The dynamics of coupling between deformation and fluid flow in the Earth's crust: implications for ore genesis

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Abstract

Permeability and fluid pathways in fracture-controlled hydrothermal systems are governed by a dynamic competition between permeability-creation processes and permeability-destruction processes. Permeability evolution is coupled with the evolution of fluid pressure and stress states. Key permeability-creation processes are micro-scale to macroscopic fracture growth, and the generation of damage zones during co-seismic slip on faults or aseismic creep on faults and shear zones. The competing permeability-destruction processes include crack-healing and sealing, compaction and pore cementation. High rates of permeability destruction in hydrothermal systems require ongoing permeability enhancement to sustain high fluid fluxes and ore genesis. In aseismic regimes, competition between permeability-creation processes and permeability-destruction processes can lead to continuous flow in deep level hydrothermal systems. However, in seismogenic regimes, rapid co-seismic permeability-enhancement is followed by progressive permeability-destruction in the intervening interseismic periods, and leads to episodic flow. The results of high pressure experiments are used to illustrate how pore fluid factors and stress states are dynamically coupled with permeability evolution in hydrothermal regimes.

Particularly in the seismogenic mid- to upper crust, large changes in permeability during the seismic cycle govern relative rates of change of fluid pressure around active faults and shear zones. Rapid, post-seismic recovery of pore fluid pressures, relative to rates of shear stress recovery, leads to growth of hydrofracture networks prior to successive fault rupture events. Pre-rupture hydrofracture networks do not develop where post-rupture fluid pressure recovery is modest relative shear stress recovery. At elevated temperatures, low rates of pore fluid pressure recovery relative to shear stress recovery promote ductile shear failure and grain-scale permeability enhancement within shear zones prior to rupture events.

The influence of pore fluid pressure cycling, shear stress cycling, and deformation processes in controlling the evolution of permeability, flow localisation, and flow anisotropy at the deposit scale are illustrated for mesothermal and epithermal lode gold systems.

Keywords: *deformation, fluid flow, permeability, ore genesis*

Introduction

At elevated temperatures and confining pressures, most crystalline rocks have intrinsically low permeability. Sustained fluid migration in hydrothermal systems is dependent on the development and maintenance of high permeability. This paper uses field-based, experimental and modelling studies to emphasise that permeability is very short-lived relative to the timescales of operation of hydrothermal systems. Ongoing deformation and high pore fluid factors are necessary for repeated regeneration of the permeability required to facilitate both grain-scale pervasive flow and the development of macroscopic fracture networks which form fluid pathways in hydrothermal systems. Examples of fault- and fold-related lode systems are used to illustrate how (1) fluid flow is localised preferentially in those parts of active structures with the highest time-averaged permeability, and (2) simple structural controls lead to anisotropy of flow.

Controls on fluid flow

The dependence of fluid flow in porous media on driving forces, the transport properties of the media, and the fluid properties, is described by Darcy's Law. For purely pressure-driven, one-dimensional horizontal flow, the dependence of fluid flux (fluid volume, Q, across cross-sectional area, A, per unit time t) on hydraulic pressure gradients (dP/dx), is given by

$$Q/At = (k/m)(dP/dx) \qquad (1)$$

The constants of proportionality in this relationship are the permeability (k) of the rock, and viscosity (m? of the pore fluid. Darcy's Law assumes laminar flow, which applies in porous rocks at flow rates up to about 1 ms^{-1}.

Buoyancy-induced pressure gradients may also drive flow. At mid-crustal depths, the buoyancy-induced driving forces are less than 1 $kPa.m^{-1}$, or about 5 percent of the pressure-induced driving force in a system under lithostatic pressure. Accordingly, in overpressured hydrothermal systems, pressure-driven hydraulic gradients tend to be substantially higher than thermally-induced driving forces. Buoyancy-driven flow tends to be significant mainly in near-hydrostatic fluid pressure regimes at very shallow crustal levels, and also in overpressured fluid compartments with internal near-hydrostatic fluid pressure gradients.

Permeability is an intrinsic rock property that measures the capacity of fluids to flow through rock. Viscosity is a measure of the viscous resistance to flow of a fluid through pore spaces. Because permeability in rocks may vary over ten orders of magnitude, permeability distribution exerts the major control on the development of fluid pathways in hydrothermal systems.

Controls on permeability enhancement

At elevated temperatures in isostatically stressed mineral-fluid systems, pore geometry is controlled largely by minimisation of interfacial surface energies. Experimental studies indicate that for many mineral-fluid systems, pore connectivity is lost at porosities less than a few percent (Holness, 1997). Accordingly, at mid- to deep crustal levels most rocks will be effectively impermeable unless processes actively generate interconnected fracture networks.

