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Abstract

Implications of crustal permeability for fluid movement between terrestrial fluid reservoirs

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Abstract

A classic paper by Rubey [Geol. Soc. Amer. Bull 62 (1951) 1111] examined various hypotheses regarding the origin of sea water and concluded that the most likely hypothesis was volcanic outgassing, a view that was generally accepted by Earth scientists for the next several decades. More recent work suggests that the rate of subduction of water is much larger than the volcanic outgassing rate, lending support to hypotheses that either ocean volume has decreased with time, or that the imbalance is offset by continuous replenishment of water by cometary impacts. These alternatives are required in the absence of additional mechanisms for the return of water from subducting lithosphere to the Earth's surface. Our recent work on crustal permeability suggests a large capacity for water upflow through tectonically active continental crust, resulting in a heretofore-unrecognized degassing pathway that can accommodate the water-subduction rate. Escape of recycled water via delivery from the mantle through zones of active metamorphism eliminates the mass-balance argument for the loss of ocean volume or extraterrestrial sources.

Keywords: Permeability; Volatiles; Metamorphism; Heat flow

1. Introduction

Rubey's (1951) conclusion that most of the terrestrial inventory of volatile species (particularly H_2O, CO_2, and Cl) results from volcanic degassing was widely accepted for decades. However, Rubey's work predated the development of plate-tectonic theory, and it has since been shown that the amount of water subducted (900 Tg/year: Jambon, 1994) is significantly larger than the amount of water released by mid-ocean ridge volcanism (200 Tg/year: Jambon, 1994) and arc volcanoes (perhaps tens of teragrams/year: Ito et al., 1983; Jambon, 1994) combined. This apparent discrepancy between terrestrial sinks and sources of water (~ 700 Tg/year), combined with the recent recognition that quantities of water equivalent to several ocean volumes may be stored in the uppermost mantle in dense hydrous magnesium silicates (Smyth, 1994), poses serious problems for the hypothesis of terrestrial origin for Earth's oceans, and has helped to prompt increased interest in the possible on-going accretion of extraterrestrial volatiles (Frank et al., 1986; Deming, 1999).

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The apparent deficit between outgassing and subduction (Ito et al., 1983; Jambon, 1994; Bebout, 1995) poses a challenge for hypotheses of rapid volatile accretion on a young Earth (Delsemme, 2001), as well as for the older hypothesis of terrestrial origin for oceans (Rubey, 1951). This fundamental challenge to both theories may be mitigated by recognition of another potential terrestrial degassing pathway. Previous work ignores diffuse transport of volatiles from subducted lithosphere through the metamorphic-fluid system in tectonically active continental and island-arc crust at convergent margins. Based on a determination of the large-scale permeability of the active continental crust (Manning and Ingebritsen, 1999; Ingebritsen and Manning, 1999), we show that the potential for diffuse degassing of continental and arc crust at convergent margins exceeds the water subduction rate.

Permeability is a measure of the relative ease of fluid flow under unequal pressure and is independent of fluid properties. It is a parameter that is widely measured in the uppermost few kilometers of the Earth's crust, but direct measurement is infeasible deeper in the crust. As an alternative to direct measurement, we have used (1) models of heat and mass transport constrained by geothermal data and (2) the progress of metamorphic reactions driven by fluid flow to arrive at a coherent permeability–depth curve for the entire crust, log $k = -14 - 3.2 \log z$ (Manning and Ingebritsen, 1999), where permeability k is in meters squared and depth z is in kilometers (Fig. 1A).

Nearly all of our data below about 10-km depth represent permeability during prograde (heating stage) metamorphism. This suggests that the deeper part of this k–z curve is most applicable to regions where the crust is being thickened and/or heated—that is, to orogenic belts. There appears to be a causal link between fluid sourcing and permeability in tectonically active crust (Manning and Ingebritsen, 1999; Ingebritsen and Manning, 1999); for example, metamorphic devolatilization reactions likely generate porosity waves that propagate upward though the crust from the zone of fluid liberation (Connolly, 1997). In the absence of a fluid phase, permeability and porosity in the middle and lower crust may be exceedingly small. Thus we expect lower permeabilities during cooling and decompression, or in the deep crust in stable cratons, where there is no active metamorphism.

