Geological implications of a permeability-depth curve for the continental crust

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ABSTRACT

The decrease in permeability (k) of the continental crust with depth (z), as constrained by geothermal data and calculated fluid flux during metamorphism, is given by log k = –14 – 3.2 log z, where k is in meters squared and z is in kilometers. At moderate to great crustal depths (>~5 km), this curve is defined mainly by data from prograde metamorphic systems, and is thus applicable to orogenic belts where the crust is being thickened and/or heated; lower permeabilities may occur in stable cratonic regions. This k-z relation implies that typical metamorphic fluid flux values of ~10^{-11} m/s are consistent with fluid pressures significantly above hydrostatic values. The k-z curve also predicts that metamorphic CO_2 flux from large orogens may be sufficient to cause significant climatic effects, if retrograde carbonation reactions are minimal, and suggests a significant capacity for diffuse degassing of Earth (10^{15}–10^{16} g/yr) in tectonically active regions.

INTRODUCTION

Permeability is a critical geologic parameter, because migrating fluids play a fundamental role in mass and heat transfer and crustal rheology (e.g., Ingebritsen and Sanford, 1998). In the standard Darcian flow model, the magnitude of fluid flux (q) is a function of the intrinsic permeability of the geologic medium (k), fluid viscosity (μ), and the pressure (P) and gravitational energy gradients acting on a unit volume of fluid. That is, in one dimension,

$$q_x = \left(\frac{k}{\mu}\right)\left(-\frac{\partial\left[P+\rho g z\right]}{\partial x}\right), \qquad (1)$$

where ρ is fluid density, g is gravitational acceleration, z is elevation above a datum, and $\partial(P + \rho gz)/\partial x$ is the energy gradient for fluid flow along the flow path x, so that the proportionality between the instantaneous volumetric fluid flux along x (q_x) and the energy gradient is the quotient (k/μ). Numerical experiments on a wide range of geologic environments show that permeability is usually the primary control on fluid flux. This is because the measured intrinsic permeability of common geologic media varies by a remarkable 16 orders of magnitude, from values as low as 10^{-23} m^2 in intact crystalline rock, intact shales, fault gouges, and halite, to values as high as 10^{-7} m^2 in well-sorted gravels. Fluid viscosity and typical driving forces for fluid flow exhibit much narrower ranges of variation.

The variation in permeability with depth is particularly important for understanding the role of fluids in crustal processes. Here we show that a crustal-scale permeability-depth curve based on geothermal data and estimates of metamorphic fluid flow (Manning and Ingebritsen, 1999) permits evaluation of the role of fluids in the brittle-ductile transition, faulting, the links between metamorphism and climate, and degassing of the Earth.

PERMEABILITY-DEPTH CURVE FOR THE CONTINENTAL CRUST

The depth dependence of permeability is poorly known for several reasons. The maximum depth of in situ sampling of permeability by direct hydraulic measurements is ~10 km (Bayuk et al., 1987; Huenges et al., 1997). Direct measurements of samples taken from exhumed terranes yield existing permeability, but not permeability during the event that formed the rock.

As an alternative to in situ or core-based hydraulic measurements, the variation in permeability with depth can be probed indirectly by (1) hydrologic models that use geothermal data as constraints and (2) the progress of metamorphic reactions driven by fluid flow. Inverse-modeling approaches constrain permeabilities in the depth range explored by geothermal studies (usually <3 km but sometimes as deep as 10 km), and return permeability as a primary result. In contrast, the primary data from studies of metamorphic systems consist of time-integrated fluid-flux (Q, or $q\Delta t$) estimates, which must be translated to time-averaged permeabilities through

$$k = \left(\frac{Q\mu}{\Delta t\left[\partial\left\{P+\rho g z\right\}/\partial x\right]}\right), \qquad (2)$$

where Δt is the duration of fluid flow and the time over which permeability is averaged. Formal error analysis indicates that, for metamorphic systems, combined uncertainties in Q, Δt, and the driving-force gradient typically result in uncertainties in k of plus or minus one order of magnitude (Manning and Ingebritsen, 1999).

