Diffuse fluid flux through orogenic belts: Implications for the world ocean

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Fifty years ago a classic paper by W. W. Rubey [(1951) *Geol. Soc. Am. Bull.* 62, 1111–1148] 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.

W.W. Rubey's (1) conclusion that most of the terrestrial inventory of volatile species (particularly H_2O, CO_2, and Cl) results from to 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 teragrams/year) (2) is significantly larger than the amount of water released by midocean ridge volcanism (200 teragrams/year) (2) and arc volcanoes (perhaps tens of teragrams/year) (2, 3) combined. This apparent discrepancy between terrestrial sinks and sources of water ($\approx$700 teragrams/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 aluminum silicates (4), poses serious problems for the hypothesis of terrestrial origin for Earth's oceans and has helped to prompt increased interest in the possible ongoing accretion of extraterrestrial volatiles (5, 6).

The apparent deficit between outgassing and subduction (2, 3, 7) poses a challenge for hypotheses of rapid volatile accretion on a young Earth (8), as well as for the older hypothesis of terrestrial origin for oceans (1). 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 (9, 10), 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 (*i*) models of heat and mass transport constrained by geothermal data and (*ii*) the progress of metamorphic reactions driven by fluid flow to arrive at a coherent permeability-depth curve for the entire crust, $\log k = -14–3.2 \log z$, where permeability k is in meters squared and depth z is in kilometers (Fig. 1*A*).

Nearly all of our data below about 10-km depth represent permeability during prograde (heating stage) metamorphism. This finding 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 (9, 10); for example, metamorphic devolatilization reactions likely generate porosity waves that progagate upward through the crust from the zone of fluid liberation (13). 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.

It has been proposed that there is a hydrologic seal or that permeability decreases markedly at the brittle-ductile transition (14–16), which occurs at 10- to 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. 1*A*) 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. 1*B*).

Results

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 (17), which is controlled by the lowest-permeability horizons. This notion 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 (18) is a reasonable proxy for the orogenic belts. These data suggest that our permeability-depth curve might apply to about 10% of the area of the continents, or about 13 million km^2.

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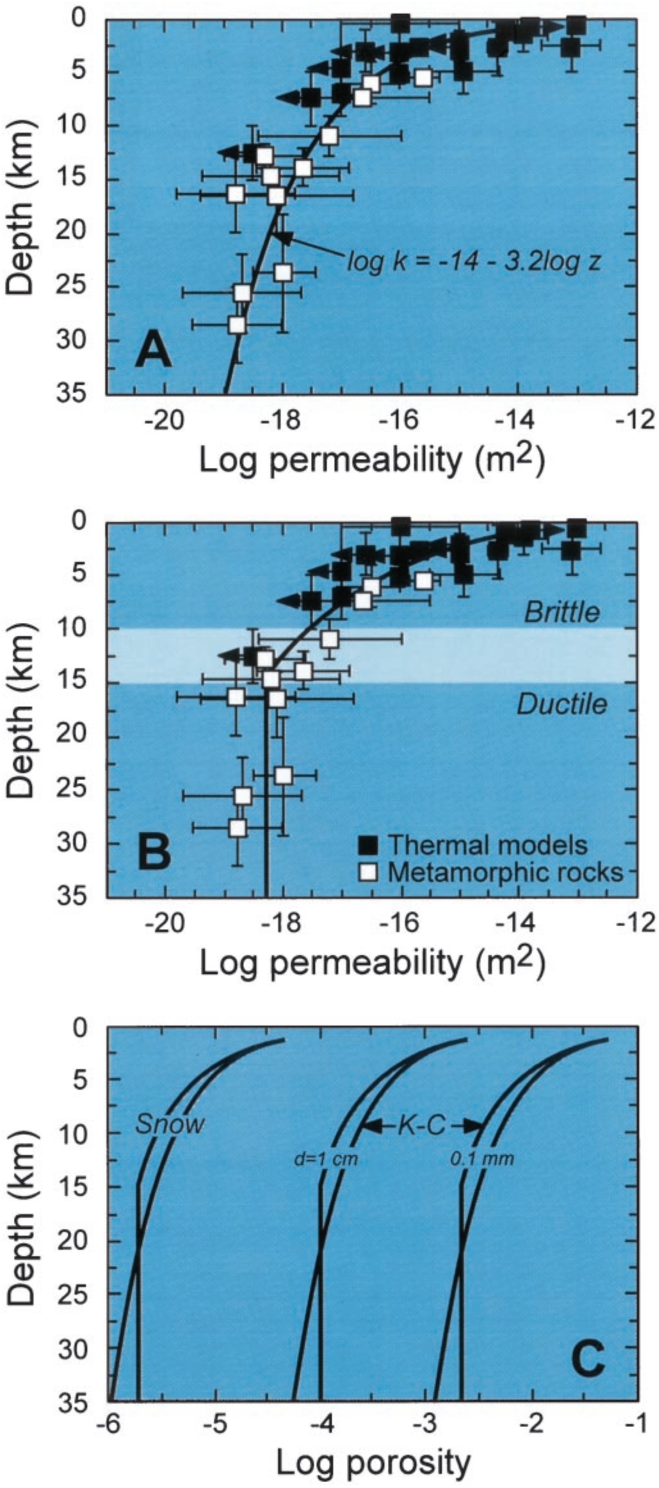