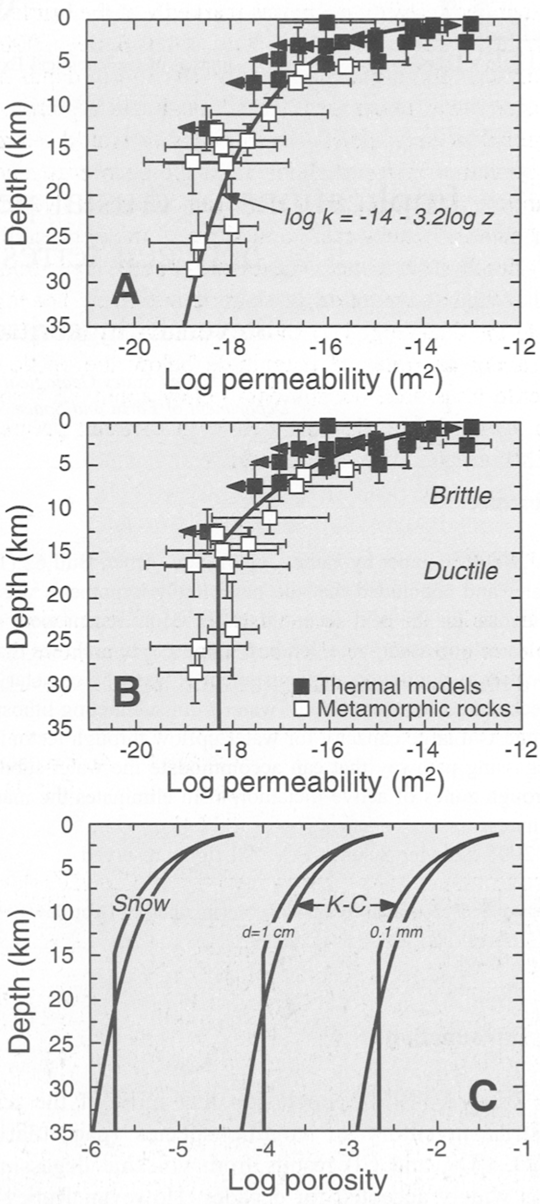


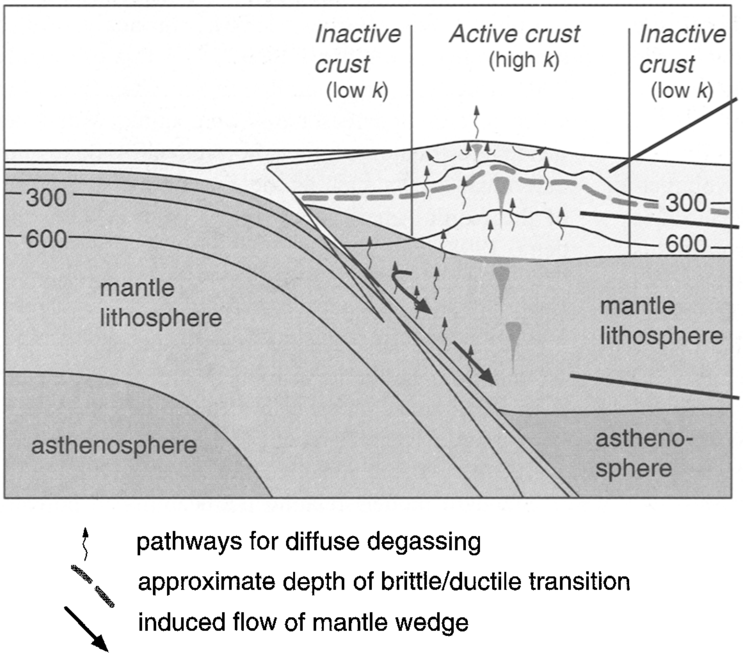
Fig. 1. Estimates of permeability based on hydrothermal modeling and the progress of metamorphic reactions showing (A) log fit to data and (B) data below 12.5-km depth fitted with a constant value of $10^{-18.3}$ m^2; and (C) complementary porosity–depth estimates retrieved from models that relate porosity and permeability: The Kozeny–Carmen (K–C) relation (Carman, 1956) for well-sorted granular media, assuming grain diameters ranging from 0.1 mm to 1.0 cm, and the parallel-plate (Snow) model (Snow, 1968) for uniformly spaced fractures. See Manning and Ingebritsen (1999) for details of the individual data and associated error estimates in (A) and (B).

It has been proposed that there is a hydrologic seal or that permeability decreases markedly at the brittle–ductile transition (Etheridge et al., 1983; Bailey, 1990; Fournier, 1991), which occurs at 10–15-km depth in crustal rocks under geothermal gradients typical of regional metamorphism. Such behavior would retard or prevent transfer of fluids from the deep crust and mantle to the upper crust and hydrosphere. However, our data indicate a change in slope of the permeability–depth relation near the brittle–ductile transition, rather than an abrupt decrease in permeability. The log fit to the data (Fig. 1A) shows permeability decaying by about an order of magnitude below the brittle–ductile transition, but the data below about 12.5 km are actually fitted just as well by a constant permeability of $10^{-18.3}$ m^2 (Fig. 1B).

