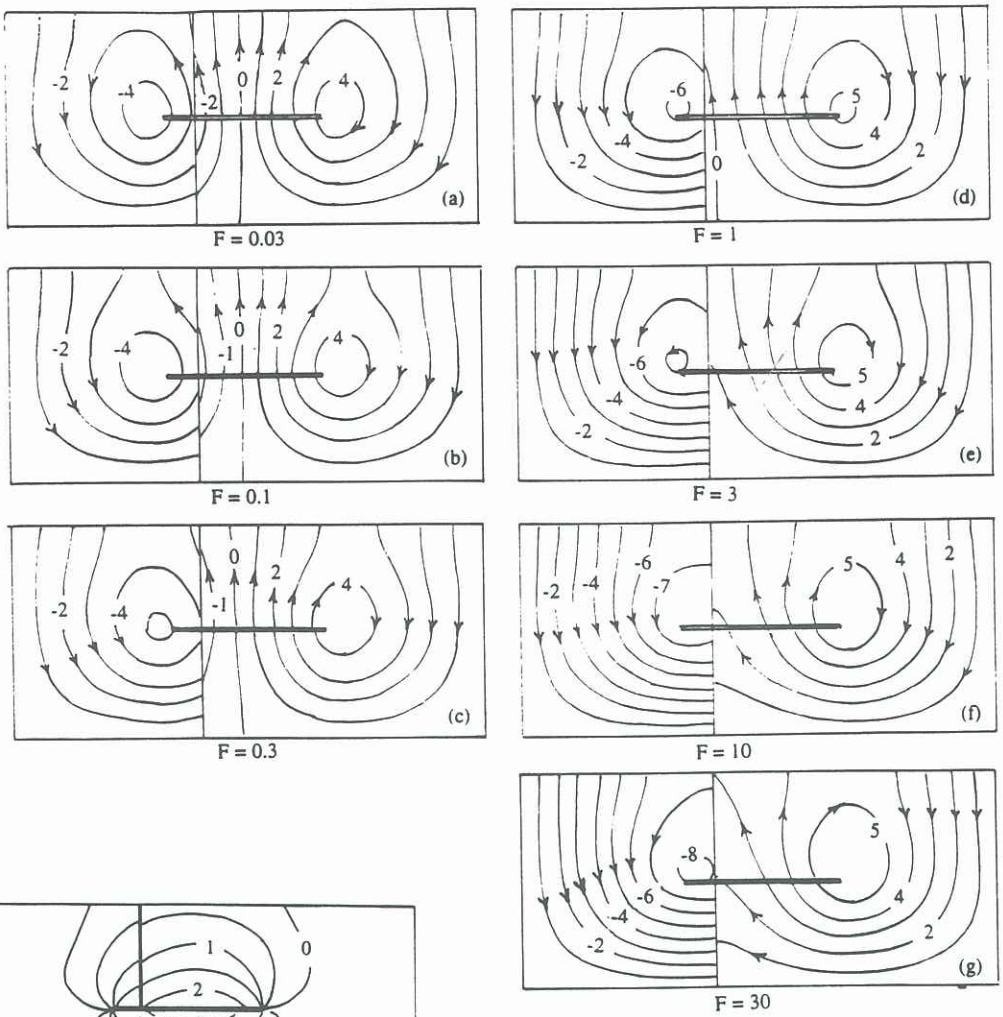
A fault nay be open or detritus-filled, but in either case the pressure difference across it is negligilble, so that the pressure gradient along it is the same as in planes parallel to the fault in the matrix on either side. Thus one juncture condition across the fault is that

$$q / k_f = u_1 / k_1 = u_2 / k_2, \tag{1}$$

where the u's represent the transport velocities and the k's, the relevant permeabilities in the media on either side of the fault. A second juncture condition expresses the divergence of the fault volume flux as the sum of the inwards transport velocities from the medium on each side. If the thickness h of the formation is taken as a length scale for the overall flow, the dimensionless version of (1) is

$$q = F_1 u_1 = F_2 u_2, \qquad F = k_f / kh, \tag{2}$$

which we call the fault flow number. When F is much smaller than unity, flow along the fault is small and the fault has little effect on the overall flow. Note that from the scaling q is of order unity (it may be numerically small in places, but not numerically large), so that when F is large, the transport velocity in the rock walls is normal to the fault, as it would be if this were a free surface. The fault then has a profound influence on the flow pattern, as Figure 1 illustrates in a simple example, where gas flow is drawn to the fault, venting to the surface.