Fig. 1. Estimates of permeability based on hydrothermal modeling and the progress of metamorphic reactions showing (*A*) log fit to data, (*B*) data below 12.5 km depth fitted with a constant value of $10^{-18.3}$ m^2, and (*C*) complementary porosity-depth estimates retrieved from models that relate porosity and permeability: The Kozeny–Carmen relation (11) for well-sorted granular media, assuming grain diameters ranging from 0.1 mm to 1.0 cm, and the parallel-plate (Snow) model (12) for uniformly spaced fractures.

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 drill holes at depths as shallow as 3 km (19). However, data from deep drill holes in crystalline rocks document near-hydrostatic fluid pressures to nearly 10-km depth (20, 21). Our permeability-depth relations (Fig. 1) are consistent with the latter value. They imply that permeabilities in the tectonically active crust are generally too high to permit large overpressures at $<$10-km depth: the volumetric rate of fluid production by various geologic processes (generally $<10^{-12}$/s) (22) is unlikely to generate near-lithostatic pressures for permeabilities $>10^{-17}$ m^2 (22, 23). It is reasonable to invoke near-lithostatic fluid pressures in the deeper crust, because analysis of phase equilibria and fluid inclusions indicate fluid pressure is close to the lithostatic load during metamorphism (24). Under lithostatic fluid-pressure gradients the driving-force gradient for vertical fluid flow is related to the density difference between rock and fluid and is $\approx$20 MPa/km.

Taking $10^{-18.3}$ m^2 as the mean permeability of the lower crust below the brittle-ductile transition (Fig. 1*B*), and assuming percolation along a lithostatic fluid-pressure gradient over an area of 13 million km^2, there is a present-day potential fluid upflow rate of about 4×10^4 teragrams/year.[§] If the rates of volatile addition to and loss from the mantle are equal, then to reconcile the mass imbalance caused by subduction, as little as $\approx$700 teragrams/year ($\approx$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 is increasing with time.

If there is significant horizontal/vertical anisotropy our curve in Fig. 1*B* may slightly overestimate the vertical permeability of the deeper crust (10). The minimum feasible vertical permeability can be calculated by assuming devolatilization of average crust at a rate of $\approx 1.4 \times 10^{-8}$ kg/(m^2·s)[6] under a lithostatic pressure gradient. This result gives a vertical permeability of $10^{-19.1}$ m^2 and a global diffuse flux of about 6×10^3 teragrams/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 midocean ridge and the CO_2 flux from volcanic arcs ($\approx$900, 200, and 40 teragrams/year, respectively) (2).

If we assume a CO_2 content similar to that observed in western U.S. springs dominated by metamorphic fluids (25), our analysis also seems to permit a global, "deep" CO_2 flux of roughly 200 teragrams/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 (26).

This analysis suggests fluid upflow through tectonically active continental crust in the range of 6×10^3 to 4×10^4 teragrams/year. Even for the lower value, only $\approx$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 $\approx$700 teragrams/year caused by subduction.

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§The global mass flux is $q_z \rho A$, where q_z is the (volumetric) vertical fluid flux, ρ is the fluid density, and A is the "tectonically active" area of the continents ($\approx 1.3 \times 10^{13}$ m^2). To calculate the volumetric flux, we assume a constant vertical permeability k_z of $10^{-18.3}$ m^2 below 12.5-km depth (Fig. 1*B*) and apply Darcy's Law ($q_z = (k_z/\mu)(-\delta[P + \rho g z]/\delta z)$, where 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 $\mu \approx 1 \times 10^{-4}$ kg/(m·s) and $\rho \approx 900$ kg/m^3. Lithostatic conditions imply that the driving force gradient ($-\delta[P + \rho g z]/\delta z$) is $\approx$ 20 MPa/km.

¶The devolatilization flux of 1.4×10^{-8} kg/(m^2·s) is the arithmetic mean of the flux data compiled by Manning and Ingebritsen (9) for crustal depths greater than 10 km. This calculation also assumes $\mu \approx 1 \times 10^{-4}$ kg/(m·s) and $\rho \approx 900$ kg/m^3.