The evolution of permeability in initially low permeability rocks during deformation involving both intragranular plastic deformation and grain-scale crack growth is illustrated by experimental studies on calcite rocks (Zhang *et al*., 1994). At low effective confining pressures, permeability increase with increasing strain can be very rapid and large. For example, at an effective confining pressure of 30 MPa, permeability increases by two orders of magnitude within 3% shortening, and increases by a further order of magnitude by 10% shortening. Only small increases in permeability occur with higher strains. Major increase in permeability, at strains as low as a few percent, is associated with growth of microcracks and rapid development of connectivity in grain-scale crack networks. Such behaviour persists well into the dominantly crystal plastic deformation regime, provided that pore fluid factors (ratio of pore fluid pressure to vertical stress) are high enough to facilitate some deformation by microcracking.

The experimental studies demonstrate that, in the mid- to deep crust when high pore fluid factors produce low effective confining pressures, grain-scale crack growth significantly enhances the permeability of active shear zones relative to their host-rocks, even though most displacement may be accommodated by microscopically ductile deformation mechanisms. A significant aspect of the experimental work is that microfracture networks can develop high connectivity and high permeability at very low strains, especially where pore fluid factors are high.

Permeability is also provided by the growth of macroscopic fracture networks in hydrothermal systems. This is particularly important in damage zones around active faults and shear zones, in fluid-active intrusive systems, and during growth of folds in mid- to upper crustal regimes. Although the geometry and types of fractures formed are governed by stress states, their growth and distribution is critically dependent on both pore fluid factors and stress states. Failure mode diagrams provide a useful tool to illustrate how the relative rates of change of pore fluid factors and stress differences control styles of fracturing in hydrothermal systems (Figure 1). Rapid pore fluid pressure rise relative to shear stress recovery leads to growth of hydrofracture networks prior to successive fault rupture events. Where post-rupture fluid pressure recovery is modest relative shear stress recovery, hydrofracture networks do not develop do not develop around faults, and permeability enhancement is localised along fault slip surfaces. At elevated temperatures, low rates of pore fluid pressure recovery relative to shear stress recovery promote ductile shear failure and grain-scale permeability enhancement within shear zones.

In overpressured hydrothermal systems at depth in the crust, self-generation of fracture permeability by migration of fluid pressure fronts is likely a key factor driving repeated permeability enhancement during crustal deformation (Cox, 2005).