2. Results

In order to use the crustal-scale permeability–depth relation of Fig. 1 to calculate a global potential for diffuse Earth degassing, we must estimate the area of the crust over which these relations might reasonably be applied, as well as the likely distribution of fluid pressure in the deeper crust. We must also consider the possibility of significant anisotropy of permeability. Conditions in the deeper, less permeable crust are the key issue, because the overall vertical permeability of the crust will be governed by the harmonic mean (Maasland, 1957), which is controlled by the lowest-permeability horizons. This implies that conditions in deep crust will restrict the potential upflow of internally derived fluids through the crust at convergent margins. At shallower depths, such fluids may readily mix into, and be redistributed by, meteoric-fluid-dominated flow systems (Fig. 2).

Because the deep crust in stable cratons is not undergoing active metamorphism and devolatilization, it is much less permeable than in orogenic belts, where permeability must be high enough to accommodate the volatiles released (Fig. 2). 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. These data suggest that our permeability–depth curve might apply to about



Above b/d transition, $P_f \sim P_{hydrostatic}$, complex fluid flow patterns influenced by topography, distribution of meteoric recharge, local heat and fluid sources

Below b/d transition, $P_f \sim P_{lithostatic}$, pervasive upflow, internally derived crustal fluids mix with minor fluid volumes from mantle wedge and degassing ponded magmas

In mantle, most fluid released between trench and arc; volatiles (1) incorporated in mantle, and then into magmas upon melting, or (2) flow through mantle wedge as discrete phase

Fig. 2. Conceptual model of fluid-flow patterns (arrows) in and below the tectonically active continental crust. In tectonically active regions, the lower crust must be sufficiently permeable to accommodate release of fluids from a variety of sources, and the permeability–depth relations of Fig. 1 may reasonably be invoked. Permeability may be lower in the inactive crust, where there are no fluid sources to create permeability.

10% of the area of the continents, or about 13 million km^2.

We will assume that fluid pressure in the deep crust is close to the lithostatic load. In sedimentary basins containing thick sequences of fine-grained material such as the Gulf Coast, near-lithostatic pore-fluid pressures are commonly observed in drillholes at depths as shallow as 3 km (Bethke, 1986). However, data from deep drillholes in crystalline rocks document near-hydrostatic fluid pressures to nearly 10-km depth (Huenges et al., 1997; Zoback and Zoback, 1997). Our permeability–depth relations (Fig. 1) are consistent with the latter value. They imply that permeabilities in the tectonically active crust are typically too high to permit large overpressures at <10 km-depth: the volumetric rate of fluid production by various geologic processes (generally $<10^{-12}$/s; Neuzil, 1995) is unlikely to generate near-lithostatic pressures for permeabilities $>10^{-17}$ m^2 (Neuzil, 1995; Ingebritsen and Sanford, 1998). It is reasonable to invoke near-lithostatic fluid pressures in the deeper crust, because analyses of phase equilibria and fluid inclusions indicate fluid pressure is close to the lithostatic load during metamorphism (Fyfe et al., 1978). Under lithostatic fluid-pressure gradients, the driving-force gradient for vertical fluid flow is the difference between the hydrostatic and lithostatic pressure gradients, or ~ 20 MPa/km.

Under these various assumptions, we can calculate the global mass flux $q_z \rho A$, where q_z is the (volumetric) vertical fluid flux, ρ is the fluid density, and A is the "tectonically active" area of the continents ($\sim 1.3 \times 10^{13}$ m^2). We invoke a constant vertical permeability k_z of $10^{-18.3}$ m^2 below 12.5-km depth (Fig. 1B) and apply Darcy's Law ($q_z = (k_z/\mu)(-\delta[P+\rho gz]/\delta z)$, where the driving force gradient $(-\delta[P+\rho gz]/\delta z)$ is ~ 20 MPa/km, μ is fluid viscosity, ρ is fluid density, g is gravitational acceleration, and z is elevation above a datum. Near the base of the crust $\mu \sim 1 \times 10^{-4}$ kg/(m/s) and $\rho \sim 900$ $\mathrm{kg/m^3}$.

This calculation suggests a present-day potential fluid upflow rate of about 4×10^4 Tg/year. If the rates of volatile addition to and loss from the mantle are equal, then to reconcile the mass imbalance due to subduction, as little as ~ 700 Tg/year (~ 2%) of this fluid would need to be water sourced ultimately from subduction zones, transported through the underlying mantle wedge, and delivered to the base of the crust. Even smaller mass flow rates are needed if the ocean volume is decreasing or mantle water mass increasing with time.

