Scales and Effects of Fluid Flow in the Upper Crust

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Two of the most important agents of geological change, solar energy and internal heat from the mantle, meet and battle for dominance in propelling aqueous and related fluids in the earth's upper crust. Which prevails and how they interact are subjects of active research. Recent work has demonstrated that both agents can propel fluids over nearly continental-scale distances in a fashion that influences a host of important geological processes and leaves a record in chemical alteration, mineral deposits, and hydrocarbon resources.

FEW SUBJECTS ARE MORE SIGNIFICANT TO MAN THAN FLUIDS in the upper crust. Groundwater is an important source of drinking and agricultural water. Hydrothermal water is a potential energy source. Past movements of hydrothermal waters have concentrated diverse metals into valuable mineral deposits. The migration of hydrocarbon liquids and gases has filled subsurface reservoirs. The tapping of these reservoirs is the basis of our transportation system and much of modern civilization. Gases moving through the upper crust from deeper levels carry information regarding processes in the lower crust and mantle. In this article I explore, through several examples, the time-space scales and the effects of fluid flow in the earth's upper crust (above ~15 km). Some attention is also given to deeper fluid movements.

Two energy sources drive fluid circulation in the crust. The first is solar radiation, which each year evaporates ~423,000 km^3 of water from the world's oceans, roughly that allowed by the solar energy influx. About 9% or ~37,400 km^3 of this water precipitates over the continents and is returned to the oceans by river (~94 to 99%) and groundwater (~1 to 6%) discharge, along with chemicals acquired in transit (*1, 2*). This process is generally referred to as the hydrologic cycle, and the flow it produces is known as hydrologic flow (Fig. 1). The second energy source driving fluid circulation in the crust is heat from the earth's interior, which drives the rock cycle and propels fluids by a variety of means including convection, compaction, thermal expansion, mineral dewatering, and organic maturation reactions. Convection is the most important of these processes in terms of the mass of water circulated per year. At least several hundred cubic kilometers of water are convectively circulated yearly near mid-ocean ridges, and this circulation has a clear effect on crust and ocean chemistry. The other processes produce a steady or episodic volatile flux toward the surface in areas of active crustal loading; these fluids can then accumulate under structural or chemical traps.

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Both the hydrologic and the rock cycles are global-scale processes, and, although they produce a host of local fluid movements, it should be no surprise that they also produce horizontal fluid movements of continental scale. Particularly the large-scale fluid movements are linked to other geologic phenomena and processes in fundamental and exciting ways. In the age of plate tectonics it is somewhat paradoxical to suggest that geologists have been thinking too small, but current work suggests that this has been the case for crustal fluid flow (*3*).

Hydrologic Flow

Roughly two-thirds of the rain that falls evaporates, either directly or with the assistance of vegetation. The other one-third recharges streams directly by overland flow, or with some delay along a path that involves infiltration, subsurface flow, and eventual discharge to springs or the stream bed. Overland and shallow groundwater flow charges streams during, and for a few hours or days after, a rainfall. Deeper groundwater flow keeps the streams fed between storms, maintaining steady baseline flow (*4*).

The deeper flow is driven by spatial variations in the elevation of the groundwater table (the surface below which the rock or soil becomes saturated with water). Infiltration "mounds" the water table until outflow balances the local recharge. The groundwater table is pinned at the elevation of the streams it recharges. The result is that the groundwater table is a subdued reflection of topography, and groundwater flow occurs on a variety of scales: local (over just one drainage divide), intermediate (over several), and regional (from highlands to the primary stream in the region) (*5, 6*).

