Fluids in Planetary Systems

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Water and other geofluids play an important role in the geochemical and rheological evolution of the Earth and other bodies in the solar system. These fluids are responsible for the formation of hydrothermal mineral deposits, affect eruption behavior in volcanic systems and the geophysical properties of the mantle, and significantly affect the way in which rocks deform and fracture. Water is required for life to develop and survive, and the search for life beyond Earth defaults to a search for water in the solar system. In this inaugural issue of *Elements*, current knowledge concerning the distribution and role of water in diverse geological processes and environments is considered.

KEYWORDS: water, fluids, fluid inclusions, mantle, deformation, volcanoes, hydrothermal deposits

Water – without it humans cannot survive, and it is unlikely that life would have developed and evolved on a waterless Earth.

Water is the most valuable resource on Earth today, more valuable than diamonds, or gold, or petroleum, or any of the countless other resources produced and used by humankind. Water is valuable not because of its cost in dollars, but rather because humans cannot live for more than about one week without it. As the human population continues to grow, and sources of clean water become fewer due to overuse and careless disposal of wastes from industrial and other human activities, water will become the commodity that fuels economic prosperity and collapse, and will become the main issue around which wars are waged.

While water shortages will continue to increase worldwide, the problem is perhaps nowhere more serious than in the Middle East. In discussing the "water crisis" in the Middle East, former King Hussein of Jordan stated that "water is the only issue that could take me to war with Israel" (Postel 1992). Former Egyptian President Anwar Sadat echoed these sentiments when he said that "the only matter that could take Egypt to war again is water" (Postel 1992). Boutros Boutros-Ghali, then the Minister of State for Foreign Affairs for Egypt, stated, in an address to the U.S. Congress in 1989, that "the national security of Egypt is in the hands of the eight other African countries in the Nile basin" (Postel 1992). Egypt is only one of many countries whose main, or only, source of fresh water is controlled by its neighbors. Finally, no less a source than Tom Clancy notes that "Islamic law calls water the source of life. Nations may fight over oil, but it's a trifle. Water is what stirs the blood – and causes it to be stilled."

Finding and maintaining sources of fresh water are critical to the long-term survival of the human population, and are the tasks of hydrogeologists, civil engineers, and public policy makers, among others. While the importance of fresh water to sustain the needs of our growing population is obvious, water has additional significance to the Earth scientist. In this sense, when geoscientists discuss water it is usually not H_2O *sensu stricto*. Rather, the term "water" is often used to describe the low-viscosity fluid phase that is associated with many geologic processes, even though the "water" phase may contain dissolved salts or other volatile components, such as CO_2, CH_4, N_2, and sulfur gases.

Water in Earth and planetary systems occurs in many forms and amounts. At and near the Earth's surface, water typically occurs in the liquid state as rain and in rivers, lakes, oceans, and groundwater. Most of this near-surface water is relatively pure, containing from several hundreds of ppm dissolved salts and gases up to approximately 32,000 ppm (3.2 wt%) in seawater. With increasing depth in the Earth's crust, water typically becomes not only hotter but also more saline. Thus, fluids in deep continental basins often contain as much as 30–40 wt% TDS (total dissolved solids) and have temperatures in excess of 100°C. These basinal brines, or oil-field brines, are closely associated with the generation, migration, and trapping of hydrocarbon deposits and can lead to the formation of important Zn–Pb–Cu deposits of the Mississippi Valley type.

Fluids associated with hydrothermal mineral deposits may originate as meteoric water, seawater or basinal brines, or may have a metamorphic or magmatic origin. In this issue, Kesler describes hydrothermal mineral deposits in the context of the types of fluids involved and the geologic settings associated with various deposit types. He notes the wide range in the composition and temperature of fluids that form hydrothermal mineral deposits, as well as in the concentration and source(s) of metals in the fluids. Finally, Kesler identifies key areas where further research is needed and suggests areas in which major advances are expected in this century.

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Vesuvius during the last major eruption in 1944.
Photo courtesy Benedetto De Vivo.

Throughout Earth history, various processes have served to move water from one environment to another. Volcanism is the major activity whereby water and other volatiles are transferred from the deep Earth to the near-surface geo-, hydro-, and atmospheres. Le Cloarec and Marty (1991) have estimated annual fluxes (in mol yr^{-1}) from submarine volcanism for H_2O (10×10^{12}), C (2×10^{12}), S (2.5×10^{12}), Cl (7.6×10^{10}), N (10^9–10^{10}), and ^3He (1×10^3). Subaerial volcanism contributes about 2.4×10^{11} mol yr^{-1} of SO_2, with 90% of it being emitted during non-eruptive events. The subaerial carbon flux is only about 10% of the submarine contribution, or about 3.3×10^{11} mol yr^{-1}. The escape of water during subaerial volcanism has been estimated at about 2×10^{13} mol yr^{-1}, and that of Cl at about 1.3×10^{11} mol yr^{-1}. Thus, subaerial volcanism returns the majority of H_2O and Cl to the near-surface, whereas submarine volcanism is the main source of CO_2, S, and ^3He. The relative proportions of volatile components returned to the atmosphere during volcanism depend not only on the erupted mass, but also on the magma composition (Palais and Sigurdsson 1989). The total volatile yield from basaltic magmas is 1–2 orders of magnitude greater than for high-silica or rhyolitic magma. Similarly, basaltic magmas are more enriched in CO_2 and S, as compared with rhyolitic magmas. Many trachytic magmas are very enriched in the halogens Cl and F. Finally, about three orders of magnitude more CO_2 and over one order of magnitude more SO_2 are added to the Earth's atmosphere each year from anthropogenic sources than from submarine and subaerial volcanic sources combined.