Permeabilities obtained from geothermal models are large-scale (kilometers or more) effective values, whereas permeabilities from metamorphic studies are based on compositional data from assemblages of hand specimens (centimeter scale). It has been suggested that permeability depends on the volume sampled (Brace, 1980; Clauser, 1992). However, data from two intensively studied localities—the Uinta sedimentary basin, Utah, and the Mirror Lake fractured-rock site, New Hampshire—suggest that mean permeability is similar at all scales, as long as care is taken to ensure that the sampled population is representative. Variance about the mean may decrease with increasing measurement scale (Fig. 1). For the purposes of this study we assume that, with high sample density, mean permeabilities inferred from large-scale geothermal models are directly comparable to mean permeabilities inferred by hand-specimen-scale sampling of metamorphic localities.

Combination of the geothermal and metamorphic data indicates that permeability decreases with depth on a crustal scale (Fig. 2A; Manning and Ingebritsen, 1999). More important, the k-z curve implies that depth, not metamorphic setting or lithology, is the most important control on crustal-scale permeability. The geothermal and metamorphic data agree where there is overlap, and constrain a logarithmic permeability-depth function described by log k = –14 – 3.2 log z, where k is in meters squared and z is in kilometers. The constant in the k-z fit equation, which gives k at 1 km depth, is similar to Brace's (1980) average crustal value. This is sensible because Brace's compilation strongly weighted near-surface data. The agreement between the geothermal and metamorphic data where there is overlap (Fig. 2A) is consistent with the absence of scale effects implied by Figure 1.

The crustal-scale k-z relation from geothermal and metamorphic data appears to be at least as coherent as typical k-z data relations determined by direct hydraulic measurement of the upper crust. Upper crustal permeability measurements typically show 10^4-fold variation even within particular ash-flow tuff (Winograd, 1971) and soil units (Mitchell, 1993), and often document similar variability at particular depth horizons on a basin-wide scale (Fig. 3A). Even data from the Pierre Shale—an unusually homogeneous lithologic unit—suggest a fairly scattered k-z relation (Fig. 3B).

We have explained the relative coherence of the metamorphic data (Fig. 2) in terms of the permeabilities required for certain limiting processes (Manning and Ingebritsen, 1999). If permeability were any lower than ~10^{-19} m^2, rocks could not devolatilize during prograde metamorphism, as they are observed to do, even under the lithostatic fluid-pressure conditions implied by petrologic evidence. If metamorphic permeabilities were any greater than ~<10^{-18} to 10^{-17}, heat transfer in metamorphic terranes would be dominated by advection, whereas conduction is almost universally inferred (Fig. 2B).

The geothermal data are derived from diverse environments, but the deeper part of our *k-z* curve is based almost entirely on data from prograde metamorphic systems, and is thus most applicable to regions where the crust is being thickened and/or heated; i.e., to orogenic belts. Lower permeabilities might be expected during retrograde metamorphism, or in the deep crust in stable cratons. The values of *k* from metamorphic systems likely reflect the maximum principal component of the permeability tensor, because estimates from metamorphic fluxes are based on flow within lithologies; mean flux (and permeability) normal to lithologic contacts is typically lower (e.g., Bickle and Baker, 1990).

EFFECT OF THE BRITTLE-DUCTILE TRANSITION

It has been proposed that permeability decreases markedly at the brittle-ductile transition (Bailey, 1990; Fournier, 1991), which occurs at 10–15 km depth in typical crustal rocks along regional metamorphic geotherms. Our *k-z* curve (Fig. 2) shows that in the upper ~12 km of the crust, *k* varies widely at any given depth, but on average decreases by about 10^4 between 1 and 12 km depth. Below ~12 km, *k* is not a strong function of depth. Although the logarithmic fit to the data (Fig. 2A) indicates permeability decaying from about 10^{-18} m^2 to 10^{-19} m^2 between 15 and 35 km depth, the data below 12.5 km are fitted equally as well by a constant *k* value of ~$10^{-18.3}$ m^2.