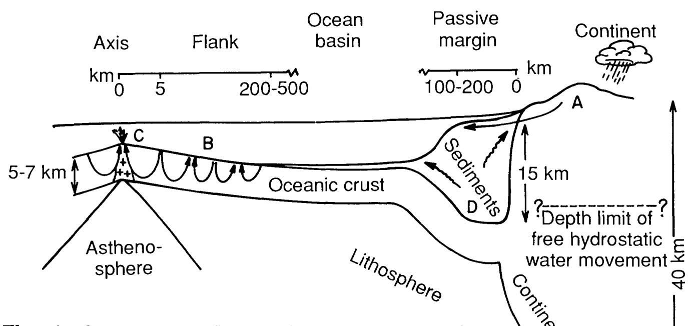
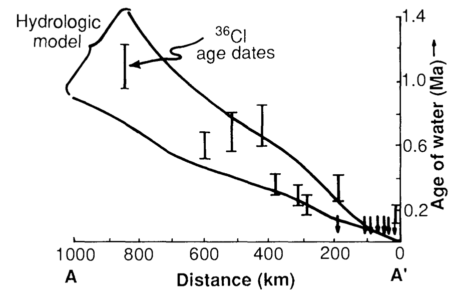
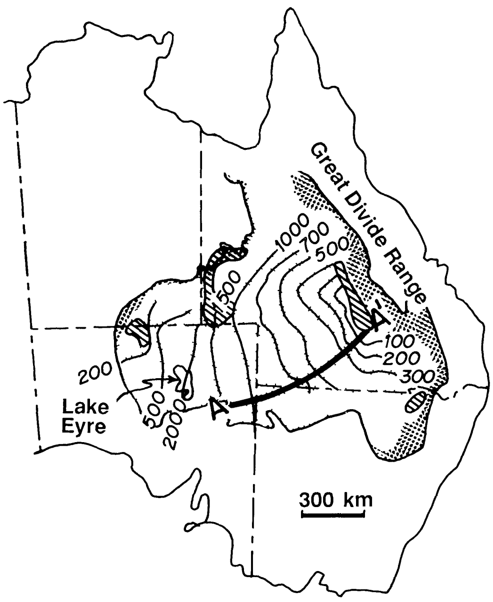


Fig. 1. Some yearly fluxes of water through the earth's upper crust by various processes (letters indicate tectonic settings); (A) hydrologic flow, 37,400 km^3 $year^{-1}$; (B) free convection, >240 km^3 $year^{-1}$; (C) forced convection, 40 km^3 $year^{-1}$; (D) compactive expulsion, ~3 km^3 $year^{-1}$. Compactive expulsion is estimated by doubling the efflux at subduction zones (*67*) to account for expulsion from sedimentary basins. Other values are discussed in the text.

Fig. 2. Water in the J aquifer of the Great Artesian Basin of Australia (shaded) increases in age from recharge along the Great Divide Range (darker shading) to discharge near Lake Eyre. Isotopic and hydrologic age estimates (contoured in thousands of years) agree well. Diagonal lines indicate measurable ^{14}C in J aquifer water. Ma, million years ago. Adapted from (*11, 13*).





A couple of basic observations follow from this discussion. Because average recharge is dictated by infiltration but not permeability (which determines only the height of the mound), local flow velocities can be easily estimated. For example, for a typical infiltration of 25 cm $year^{-1}$ (a vertical water flux of 25 cm^3 of water per square centimeter of surface area per year) and a soil porosity of 25%, the average recharge flow velocity will be 1 m $year^{-1}$. The flow velocity will increase or decrease along the subsurface flow path as variations in permeability focus or defocus the flow. The area of discharge is commonly less than the area of recharge (*6*); therefore, some focusing of flow in the subsurface occurs in many systems. If we take a typical local catchment 10 km in width (*5*) and an average fluid velocity of 2 m $year^{-1}$, a typical residence time for local groundwater flow might be 2500 years. There will be a full spectrum of residence times up to this magnitude in active (nonstagnant) parts of the local catchment and much longer residence times for the (defocused) intermediate and regional-scale flows outside the local catchment. The longer residence times are more difficult to estimate because there is generally no simple way to determine the fraction of recharge that is diverted to the larger scale systems.

Hydrologic flow tends to be shallow for several reasons. First, there is a natural tendency toward shallow flow. Simple calculations show that even in the unlikely case that uniform permeability persisted to great depths, greater than half the flow in the 10-km-wide local catchment discussed above would occur above a depth of 1 km and 90% above 3.6 km (*7*). Second, in many systems most of the flow is intercepted by high-permeability strata. The basal units in many sedimentary basins, for example, are high-permeability sands or karst terrains. Flow in such basins behaves almost as if none were allowed beneath these units (*6*), an observation that has led to the convenient and frequently used fiction of "impermeable basement." Finally, where rocks are soluble (salt or carbonate), dissolution will occur to river level. Caves and breccias developed to this baseline elevation flatten the water table and diminish deeper groundwater flow (*8*).

Work over the last decades has led to an increasing appreciation of the magnitude, persistence, and general importance of regional-scale hydrologic flow. Regional flow is most obvious and best investigated in arid areas with simple geology, where the complicating effects of local drainage systems are minimized. The Great Artesian Basin in Australia provides a spectacular example.

This basin underlies 22% of the continent of Australia (Fig. 2). The 3 km of Mesozoic sandstones, siltstones, and mudstones that comprise the basin are bent into a saucer shape but are otherwise little deformed. Aquifer recharge occurs where the permeable units outcrop at the margins of the saucer (dark-shaded areas of Fig. 2), particularly the western side of the Great Divide Range at elevations of 600 to 1500 m. Discharge is mostly through springs in the southwest near Lake Eyre (*9*).