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The contribution by De Vivo, Lima, and Webster summarizes the important role of volatiles in magmatic-volcanic systems. Much of the information available today on volatile contents of magma bodies beneath volcanoes comes from studies of silicate melt inclusions. DeVivo et al. summarize the history of research on silicate melt inclusions and their importance in understanding the evolution of magmatic-volcanic systems. Our ability to interpret results from silicate melt inclusions depends on the availability of experimental data on volatile solubilities in melts, and DeVivo et al. discuss results for the important volatiles H_2O, CO_2, S, and Cl. Finally, they describe the relationship between volatile exsolution and eruptive processes at Mt. Somma-Vesuvius, Italy.

While volcanism brings deep-seated volatiles to the near-surface environment, water and other components are transported from the surface to the interior of the Earth at subduction zones. The amounts of water and carbon dioxide that are subducted each year are estimated to be 8.7×10^{11} and 2.2×10^{11} kg, respectively (Peacock 1990). Only about 10% of this amount can be accounted for in arc magmas, and the remainder is likely removed from the subducting slab during metamorphism or lost from arc magmas during volcanism. Based on mass balance and other constraints, Jambon and Zimmerman (1990) similarly concluded that water must be lost from oceanic crust before incorporation back into the mantle via subduction. Abundant evidence exists to support the loss of fluids from the subducting slab at intermediate depths to produce quartz veins and hydrated minerals (Bebout and Barton 1989). Phase equilibria predict that dehydration of subducted serpentinites results in the loss of water at sub-arc depths and provides a source of water for arc magmas. Conversely, the retention of much of the carbonate in the original rock to depths exceeding 200 km provides a source for carbon dioxide in deep mantle melts (Kerrick and Connolly 1998). Based on oxygen isotopic data and salinities of fluid inclusions in eclogites, Philippot et al. (1998) estimated that 100–200 ppm Cl could be recycled into the mantle during subduction of altered oceanic crust. This interpretation is consistent with Cl concentrations ranging from 760 to 1500 ppm in glass inclusions from a subduction-related basalt at Fuego Volcano, Guatemala (Harris and Anderson 1984). Alt et al. (1993) studied the cycling of sulfur in subduction zones and, based on sulfur isotope data and sulfur abundances, concluded that sulfur in volcanic glasses was derived from subducted sediments.

As noted above, some of the volatiles contained in the subducted slab are returned to the surface through volcanic activity while the remainder is transported into the mantle. The mantle also contains juvenile water that has not previously been part of the Earth's hydrosphere (Bodnar 1999). Studies of mantle xenoliths (Green and Radcliffe 1975) and of nominally anhydrous minerals from the mantle (Aines and Rossman 1984; Katayama and Nakashima 2003; Rossman and Smyth 1990) have shown that the mantle contains abundant water. Smyth (1994) determined a model for the hydrous magnesium silicate wadsleyite [$Mg_7Si_4O_{14}(OH)_2$] and estimated a maximum water content for this phase of 3.3 wt%. This implies that the transition zone in the mantle could contain several oceans-worth of water if the phases were fully hydrated. In the third paper of this issue, Ohtani summarizes the various mechanisms that operate to return water to the mantle, as well as the mineralogical reservoirs for water in the mantle based on experimental and theoretical data. The geophysical evidence (and implications) for water in the Earth's mantle are also considered by Ohtani.