Deviations from the fitted equation are greater by about a factor of 2 in the upper 10 km. The data are consistent with a higher variance and stronger depth dependence of *k* above 10–15 km, probably resulting from the higher rock strengths in the brittle regime, and effectively constant *k* below 10–15 km. They thus support a general distinction between the hydrodynamics of the brittle upper crust, where topography and magmatic heat sources dominate patterns of flow and externally derived (meteoric) fluids are common, and those of the ductile lower crust, dominated by devolatilization reactions and internally derived fluids. The absence of a permeability discontinuity or barrier at the transition implies that fluids produced in the middle and lower crust during metamorphism can readily be transmitted to the upper crust, where they can mix with meteoric fluids, and the *k-z* curve (Fig. 2) provides a quantitative basis for linking the two flow regimes.

IMPLICATIONS FOR FLUID PRESSURES AND FAULT BEHAVIOR

The crustal-scale *k-z* curve (Fig. 2) is consistent with the lithostatic fluid pressure inferred for areas of active metamorphism provided vertical permeability (k_z) is about 10% of horizontal permeability (k_x). Using the *k-z* curve we calculate via equation 1 that metamorphic fluid flux *q* ($q = Q/\Delta t$) values of ~10^{-10} m/s would be needed to maintain lithostatic pore-fluid pressures at depth (Fig. 4). Average *q* values for prograde metamorphism are somewhat lower, ~10^{-11} m/s (1.4×10^{-8} kg/[m^2-s]) (Manning and Ingebritsen, 1999). Nevertheless, phase equilibria and fluid inclusions in metamorphic rocks from deeper

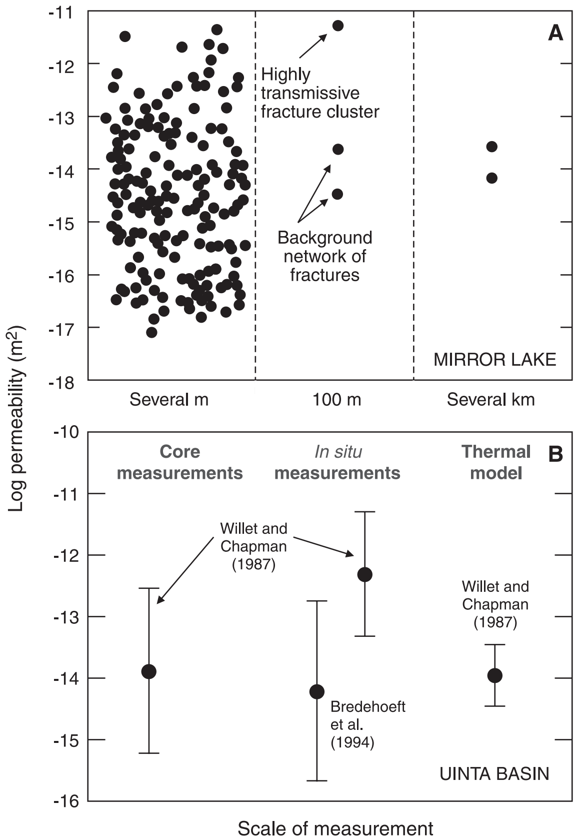

Figure 1. Upper crustal permeabilities determined at several distinct sampling scales at well-studied localities. A: At Mirror Lake, New Hampshire, mean permeabilities obtained by direct hydraulic measurement of metamorphic rocks at scales of several meters and ~100 m are consistent with values estimated at scales of several kilometers using numerical model constrained by water-budget data (Hsieh, 1998). B: In Uinta basin, Utah, mean permeabilities determined by direct hydraulic measurement of sedimentary rocks at core and well-test (in situ) scales are consistent with basin-scale values estimated using numerical model constrained by geothermal data. However, this is only if representative subset of in situ measurements is selected (Bredehoeft et al., 1994); simple average of in situ values from Uinta basin is likely biased by oversampling of permeable zones (Willet and Chapman, 1987).

