

Permeability measurement technique

Permeability measurements were made by using the steady-state flow method, which consists of imposing a known pore-pressure difference across the specimen and measuring the resultant flow rate, which is proportional to permeability. Pore-fluid pressures on both sides of the specimen were controlled by using high-precision, servo-controlled volumeters (Zhang et al., 1994). Typical pore-pressure differences used were 1–4 MPa, and the minimum permeability that could be measured reliably with this method was found to be $5 \Delta 10^{-21} \text{ m}^2$. Previous experimental work indicates that permeability measurements are reproducible to within 20% (Zhang and Cox, 2000). In each experiment, permeability measurements were first made at 500 °C. At this temperature slow kinetics precluded any reaction of antigorite + carbonate, yet was high enough to cause the metal jacket to bond tightly against the specimen and prevent any hydraulic short circuits around the sample. In every case, fluid flow across the sample was completely impeded, indicating a starting specimen permeability of $<10^{-21} \text{ m}^2$. For graphical purposes, we assume that the starting serpentinite permeability is 10^{-22} m^2 .

Once each experiment attained the target temperature, reaction and dehydration were indicated by the expulsion of water from the specimen. The rate of fluid expulsion and therefore reaction was measured by the retraction rate of the volumeter pistons, which are servo-controlled to maintain a constant pore pressure on both sides of the specimen. The generation of pore fluid by dehydration within the specimen during permeability measurement sets up a non-linear fluid pressure gradient across the specimen.

The analysis below demonstrates that the steady state flow technique can be used to measure permeability, even in an actively dehydrating material.

Transient saturated flow through a porous medium producing excess fluid at a constant rate is described by (Freeze and Cherry, 1979):

$$(\zeta + n\eta) \frac{\epsilon P}{\epsilon t} + \frac{K}{\psi g} \frac{\epsilon^2 P}{\epsilon x^2} = 2 W \quad (1)$$

where ζ is the compressibility of the rock, n is porosity, η is the compressibility of the fluid, $\epsilon P/\epsilon t$ is the change of pore pressure with time, K is hydraulic conductivity, $\epsilon^2 P/\epsilon x^2$ is the gradient of the pore pressure profile and W is the volume rate of dehydration fluids released per unit volume of specimen.

Assuming that the permeability measurement occurs on a short enough time scale so that W can be approximated as constant (which will be demonstrated subsequently) and pore pressure at any point in the sample is quasi-steady state in time, then

$$\frac{K}{\psi g} \frac{\epsilon^2 P}{\epsilon x^2} = 2 W \quad (2)$$

therefore,

$$\frac{dP}{dx} = 4 \frac{Wx}{K} + 2A \quad (3)$$

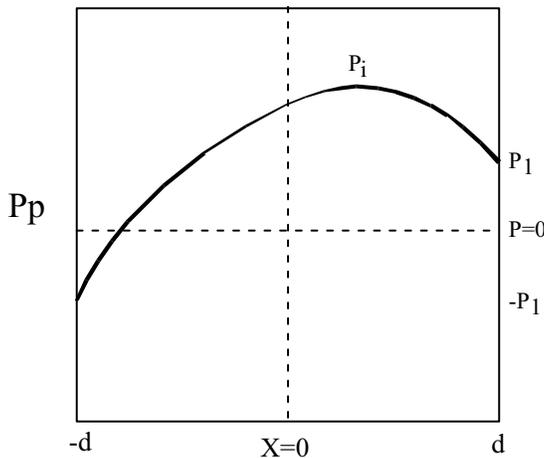
and

$$P = \frac{4Wx^2}{2K} + Ax + 2B \quad (4)$$

where A and B are constants

When a pore pressure difference is applied across the sample, with boundary conditions corresponding to P_1 and $-P_1$, the pore pressure profile is an asymmetrical quadratic function as shown in Figure 1:

Figure 1



Using the two boundary conditions to solve for the two unknowns A and B, we get $A = P_1/d$ and $B = Wd^2/2K$, where d is the half length of the specimen.

This yields the pore pressure profile:

$$P = \frac{W(d^2 - x^2)}{2K} + \frac{P_1 x}{d} \quad (5)$$

The first term on the right hand side of equation (5) is the independent solution for the pressure profile of a dehydrating specimen with no pore pressure difference across the specimen. The second term on the right hand side of equation (5) is the solution for the profile of a constant volume (non-dehydrating) system with an applied pore pressure difference. From (5), the flux of fluid (Q) flowing through any portion of the sample can be calculated by

$$Q = 4K \frac{dP}{dx} = 4K \left(-\frac{2Wx}{K} + \frac{P_1}{d} \right) = -8Wx + \frac{4KP_1}{d} \quad (6)$$

Since the fluid flux at both ends of the specimen is monitored before and after a pore pressure difference is imposed, the hydraulic conductivity K (or permeability) can be calculated using equation (6).

Another important factor that must be considered when conducting such permeability measurements is whether the quadratic pore pressure profile has equilibrated

on the time scale of the permeability measurement. The critical time (ϑ) for equilibration may be defined as (Braun et al., 2003):

$$\vartheta \propto \frac{\zeta d^2 \sigma}{k} \quad (7)$$

where k is the permeability of the specimen and ζ is the compressibility of the rock and μ is the viscosity of the fluid. We use this equation as the most conservative case where the rock has a very low permeability and the rock's compressibility is higher than for water. Using $\zeta = 5 \times 10^{-10} \text{ Pa}^{-1}$ (the high end of compressibilities for rock), and $k = 10^{-20} \text{ m}^2$ (the lowest permeabilities), we find that the time needed for equilibration is 210 seconds, which is well within the duration of a typical permeability measurement (~900 seconds).

It is also interesting to note that from the first term on the R.H.S. of equation (5) it is possible to calculate the maximum pore pressure (P_i on Figure 1) perturbation at the time of maximum fluid expulsion

$$P_i \propto \frac{W d^2 \sigma}{2k} \quad (8)$$

At very early stages in the highest temperature experiments $W \sim 4 \times 10^{-4} \text{ sec}^{-1}$, and $k = 10^{-20} \text{ m}^2$. Using these values we get $P_i = 84 \text{ MPa}$ which is less than the minimum confining pressure of 100 MPa. This pore pressure perturbation drops rapidly once permeability increases and the reaction rate drops.

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