If there is significant horizontal/vertical anisotropy, our curve in Fig. 1B may slightly overestimate the vertical permeability of the deeper crust (Ingebritsen and Manning, 1999). The minimum feasible vertical permeability can be calculated by again assuming a lithostatic pressure gradient, $\mu \sim 1 \times 10^{-4}$ kg/(m/s) and $\rho \sim 900$ $\mathrm{kg/m^3}$, and devolatilization of average crust at a rate of $\sim 1.4 \times 10^{-8}$ $\mathrm{kg/(m^2/s)}$ (the arithmetic mean of flux data compiled for crustal depths greater than 10 km: Manning and Ingebritsen, 1999). This gives a vertical permeability of $10^{-19.1}$ m^2 and a global diffuse flux of about 6×10^3 Tg/year. Even for this minimum estimate of vertical permeability, the potential for fluid upflow is significantly larger than the subduction flux, and larger than other globally significant volatile fluxes such as the estimated H_2O and CO_2 fluxes at the mid-ocean ridge and the CO_2 flux from volcanic arcs (~ 900, 200, and 40 Tg/year, respectively: Jambon, 1994).

If we assume a CO_2 content similar to that observed in Western US springs dominated by metamorphic fluids (Barnes, 1970), our analysis also seems to permit a global, "deep" CO_2 flux of roughly 200 Tg/year, a value similar to the CO_2 flux from volcanic arcs and reasonably compatible with independent estimates of metamorphic CO_2 fluxes for individual events such as the Eocene metamorphism of the North American cordillera (Kerrick and Caldeira, 1998).

This analysis suggests fluid upflow through tectonically active continental crust in the range of 6×10^3–4×10^4 Tg/year. Even for the lower value, only ~ 10% of this flux would need to be water derived from subduction zones and transported through the underlying mantle wedge to reconcile the mass imbalance of ~ 700 Tg/year due to subduction.

Standard models relating permeability to porosity suggest very low connected porosities in the deeper part of the crust, generally <0.002 and perhaps $\ll 0.002$ (Fig. 1C). Such low porosities suggest geologically short residence times ($<10^5$ years) for free fluids generated in, or in transit through, the deep crust (transit times are calculated from fluid particle velocities defined by q_z/n, where n is effective or connected porosity).

3. Discussion

Geochemical data are compatible with the suggestion that 2–10% of the fluid upflow in the tectonically active crust may originate as water from subducted lithosphere that passed through and reacted with the mantle wedge. Mantle-derived fluids are known in a variety of metamorphic belts based on He, C, and Sr isotopes (Kamensky et al., 1990; Dahlgren et al., 1993; Oliver et al., 1993; Dunai and Touret, 1993). The mantle contribution to the total fluid flux in these localities is evidently quite variable. Preservation of mantle signature is favored by volatile transport to the uppermost mantle or lower crust by mantle-derived magmas that exsolve volatiles transported from their deeper source. Such exsolved fluids are then incorporated into, and variably diluted by, the more voluminous reservoir of crustally derived and recycled volatiles.

Our argument demonstrates that, even in the absence of an extraterrestrial source, neither the volume of the world ocean nor the volatile content of the mantle need change significantly with time. Transport of 700 Tg/year of subducted water through the crustal metamorphic-fluid system is feasible, and would yield a steady-state balance between degassing and regassing with respect to H_2O. This additional pathway for volatile loss from subduction zones is consistent with geochemical and geophysical constraints which preclude substantial volatile addition to the mantle over time. Subduction-zone metamorphic rocks show decreasing volatile content with increasing depth of burial, requiring that subducted oceanic crust loses substantial H_2O and CO_2 during production of eclogite-facies minerals (Peacock, 1993). The K_2O/H_2O of subducted lithosphere (Jambon and Zimmermann, 1990) and B-isotopic compositions of mid-ocean ridge basalt (Chaussidon and Jambon, 1994) preclude transport of significant volatiles beyond the depths of arc magma generation. Modeling of the thermal evolution of the mantle with volatile-dependent rheology suggests that $<30–40\%$ of subducted water is returned to the mantle (Franck and Bounama, 2001). Finally, the narrow width of the 410 km seismic discontinuity dictates that the mantle contains <0.2 wt.% H_2O (Wood, 1995), inconsistent with storage of the large volume of subducted H_2O that is required if there is a steady-state extraterrestrial source or ocean volume is decreasing.

Transport of subducted volatiles though the metamorphic-fluid system of tectonically active continental crust comprises a previously unquantified degassing pathway that vitiates the mass-balance arguments against a terrestrial origin for the world ocean (Rubey, 1951) or the early accretion of volatiles by cometary impact on a young Earth (Delsemme, 2001). In this respect, the 50-year-old Rubey hypothesis seems as robust as ever.

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