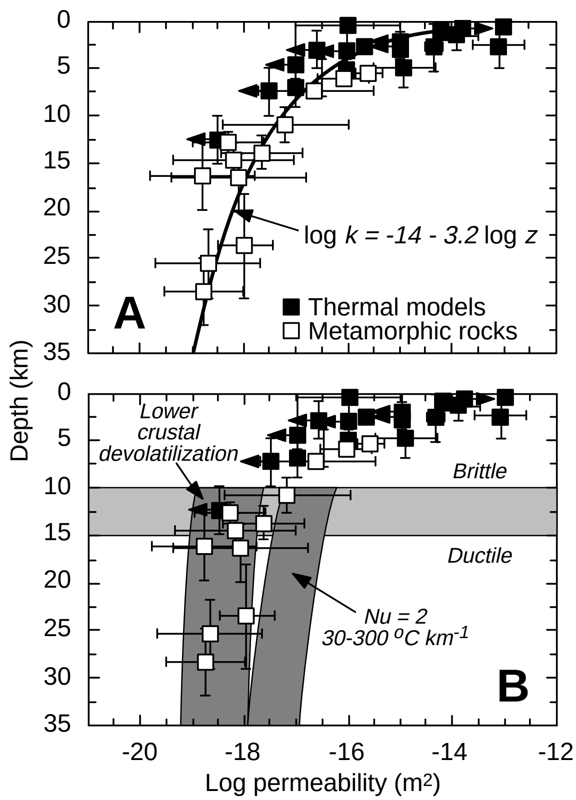

Figure 2. A: Permeability as function of depth in continental crust, based on constraints afforded by geothermal data (solid squares) and metamorphic systems (open squares). Solid line shows logarithmic fit to all data. B: Same data as in A, but with curves added to illustrate process-limiting values. Range shown for lower crustal devolatilization assumes flux of 10^{-8} kg/(m^2-s) (10^{-11} m/s) and driving-force gradients of 20 and 1 MPa/km, reflecting vertical to subhorizontal flow. Values shown for thermal Nusselt number of 2 represent temperature gradients of 30–300 °C/km, encompassing expected ranges for crustal metamorphism, and driving-force gradient of 1 MPa/km. See Manning and Ingebritsen (1999) for full details of individual datums.