The lowermost multilayered sand package, referred to as the J (for Jurassic) aquifer, is artesian. Over 4700 artesian wells have been drilled into the J aquifer, excellent records have been kept of production and changes in head, permeabilities and porosities have been measured in a host of field tests and inferred from the response to artificial discharge since the 1890s, and a model has been constructed of the entire aquifer that simulates its response to development and predicts future flows (*9, 10*). That model indicates that, before development in the 1890s, flow velocities in the J aquifer ranged from 0.5 to 1 m $year^{-1}$ and that the transit time for water to cross the 900-km-wide basin from east to west was about 2 million years (*11*). Interestingly, although man's 100 years of exploitation have reduced the artesian head and well discharges, a new equilibrium between recharge and discharge seems to have been reached in the 1970s. Further changes are not expected, provided usage remains the same (*9*).

Various data support the transit times predicted by the hydrologic model. (i) Water chemistry changes systematically along flow lines, indicating increasing chemical equilibration with the host rock as the contact time increases (*11, 12*). (ii) Waters with measurable ^{14}C occur only within about 120 km of margins where recharge is taking place (crosshatched areas of Fig. 2). Farther into the basin the water is old enough that the ^{14}C has decayed below detection limits. Most spectacularly, (iii) recent accelerator measurements of ^{36}Cl along the east-west trend indicated in Fig. 2 directly confirm the hydrologic estimates of fluid age (*13*). Such agreement between completely independent hydrologic and isotopic estimates of water age confirms that at least under relatively simple geologic conditions we can indeed estimate flow velocities and residence times over large distances and that fluids can make continental-scale journeys that take millions of years to complete.

Observations in North America indicate that the scale and rate of hydrologic crustal flow so clearly shown in Australia occur in areas of very different structure and climate. For example, the origin of saline waters discharging from natural springs in central Missouri indicates a scale of flow comparable to that in Australia. Isotope and trace element data and a completely independent regional groundwater flow analysis indicate that the waters discharging in central Missouri fell in the Rocky Mountains over 1000 km away, obtained their salinity by dissolving Permian evaporite rocks in Kansas, chemically reacted with siliceous clastic rocks or basement, and passed through the Missouri carbonates with very little interaction (presumably because they were already equilibrated with carbonate rocks) (*14*). Many other examples of regional-scale fluid flow have been documented in North America and elsewhere (*15*). Some workers have suggested that large-scale hydrologic flow is responsible for the formation of Mississippi Valley–type lead-zinc (MVT) deposits common on the margins of many basins and that hydrologic flow assists secondary migration of hydrocarbons (*16*).

The impression should not be given that water can reside in the crust for only a few million years. Any water disconnected from active flow, lying outside the very permeable (100 to 1000 millidarcies) aquifers we have been discussing, can remain in the crust for much longer periods of time. Also, any fluid that acquires unusually high density, by evaporation or salt dissolution, for example, may sink through permeable units, pond at depth, and be difficult to remove even though it is stored in permeable rocks. Recent observations in the earth's archean shields (rocks formed more than 2700 million years ago) suggest that this may commonly happen (*17*). Groundwater salinities, observed in mines and deep drill holes, increase markedly at depth. Geochemically the brines are similar to so-called oil field brines found today in basins such as the Michigan Basin, except that the brines have equilibrated at lower temperatures both chemically and isotopically with their enclosing rocks over the long times they have been in contact (*18*). The brines seem to have formed as typical basin brines, saturated or nearly saturated with NaCl, in overlying sedimentary cover long since eroded. They apparently sank, because of their density, into permeable fractures in what is now archean shield (*17*). The presence of such brines in crystalline basement terrains, especially at depths of 12 km (*19*), suggests that, although fractured basement may be of relatively low permeability, it is far from "impermeable" (*20*).

In summary, hydrologic flow may enter the earth's crust for short or long periods and may traverse small or very large, continental-scale, distances. Although hydrologic penetration of the crust is dominantly shallow, very deep penetration may also occur.