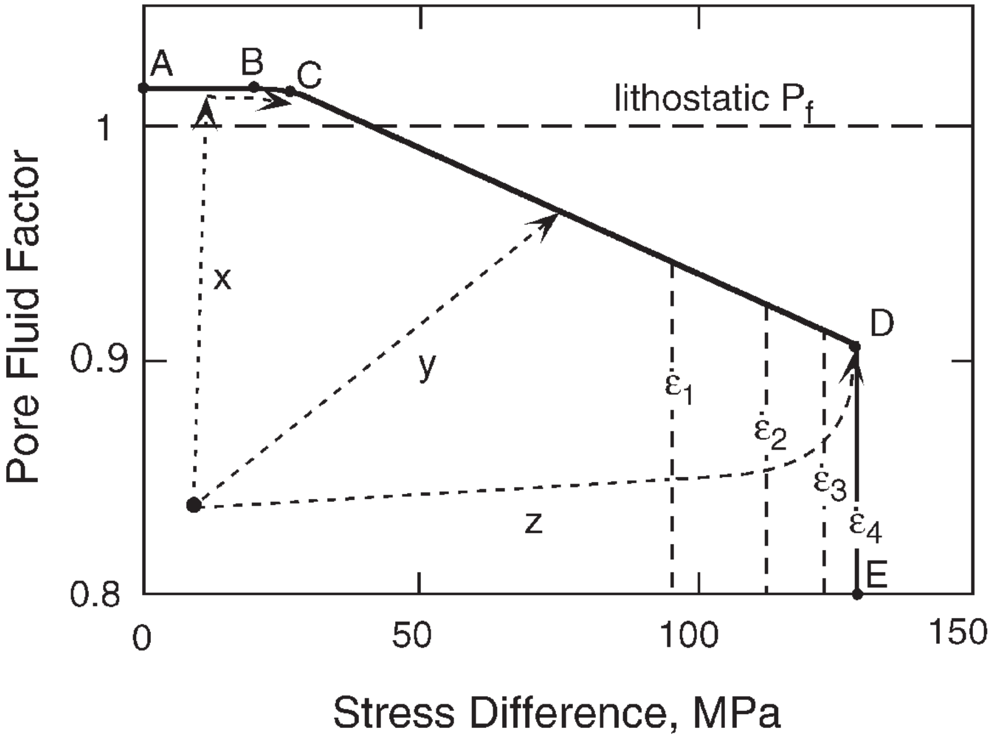

Figure 1. Failure-mode diagram illustrating brittle and plastic failure envelopes as a function of pore-fluid factor and stress difference. The diagram is constructed for optimally-oriented reverse faulting at a depth of 12 km in rock with a cohesive strength of 10 MPa, tensile strength of 5 MPa, and friction coefficient 0.75. The failure envelope is indicated by the curve ABCDE. Hydraulic extension failure occurs in the interval AB; extensional shear occurs between B and C; brittle shear failure occurs between C and D. Strainrate-dependent ductile shear failure envelopes are shown qualitatively for various strainrates ($\dot{\varepsilon}_1 < \dot{\varepsilon}_2 < \dot{\varepsilon}_3 < \dot{\varepsilon}_4$). At a high rate of increase of pore-fluid factor relative to stress change (path x), failure may first occur by extension fracture, followed by extensional shear failure at B, then by shear failure at C. For increase in both pore fluid factor and stress difference along path y, brittle shear failure is induced. For rapid increase in shear strength relative to the rate of increase of pore-fluid factor (path z), failure may first occur by ductile creep at increasing strain rates, until brittle shear failure occurs at D (after Cox, 2005).

Episodic flow versus continuous flow

At depth in the Earth's crust, especially at elevated temperatures in the presence of reactive pore fluids, healing and sealing of fractures can cause fracture connectivity and permeability to decrease on time-scales that are short relative to the lifetimes of hydrothermal systems. Similarly, dissolution-precipitation creep and intergranular cementation rapidly destroy permeability in fault damage products. The internal structure of veins in mid- to upper crustal fracture systems provides spectacular evidence for repeated fracturing and fracture-sealing during progressive deformation. For example, crack-seal microstructures in extension veins indicate that vein formation can involve up to several thousand fracturing and sealing events. Epithermal vein systems similarly provide evidence of repeated episodes of permeability enhancement and permeability destruction. Fault-related breccias and laminated fault-fill veins in hydrothermal systems also provide evidence for repeated permeability enhancement and destruction during mineralisation within actively deforming structures.

A key result from experimental studies (eg, Brantley *et al.*, 1990; Zhang *et al.*, 2001; Tenthorey et al, 2003), and from observations of natural fracture systems is that, because permeability is rapidly destroyed by mineral precipitation, fluid flow cannot be maintained unless ongoing deformation repeatedly regenerates fracture connectivity. Accordingly, permeability evolution and the nature of flow are controlled by competition between rates of fracture growth and rates of crack healing and sealing during deformation. In aseismic regimes, competition between deformation-driven permeability-creation processes and permeability-destruction processes can lead to continuous flow in deep level hydrothermal systems. However, in the seismogenic regime, rapid co-seismic permeability-enhancement and progressive permeability-destruction in the subsequent interseismic period, generates episodic flow regimes and associated fault-valve behaviour.

Flow localization

Although fluid flow tends to be localised within actively deforming, and therefore permeable structures, flow tends to be distributed very unevenly through these structures. Flow localisation within particular parts of structures is controlled largely by differences in fracture apertures, density and connectivity along structures.

For fracture-controlled flow in networks of randomly distributed fractures that are not fully interconnected, bulk permeability is given by

$$\mathrm{k} = (\mathrm{p}/120).\, f\, a^3 r^2 / l^3 \tag{2}$$

where a is the mean fracture aperture, r is the mean fracture length, l is the mean fracture spacing, and connectivity f is 0 £f £1 (Guéguen and Dienes, 1989). Although fracture orientations are seldom random, this relationship highlights the importance of fracture connectivity, fracture density and fracture apertures in controlling flow rates and fluid pathways. A key feature of this relationship is that permeability increases with the cube of fracture aperture. This relationship provides the basis for understanding flow localisation and ore localisation in both contractional and dilational bends and jogs in faults, as well as in structures such as branches, relays and terminal splays in fault systems, as well as in various fold-related and boudinage-related structures formed during folding. Permeability anisotropy in structural pathways provides a significant influence deposit-scale flow directions and shapes of ore shoots.

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