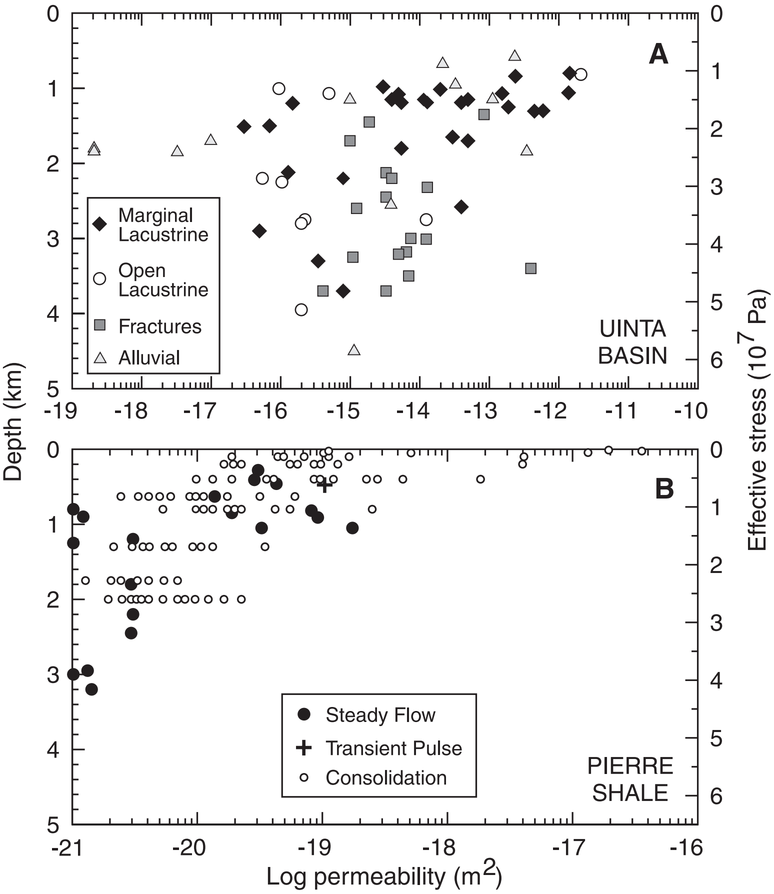

Figure 3. Permeability determined by direct hydraulic testing as function of depth or effective stress in upper (<5 km) crust. A: Results of drill-stem tests in variety of sedimentary facies in Uinta basin, Utah, showing ~10^4-fold variation at any particular depth (after Bredehoeft et al., 1994). B: Results of tests on core from Pierre Shale, showing ~10^2 fold variation at any particular value of effective stress (depth) (after Neuzil, 1986).

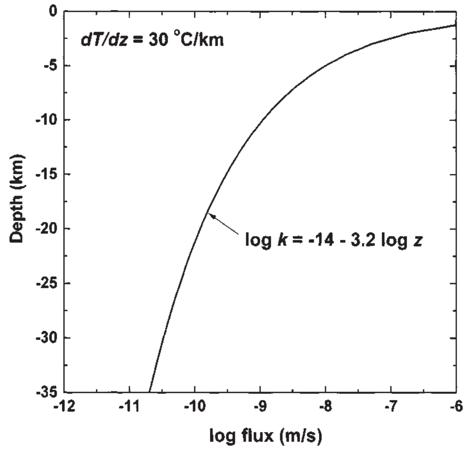

Figure 4. Fluid flux required to maintain lithostatic pore-fluid pressures, calculated on basis of Darcy's law (equation 1), permeability-depth (*k-z*) relation depicted in Figure 2, and typical temperature (*T*) gradient.

crustal settings typically indicate that fluid pressure is close to the lithostatic load (e.g., Fyfe et al., 1978). We have noted that the values of k from metamorphic systems (Fig. 2) likely reflect the maximum principal component of the permeability tensor. In many cases this component seems to be subhorizontal, so these observations can be reconciled by assuming k_z/k_x ~1/10, which would effectively reduce the required fluid flux from ~10^{-10} m/s to ~10^{-11} m/s, the average metamorphic q value. A modest anistropy ratio would also help reconcile one of the major issues in crustal petrology today: the discrepancy between numerical models (e.g., Hanson, 1997), which predict subvertical (upward), down-temperature flow, and field-based studies, which often infer subhorizontal, up-temperature flow (e.g., Ferry, 1992). The simplest explanation is that some of the field data reflect locally enhanced horizontal permeability due to lithology, metamorphic foliation, or folding (Skelton, 1996). The resulting anisotropy may temporarily deflect flow-path lines from the dominantly vertical orientation that is required by fluid pressures elevated well above the local hydrostat.

A seminal study of thrust faulting by Hubbert and Rubey (1959) demonstrated the critical influence of fluid-pressure effects. It has also been proposed that the fluid-pressure regime may control the behavior of great transform faults such as the San Andreas (e.g., Irwin and Barnes, 1975; Byerlee, 1990; Rice, 1992). Kennedy et al. (1997) used $^3He/^4He$ ratios to infer upward fluid fluxes of 3×10^{-11} m/s to 3×10^{-10} m/s in the San Andreas fault system. Our *k-z* curve (Figs. 2 and 4) suggests that, even in the absence of anisotropy, such fluxes could reasonably be expected to cause elevated fluid pressures at 15 km depth, the approximate base of the seismogenic crust in the California Coast Ranges. Significantly elevated fluid pressures at the base of the seismogenic zone would help to explain the mechanically weak behavior of the fault (e.g., Zoback et al., 1987).

IMPLICATIONS FOR OROGENY, PALEOCLIMATE, AND EARTH DEGASSING

If we accept that metamorphism takes place under conditions at or near lithostatic fluid pressure, we can assess the implications of the *k-z* curve with respect to the fluid flux. It has been suggested that metamorphism during major orogenies may release sufficient CO_2 to significantly influence the composition of the atmosphere (cf. Kerrick and Caldeira, 1993). Our *k-z* curve provides an independent test of this hypothesis; previous models of CO_2 production during metamorphism do not account explicitly for crustal permeability.