Rock Cycle–Driven Flow

As impressive as the hydrologic-driven flow is, it is only part of the story. Magma intrusion, associated especially with rifting at mid-ocean ridges, convects large quantities of water through the crust each year. Plate rifting and collision create surface topography, which is erased by erosion. The products of erosion accumulate to depths of up to 15 km in sedimentary basins. The sediments compact and emit water like a sponge under their own weight. At the same time, warming during burial to greater depths in the earth's thermal profile causes the pore fluids to expand, triggers chemical reactions that liberate water first from clays and then from other hydrated minerals, and decomposes organic matter to oil and gas. The result of all these processes is that fluids (both aqueous and hydrocarbon) are expelled from any area of active loading, whether the loading is due to sedimentation, volcanic activity, or tectonic overthrusting. Because of the relatively high temperatures of convection and the high overpressures (relative to hydrostatic) generated in load-driven expulsion, these mechanisms of crustal fluid flow have a disproportionate chemical and tectonic significance.

Thermal convection. From a planetary perspective, the great preponderance of aqueous crustal convection occurs along ocean rifts, where the earth's cool outer shell or lithosphere is broken and the plates on either side move apart, causing magmas to segregate from the mantle to form the oceanic crust (*21*). Recent seismic surveys show that even at fast-spreading ridges (total opening rate of 10 to 18 cm $year^{-1}$) axial magma chambers are only a few kilometers wide from their tops, 1.2 to 2.4 km below the sea floor, to the Moho at a depth of 6 to 7 km (*22*). Such narrow magma chambers can form at the sites of sea-floor spreading only if heat is removed by pore water convection that penetrates the entire crust within 40,000 years of its formation (*23*). Deep axial convection is also indicated by the 6-km-wide band of depressed heat flow that parallels the ridge in the Galápagos area and the ridge-parallel bands of high and low heat flow observed still farther from the ridge. Convection is probably terminated in ultramafic rock below the seismic Moho because these rocks hydrate to serpentinite, a very plastic rock that easily deforms to seal any fractures that might occur. The heat flow pattern shows in addition that a significant part of the axial convection circulates toward the ridge from adjacent areas along flow lines oriented perpendicular to the ridge axis (*24*).

The fluids that interact with the axial magma chambers vent at 350°C. Plumes of black smoke form when these fluids mix with seawater and precipitate their dissolved minerals as fine sulfide particles. These black smokers locally mark the exact axis of sea-floor spreading (Fig. 1). Vent sites teem with life. Tube worms and mussels feed off bacteria sustained by the oxidative contrast between seawater and reduced gases in the vent fluids (*25*). Some investigators have suggested that ridge axis vents, with their strong temperature gradients, appropriate chemical constituents, catalytic sulfide-covered surfaces, and fluid fluxes making an ideal environment for molecular synthesis may be the gardens of Eden where life on the earth began (*26*).

Where estimates of the average rate of thermal venting have been made at "normal" intermediate and fast-spreading ridges, the advective heat flux exceeds the local rate at which heat can be supplied by steady sea-floor spreading (*27*), and thus the hydrothermal venting must be variable. More dramatically, a warm ^{3}He-rich plume of fluid with large grain-size particulates entrained has recently been discovered and investigated in the ocean at the Juan de Fuca Ridge off the Oregon coast. The volume of the plume and the size and density of its entrained particulates indicate that it was discharged at rates 10^2 to 10^3 times those previously encountered (*28*). Hydrothermal vents are rare at slow-spreading ridges such as the mid-Atlantic Ridge, although some have recently been discovered (*29*). Magma chamber formation and high-temperature convection thus appear to be increasingly episodic near transform faults and at slow-spreading ridges, and in some cases are highly episodic.

The crustal residence times of seawater involved in normal ridge-axis convection are short. Isotopic measurements on the venting fluid indicate that <10 years elapse from the time the fluids undergo major basalt-water interaction (probably at about 150°C near the base of the upflow part of the path) to the time of surface discharge (*30*). Models of convection toward the ridge axis can accommodate flow velocities of this magnitude with reasonable rock parameters (*31*). Upflow velocities of 1000 m $year^{-1}$ and inflow and horizontal flow velocities an order of magnitude less are indicated for near-axis plate permeabilities of ~ 5 millidarcies and flow fracture porosity of $\sim 0.1\%$. The total crustal residence time for fluid circulation over a ≤ 15-km loop at ridge axes suggested by such models is ~ 100 years (*32, 33*). Turbulent flow models are required for the very rapid discharge events inferred at the Juan de Fuca Ridge. Several very different concepts and models of axial convection during times of normal discharge have been suggested (*34*). Highly variable flows require nonlinear chemical or mechanical control of permeability.

If axial convection (Fig. 1) removes all the excess heat introduced into the crust by magmatism ($\sim 14 \times 10^{18}$ cal $year^{-1}$ at the ridge axis) as seismic and other observations suggest, ~ 40 km^3 of 350°C fluids vent at ridge axes each year (*35*). Ridge-axis convection is but a small part of the total convection through the ocean crust, however.