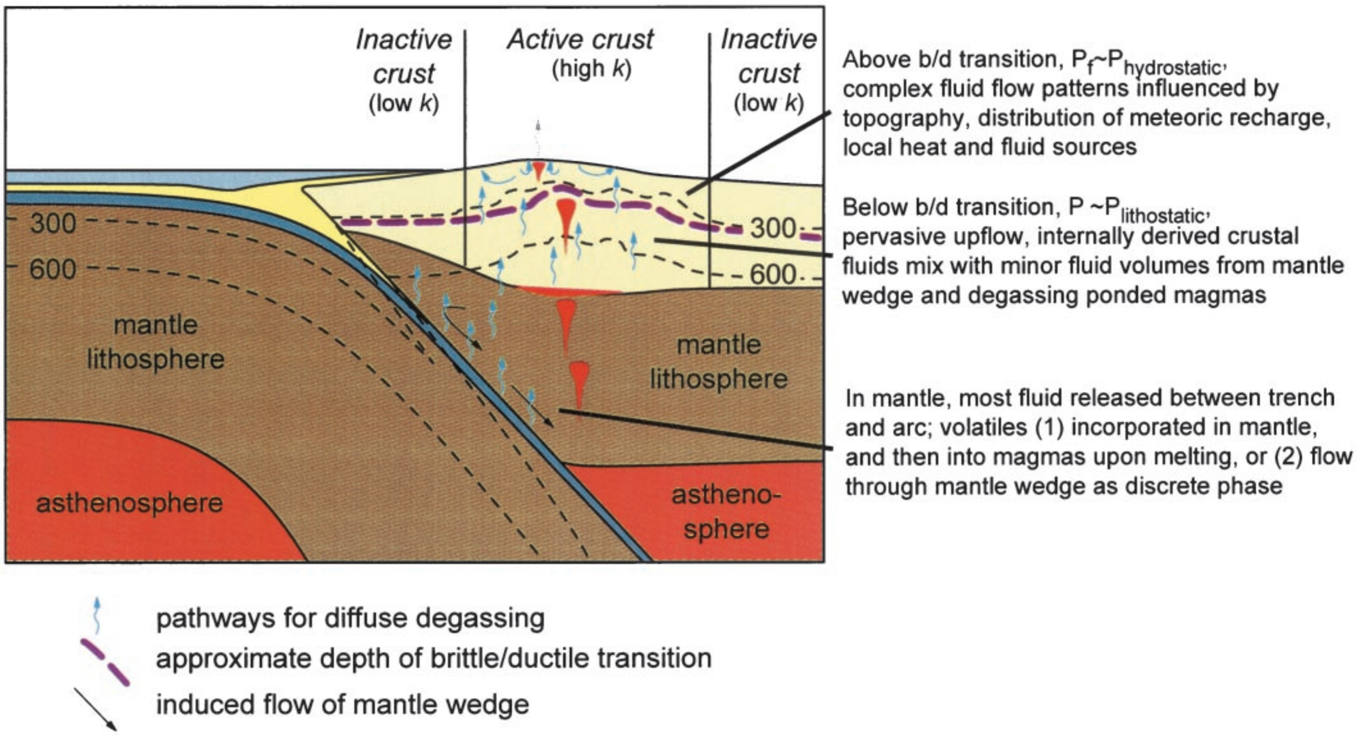

Fig. 2. Conceptual model of fluid-flow patterns (blue arrows) in and below the tectonically active continental crust. In tectonically active regions the lower crust must be sufficiently permeable to accommodate release of fluids from a variety of sources, and the permeability-depth relations of Fig.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

Standard models relating permeability to porosity suggest very low connected porosities in the deeper part of the crust, generally <0.002 and perhaps ≪0.002 (Fig. 1*C*). Such low porosities suggest geologically short residence times (<10^5 years) for free fluids generated in, or in transit through, the deep crust.‖

Discussion

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 is not incompatible with geochemical data. Mantle-derived fluids are known in a variety of metamorphic belts based on He, C, and Sr isotopes (27–30). 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 teragrams/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 that 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 (31). The K_2O/H_2O of subducted lithosphere (32) and B-isotopic compositions of midocean ridge basalts (33) 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 (34). Finally, the narrow width of the 410-km seismic discontinuity dictates that the mantle contain <0.2 weight % H_2O (35), 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 through 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 (1) or the early accretion of volatiles by cometary impact on a young Earth (8). In this respect the 50-year-old Rubey hypothesis seems as robust as ever.

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‖Transit times are calculated from fluid particle velocities defined by q_z/n, where n is effective or connected porosity.

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