Metamorphic CO_2 fluxes of $\geq 2 \times 10^{18}$ mol/m.y. (~300 kg/s) are believed to be sufficient to double the atmospheric CO_2 content and cause 1.5 to 2 °C warming (Kerrick and Caldeira, 1993). Our *k-z* curve suggests that for reasonable CO_2/H_2O ratios (≤0.1 by weight), orogenic belts $>10^5$ km^2 in area may generate the requisite flux to the atmosphere, provided that there is little CO_2 uptake by retrograde metamorphism (Fig. 5). Furthermore, subsurface transit times should be geologically rapid—$\leq 10^6$ yr for ≤1% porosity—so that the orogenies (duration ~10^7 yr) and the resulting flux of metamorphic fluids to the atmosphere would be essentially synchronous. If the average CO_2 contents of metamorphic spring waters in the western United States (~0.03 by weight; Barnes, 1970) are representative of fluids emanating from orogenic belts, then active mountain belts similar in size to the Alpine-Himalayan chain may influence climate. Large orogenies involving carbon-rich rocks may influence climate even if we assume that average vertical permeabilities are ~10 times lower than the values suggested by the *k-z* curve.

If we assume that the deep crust in stable cratonic regions is much less permeable than in orogenic belts, we can use the *k-z* curve to estimate the global potential for diffuse Earth degassing through tectonically active continental crust. The global distribution of major zones of seismicity and CO_2-rich springs (Barnes et al., 1984) is a reasonable proxy for the orogenic belts,

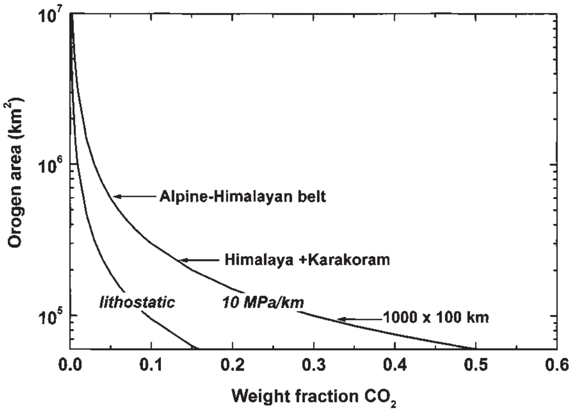

Figure 5. Size of orogen required to produce 2×10^{18} mol CO_2/Ma, for two fluid-pressure gradients (lithostatic and 10 MPa/km), typical temperature gradient, and mean crustal permeability of $10^{-18.3}$ m^2.

and suggests that our *k-z* curve may apply to as much as 10% of the area of the continents at any given time, or ~1.3×10^7 km^2. Taking $10^{-18.3}$ m^2 to be the approximate mean permeability of the lower crust suggested by the *k-z* curve, and assuming percolation along a lithostatic fluid-pressure gradient, the potential global degassing rate is ~3×10^{16} g/yr.

Some unknown fraction of fluids involved in prograde metamorphism at depth does not reach the surface, because upward flow will drive hydration and carbonation reactions. Another significant caveat is that, because *k* at depth during prograde metamorphism is presumably controlled, at least in part, by fluid production, our *k-z* curve may not be applicable to the entire crustal section simultaneously. Nevertheless, even if the mean vertical permeability in orogenic belts is 10 times lower than the values given by the fitted curve, and most of the metamorphic fluid (~66%) is taken up by retrograde reactions, the potential diffuse degassing of Earth (~10^{15} g/yr) appears to be as large or larger than other globally significant volatile fluxes such as the estimated H_2O (2×10^{14} g/yr) and CO_2 (3.5×10^{13} g/yr) fluxes at mid-ocean ridges, water recycled by subduction (8.8×10^{14} g/yr), and the CO_2 flux from volcanic arcs (9.2×10^{13} g/yr) (volatile fluxes compiled by Jambon, 1994). This suggests that diffuse Earth degassing through tectonically active continental crust may play a significant role in mediating the terrestrial inventory of volatile species over geologic time.

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