The total heat introduced into the crust and lithosphere at mid-ocean ridges is about 100×10^{18} cal $year^{-1}$. The heat not accounted for by excess surface heat flow is about half the total or $\sim 50 \times 10^{18}$ cal $year^{-1}$ (*36*). Flank convection (Fig. 1) removes the heat not removed by ridge convection or $\sim 36 \times 10^{18}$ cal year^{-1}. The temperature of effective flank venting is <150°C; therefore, the total flank circulation is >240 km^3 year^{-1} (*37*). Ridge and flank convection together significantly hydrate, sulfidize, oxidize, and add magnesium and possibly sodium to the oceanic crust [pp. 351 and 359 in (*1*); (*36*)]. This alteration probably affects the chemistry of volcanism and associated mineralization when the ocean crust is subducted. The loss of magnesium to the crust is credited with resolving a major imbalance in the global magnesium flux [see p. 362 in (*1*)].

The pattern of heat flow away from ridges and their narrow axial magma chambers indicates that flow occurs through the entire oceanic crust (to a depth of 5 to 7 km) at mid-ocean ridges and flanks. Isotopic investigations show that, in the thicker continental crust, intrusive-driven convective circulation extends to a depth of at least 10 km (*38*). Laboratory measurements and extrapolation of field measurements suggest that permeabilities of 0.1 to 10 millidarcies are expected in fractured crystalline rocks at depths of 10 km (*39*). The depth of convective penetration in the continental crust may be limited by the ~350°C isotherm, the temperature above which fractures are thought to rapidly heal by pressure dissolution of asperities near intrusives (*32, 40*), and a temperature close to the transition to ductile rheology for crustal rocks. The time an intrusive takes to cool by convection depends mainly on the permeability of the surrounding host rock and the size of the intrusive. For intrusives a few kilometers in dimension, there is a surprisingly abrupt transition at a few hundredths of a millidarcy, below which cooling occurs essentially entirely by conduction and above which cooling is essentially entirely by convection. At a permeability of 1 millidarcy, an intrusive a few kilometers in dimension will convectively cool in a few thousand years; at 5 millidarcies, the convective cooling time will be one-fifth as long (*41*). Most geothermal systems have lifetimes of about 1 million years. Heat must therefore be supplied on a continuing basis by pulses of magmatic intrusion.

Fluid expulsion. Side-scan sonar surveys of continental shelves show that at least there the vertical flux of volatiles is as common and widespread a crustal phenomenon as convection or hydrologic flow through aquifers. Evidence for volatiles (gas and water) streaming from depth through the continental shelves is provided by pockmarks and seepages that are virtually ubiquitous in some areas (*42*). The pockmarks are typically tens to hundreds of meters in diameter and are best thought of as small explosion craters formed when gas, temporarily trapped at shallow depths, ruptures the overlying sediment and escapes. Once formed, pockmarks often serve as escape conduits for CO_2, CH_4, and other hydrocarbon gases that deposit calcite and other minerals. In addition to forming pockmarks, gas helps to mobilize mud diapirs. Gas-exhaling mounds 100 m high and 2 km in diameter have been observed in the Gulf of Mexico, for example (*42*). Volatiles (water and gases) seeping through the surface at pockmarks or elsewhere support chemosynthetic communities of tube worms and mussels similar to those found at the mid-ocean hydrothermal vents. Such communities appear to be common on the shelf slope in the Gulf of Mexico. The biggest chemosynthetic communities are associated with oil seepages. The relatively heavy carbon isotopic signatures indicate that the gases in the Gulf seepages were produced at least 2 km below the surface (*43*). Three-fourths of the world's major hydrocarbon reservoirs were discovered from surface seeps or expressions of some kind. Methane seepage to the oceans in the North Sea alone may exceed 2.6×10^{12} g year^{-1} (*42*).

Under the right circumstances, the ubiquitous nature of gas seepage can be directly seen. Under the temperature and pressure conditions of the outer shelves, gas is frozen at shallow depths in sediment pores as clathrates (*44, 45*). Clathrates, a type of gas-water ice, form at low temperatures (sea depths >500 m) where the concentrations of CH_4 and CO_2 generated by shallow bacterial decomposition, or deeper thermal maturation of organic matter, exceed their solubilities in the pore waters. The depth to the base of the clathrate zone, which is an excellent seismic reflector, is determined largely by temperature, and thus this zone tends to be parallel to the ocean bottom. Seismic surveys show that bottom-simulating reflectors (BSRs), which may be the base of clathrate layers, are present over 25,000 km^2 on the Louisiana slope alone (*46*). If all BSRs are clathrate, the amount of carbon contained in clathrates in the outer continental margins and in permafrost regions could exceed that in all fossil fuel deposits (*45*).