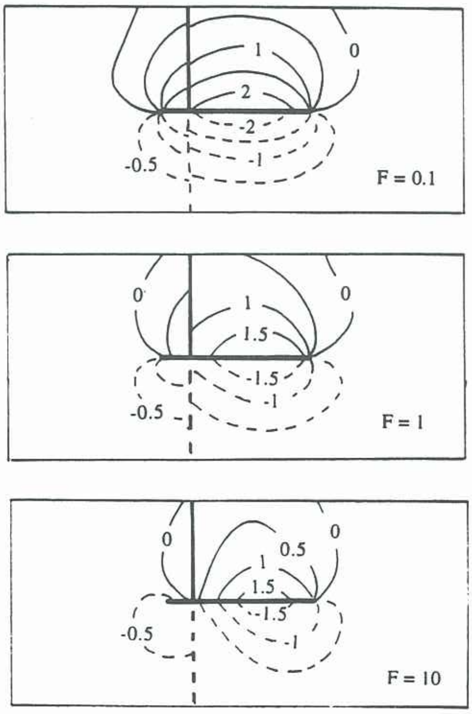


Figure 1: (Above) Flow patterns generated by a heat source at mid-depth (horizontal double line) in the presence of a fault (vertical line, left of center) for various values of the fault flow number, F. At large values of F, the flowpattern becomes independent of F.

Figure 2 ; (At left) Condensation distributions for 3 of these flow fields. As F increases, the flow becomes somewhat more intense but more nearly parallel to the isotherms, so that the condensation rate in the matrix in fact decreases. Condensation is concentrated in the upper half of the fault; evaporation below.

FLOW-CONTROLLED REACTION PATTERNS

When the circulating fluid contains a solute if liquid, or a condensible constituent if it is gaseous, whose equilibrium concentration is a function of temperature, c = c(T), the rate at which reaction or condensation can proceed is frequently controlled by the rate at which the constituent is delivered to the reaction site (usually slow), rather than by the reaction kinetics(which may be rapid). In this type of flow controlled reaction the rate of deposition is

$$Q = -\left(\frac{\partial c}{\partial T}\right) u \cdot \nabla T \qquad (2)$$

and when F>>1 and $\partial c / \partial T > 0$, mineralization or condensation is most rapid in faults, with focussed, vertically moving flow crossing the isotherms from hotter to colder regions. When multiple solutes are present, equation (2) allows calculation of the relative deposition rates of each. The common association between mineral deposition and fractures, particularly in brecciated (rubble-filled) 'jogs', has long been familiar to economic geologists and miners.

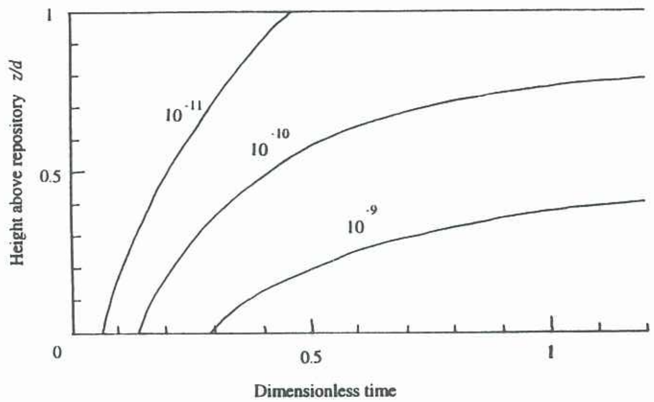


Figure 3: The rise of a reflux region above a heated repository towards the surface as a function of time for several values of the reflux parameter P (see text). If P = 10 , reflux is occurring throughout the region to the upper surface within a dimensionless time of 0.43, but if P = 10 , reflux (which began later) occurs only in the lower 40 % of this region after a time of 1.2.

Another, more somber, application concerns the dribble-back or reflux of condensed liquid water in a fault traversing a thermally hot nuclesr waste repository in the unsarurated region above the water table. Gas circulation, driven by the temperature field, is slow enough that the gas is close to saturation with respect to water vapor because of the presence of residual liquid water in the unsaturated matrix blocks. As the gas rises in the fault above the repository, it moves to lower ambient temperatures and, according to (2), liquid water is condensed with a distribution exemplified in Figure 2, For a given thermal loading, the dimensionless time (scaled by the thermal diffusion time) at which reflux commences depends on the product P of three sets of quantities: (i), The Fault Flow number times the Rayleigh number, which determines the intensity of the moist gas circulation in the fault, (ii), the coefficient on the right of equation (2), and (iii), the ratio of the 'matrix wetting diffusivity' to the thermal diffusivity, which determines the ability of the matrix to absorb the condensate by capillary suction. Figure 3 shows typical reflux onset times in terms of the thermal diffusion time (ca 1700 yr).

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