Subsurface pressure measurements, greatly facilitated by the recent development and deployment of the repeat formation tester, provide a remarkable picture of how water and volatile expulsion from the deeper parts of sedimentary basins is occurring. It has been known since the 1960s that pore fluid pressures can reach high (close to lithostatic) values in areas of active sedimentation below depths of about 3 km. In parts of the Texas and Louisiana Gulf Coast, for example, pressures are encountered that could support a column of water standing up to 4.5 km above the surface (*47*). Such pressures are produced by a combination of compaction, thermal expansion, and chemical reactions that lead to dewatering of clays (*48*). What has not been appreciated until relatively recently is that the overpressured zones below ~3 km in the Gulf and elsewhere may be divided into compartments (*49*). Within each compartment, the pressure gradient is hydrostatic and the pore fluids are free to circulate. The pore fluids are not free to move out of a pressure compartment except when the walls of the compartment rupture. An example of two fluid compartments penetrated by a single drill hole is shown in Fig. 3. Pressures approach lithostatic values (the pressure required to lift the overlying rock and fluid mass) at the two seals. The major oil fields of the North Sea (Eldfisk, Tor, and Ekofisk, for example) occur just above the top seal of the lower fluid compartment. Geochemical evidence, particularly biomarkers, shows unambiguously that the source of the oil is the Kimmeridge Shale (Upper Jurassic) in the lower compartment (*50*). Evidence such as the mismatch between the relative solubility of the various molecular components of oil in water and the mix of these components in oil reservoirs, as well as the ability to match oil and its source rock without taking into account the relative aqueous solubilities of the components, has persuaded many that oil migrates as a separate fluid phase (*51, 52*). Episodic release of fluids from a pressure compartment provides a plausible mechanism that would allow water and oil to migrate together but as separate phases.

The seals between compartments seem to be chemical: they initially form (and tend to stay) near the 95°C horizon, they crosscut lithologic units, and they are often indurated with silica or calcite to a degree that dramatically slows drilling when they are encountered (*49*). The specter of such an effective yet spatially restricted (~200 m thick) chemical control of permeability in basins is nothing short of revolutionary. Pressures at the tops of different compartments range from ~0.9 lithostatic to ~0.6 lithostatic; these values suggest that the compartments periodically rupture and partially drain, and that the interiors of the compartments are permeable enough to allow such drainage. It is conceivable that the compartment interiors are permeable enough that fluids within them are slowly convecting, driven by temperature gradients sustained by the contrasting thermal conductivities of different sediment types (*53*). Such slow convection could produce the high fluid:rock ratios required by observed chemical alteration (*54*) and might help maintain seal integrity.

Gas generation at greater depths could affect overpressure development and hydrocarbon migration. The change in total reactant plus product volume is much greater for deep thermogenic gas than for hydrocarbon generation (*55*). Therefore, gas generation at depth could be a significant contributor to overpressures in many areas (*56*). At high pressures, gas and oil are a supercritical mixture from which oil will progressively segregate as pressure is released. The ratios of oils of different molecular weights are distributed with depth in the Mahakam Delta in just the fashion (heavier *n*-alkanes deep, lighter *n*-alkanes at shallower depths) expected if these oils were precipitated from an upward-streaming gas phase (*52*).

The rupture of overpressured compartments appears to be directly recorded in two kinds of mineral deposits in the U.S. Gulf Coast Basin. Geologic relationships suggest that reduced formation waters venting from the overpressured zones along growth faults in Texas precipitated pyrite in adjacent aquifers. This pyrite then acted as a reductant to precipitate uranium from oxidized meteoric waters infiltrating these same units. The resulting roll-front uranium deposits record many episodes of oxidation and rereduction that reflect pulses of venting from the overpressured zones (*57*). Similarly, thin sulfide layers in the anhydrite caps of salt domes appear to record pulses of reduced basin brine coursing across the salt-anhydrite interface (*58*). During dome growth, the salt is steadily dissolved by meteoric water. Sulfides are precipitated at the salt-anhydrite interface when pulses of brine are expelled from the overpressured zone through faults at the margins of the salt. Paleomagnetic dating of the sulfides in the anhydrite cap suggest that dewatering pulses may occur at intervals of about 300 years (*59*). Similarity of the iron variation in sphalerite between sulfide bands in the Gulf Coast salt domes and in sphalerite overgrowths in MVT deposits (*60*) supports the notion that MVT deposits are produced by episodic basin dewatering (*60, 61*).

Phenomena in sedimentary basins are similar to those encountered during higher temperature crustal metamorphism. Metamorphic fluids are lithostatically pressured. Similar problems with the surprising intensity of metasomatic and isotopic alteration are encountered in metamorphic terrains and have led metamorphic petrologists to suggest novel ways, such as incipient cataclastic failure, to increase permeability enough to allow attainment of high fluid:rock ratios (*62*). Gold deposits mark the sites of fluid escape from greenstone metamorphic terrains and form just above or in the zone when fluid pressures drop from lithostatic to hydrostatic (*63*). Streaming of volatiles such as CO_2 from the lower crust or mantle might desiccate the crust and produce granulite terrains (*64*).

The horizontal and vertical scales of load-driven fluid flow may be large. The horizontal scale may be hundreds of kilometers around basins, if MVT deposits are a valid guide (*61*). Much of the east coast of the United States west of the Appalachian Mountains may have been altered by fluids squeezed out of sediments loaded by the Appalachian overthrust (*65*). The dewatering appears to have reset paleomagnetic pole positions and has led to a major reevaluation of paleomagnetic data from this area (*66*). The vertical scale, if metamorphic fluid movement is included, is crustal. The volume of fluids expelled may be large (>4 km^3 of water per square kilometer of overthrust surface) (*67*).

Interactions

Interactions between the hydrologic and rock cycles can produce a great variety of features. As described above, interactions between fluids driven by the sun and earth have produced uranium deposits with the deep earth fluids providing the reductant and the hydrologic fluids the uranium. Another interesting interaction takes place in the Great Artesian Basin of Australia. Waters in the J aquifer there intercept radiogenic volatiles generated in the underlying crust. The ^{4}He and ^{40}Ar accumulate in the J aquifer waters over their 2-million-year transit time at rates that far exceed the capacity of local generation by radioactive decay and approach the production rate expected for the entire crust (*68*). Some of the implications of this data are startling and yet to be fully worked out. What is presently clear is that unique data on the movement of radiogenic volatiles through the crust of eastern Australia over a 2-million-year time scale are provided by the interception of these volatiles by water steadily moving through the J aquifer.

Highly nonlinear chemical, physical, and biological feedbacks to permeability produce a host of other features. For example, the interplay between physical rupture and chemical plugging is responsible for hydrothermal explosions (*69*), episodic basin dewatering, possibly megaplume discharge, and pockmark formation by clathrate breakdown or deep gas venting. As recognized for a long time, there is a strong interplay between fluid pressure and tectonics (*70*). Reduction of sliding friction by fluid overpressuring is required for low-angle overthrusting. Shale diapirism caused by fluid overpressuring can pierce the stratigraphy of a basin, forever altering its permeability structure and pattern of fluid movement (*56*). Tectonic slippage along faults can alternately suck fluid into the earth's crust and then expel it. Stream flows have increased for months after earthquakes by this mechanism (*71*).

Understanding crustal fluid flow demands knowledge of the full history of geologic preparation. Dendritic river sands formed in deltas later collect oil-bearing fluids and funnel them to restricted inland locations when the deltas are involved in continental collisions. The largest accumulations of hydrocarbons (tar sands) on our planet were produced by this interaction between the hydrologic and rock cycle (*72*). Recent work shows that in the Salton Sea geothermal system a deep saline brine (nearly saturated at 25°C with NaCl) and a water of much lower salinity form a layered convection system. The brine is heated by magmatism produced during crustal rifting. As a result, the brine convects and its surface is upwarped to nearly the maximum level allowed by its thermal reduction in density. Heat from the sloping brine interface drives a countercurrent convection of overlying meteoric water. The brine interface, which fluctuates up and down in response to intrusive events, is the locus of particularly intense mineral reaction and sulfide precipitation (*73*). Without the prior accumulation of a deep brine, the space and time variability of fluid flow in the Salton Sea geothermal area would be quite different.

Perspective and the Future

The examples discussed above illustrate that fluid flow in the earth's crust is driven by several kinds of forces—fundamentally those deriving energy from the sun above and the mantle below. The relative importance of these forces has been debated for a very long time. For over 100 years beginning in the 1780s the Neptunists, who held that all mineral deposits were derived from ocean (later generalized to include fresh) water penetrating downward, debated the Plutonists, who held that mineralization was derived from the expulsion of magmatic volatiles (*74*). Today's discussions of the mechanisms of (secondary) oil migration and the formation of MVT deposits continue the spirit of this debate.

The time scale of steady hydrologic flow in the earth's crust ranges from a few hours to millions of years; space scales from tens of meters to thousands of kilometers. It is remarkable how permeable "impermeable basement" is to convection. Axial ridge convection is rapid, mainly due to the small effective fracture porosity of igneous rocks. Fluids probably transit their 15-km convective loop in hundreds of years or less. Transit times for the weaker flank

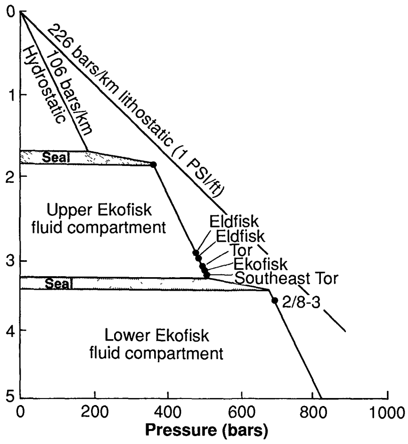


Fig. 3. Two pressure compartments penetrated by a single drill hole in the North Sea. Pressure measurements (indicated by dots) are mostly from producing oil reservoirs. Modified from (*49*).

convection are longer, perhaps ~1000 years. The crust is far more active in terms of volatile flux than we had imagined a short time ago. Flow from overpressured zones in areas of crustal loading is probably episodic. Strong variations in flow attend intrusive or tectonic events. Many kinds of chemical and thermal instabilities can modify permeability and topography on scales from meters to kilometers. Our observational base in many areas is too short to permit us to state with confidence what is typical.

Crustal fluid flow is perhaps most remarkable for its diversity. This diversity springs not only from many different driving forces but also from highly nonlinear physical, chemical, and biological feedback controls that can drastically and sometimes catastrophically modify permeability. The richly varied combinations that can result lie at the heart of the variable time and space scales of fluid flow, at the heart of societal interest (resources, earthquakes, and environmental and water quality), and at the heart of the mythological fascination and scientific challenge of the subject.

In the future we must seek to understand better the relative importance of the various kinds of fluid drive and the complex physical, chemical, and biological interactions that we now know affect fluid flow, and we need to define more precisely on all scales how fluids move through the crust. What is the nature of the high-permeability network of a sedimentary basin? What controls permeability and instabilities under overpressured conditions? What determines, and how does one describe, effective fracture porosity and permeability? What mechanisms of fluid flow are important for which kinds of resources (*75*)? What features can short-circuit the soil layer and allow chemicals rapid access to the ground-water table? What new kinds of circulation may be revealed by further ocean exploration? Recent discovery of saline springs along continental margins are especially intriguing in this regard (*76*). New instrumentation, isotope techniques, and ocean exploration, plus the vast volume of data collected in resource exploration and the computer technology to deal with and visualize that data, promise that in the near future there will be rapid scientific progress, new surprises, and continued debate and societal fascination with a subject unusually central to human well-being in the modern age.

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Fluid Processes in Subduction Zones

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Fluids play a critical role in subduction zones and arc magmatism. At shallow levels in subduction zones (<40 kilometers depth), expulsion of large volumes of pore waters and CH_4-H_2O fluids produced by diagenetic and low-grade metamorphic reactions affect the thermal and rheological evolution of the accretionary prism and provide nutrients for deep-sea biological communities. At greater depths, H_2O and CO_2 released by metamorphic reactions in the subducting oceanic crust may alter the bulk composition in the overlying mantle wedge and trigger partial melting reactions. The location and consequences of fluid production in subduction zones can be constrained by consideration of phase diagrams for relevant bulk compositions in conjunction with fluid and rock pressure-temperature-time paths predicted by numerical heat-transfer models. Partial melting of subducting, amphibole-bearing oceanic crust is predicted only within several tens of million years of the initiation of subduction in young oceanic lithosphere. In cooler subduction zones, partial melting appears to occur primarily in the overlying mantle wedge as a result of fluid infiltration.

SUBDUCTION ZONES REPRESENT SITES WHERE OCEANIC lithosphere, capped by variably hydrated oceanic crust and sediments, is consumed into the mantle. Volcanism in the overriding oceanic or continental plate generally occurs where the depth to the subducting slab is 80 to >150 km (*1*). The generation of magmas and continental crust at convergent plate margins is intimately linked to the behavior of C-O-H fluids (*2*) at depth in subduction zones. Our understanding of processes that occur at depths of ~100 km in subduction zones is based on geologic studies

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