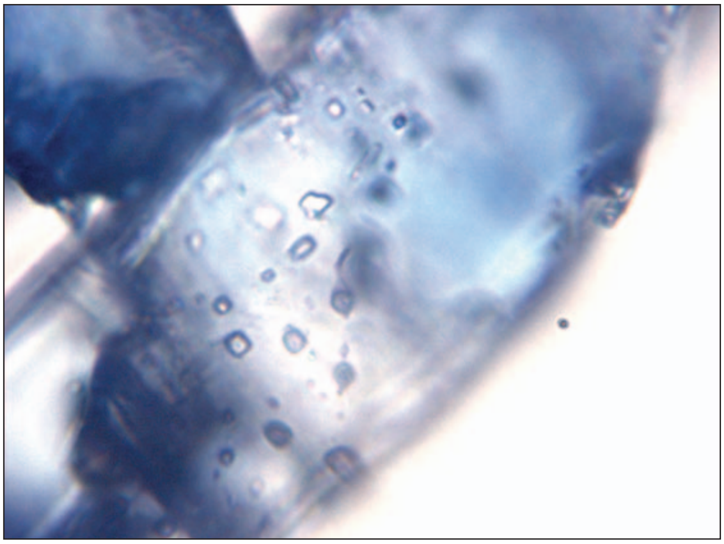
In a system, water affects both chemical evolution and rheological and physical properties. In ore-forming and volcanic systems, fluids are important agents for mass transfer, as described by Kesler and De Vivo et al., and mainly influence the chemical evolution. Conversely, the rheological and geophysical properties of the mantle are largely controlled by small amounts of water, as emphasized by Ohtani. While researchers have studied the role of fluids in the chemical evolution of geological systems for over 100 years, it is only recently that considerable attention has been focused on the important role that fluids play in rock deformation, faulting, and earthquakes. For example, Costain et al. (1987) suggested that intraplate seismicity could be related to the circulation of groundwater at considerable depths (10–20 km), and Gomberg et al. (2004) reported that elevated pore fluid pressures facilitated by high-temperature fluids may be responsible for triggering seismicity on critically stressed faults. Similarly the co-seismic release of high pressure CO_2 gas from a deep source was interpreted to be responsible for aftershocks associated with two earthquakes in northern Italy in 1997 (Miller et al. 2004). Meade and Jeanloz (1991) linked deep-focus earthquakes to dehydration of the lithosphere as it sinks into the upper mantle. High fluid pressures at depth in the San Andreas Fault have been related to fluids entering the fault system from the mantle (Kennedy et al. 1997). The current state of knowledge on the role of fluids in faulting and deformation is summarized in the contribution by Green and Jung. They note that fluid-induced faulting always involves participation of a low-viscosity fluid, and describe an unusual type of faulting in which this "fluid" is actually a nanocrystalline solid. Green and Jung also consider the role of water in the ductile behavior of nominally anhydrous minerals such as quartz and olivine and the geophysical implications of fluid-associated faulting under moderate to high stresses.

As is evident from the preceding discussion, the distribution of water in the different reservoirs in the Earth and how water moves between these reservoirs is understood, at least conceptually if not quantitatively. The same cannot be said about the amount, distribution, and movement of water on other bodies in the solar system. While little is known about water in extraterrestrial environments, it is the subject of much current research.

Perhaps the aspect of extraterrestrial water research that has been most visible to the lay person in recent years is the search for water on our nearest planetary neighbor, Mars. The suggestion that Mars currently contains water, or did so in the past, can be traced at least back to 1877 when Giovanni Schiaparelli produced the first maps of Mars and described a system of "canali" on the Martian surface. In Italian, "canali" means "channels", and Schiaparelli used this term to imply a natural feature, but the term was incorrectly translated into English as "canals", with the implication that the features were produced by intelligent beings. Interest in water, and the search for life, on Mars was further advanced in 1910 when the astronomer and science fiction writer Percival Lowell published a book entitled *Mars as the Abode of Life*. He described an advanced civilization that died out, leaving behind a system of canals that were designed to bring water from the polar regions to lower latitudes. More recently, the Mariner orbiters in the 1960s, the Viking landers in the 1970s, and the Pathfinder lander, Mars Global Surveyor, and Mars Odyssey orbiter of the 1990s contained instruments to look for chemical evidence of life on Mars.

Interest in the search for life on Mars exploded in 1996 with the announcement that researchers had discovered evidence of relic biogenic activity in the Martian meteorite ALH84001 (McKay et al. 1996). This evidence included polycyclic aromatic hydrocarbons, carbonate globules that were texturally similar to bacterially induced precipitates on Earth, and magnetite and sulfide phases that were thought to be of biogenic origin. While the interpretations of McKay et al. (1996) are not universally accepted, with various researchers questioning the low-temperature origin of the carbonates (Harvey and McSween 1996) and the biogenic origin of the magnetites (Barber and Scott 2003), the work has generated much interest in the possibility of past or present life on Mars. Life as we know it requires the presence of liquid water to develop, evolve, and survive. As such, the overall science strategy of NASA's Mars Exploration Program may be summarized as "Follow the Water".

It is generally accepted that liquid water, perhaps in the form of oceans, existed early in Mars' history and that it may have persisted for as much as 700 million years after the global mean temperature fell below the freezing point of water (McKay and Davis 1991). The Opportunity and Spirit rovers found additional evidence for liquid water on the surface of Mars, but the data cannot predict how recently that water was present. Interestingly, high-resolution images acquired by the Mars Global Surveyor Mars Orbiter Camera show landforms that have been interpreted to be geologically young and formed by water seepage from near-surface sources (Malin and Edgett 2000). If, in fact, liquid water occurs today in near-surface deposits where it is episodically released, life may also be present today beneath the Martian surface.



Numerous cube-shaped aqueous fluid inclusions within a blue halite (NaCl) crystal from the Zag ordinary chondrite meteorite. Asteroidal brines are trapped within these inclusions, which are at least 4.5 billion years old. View measures 0.5 mm across.

Photo courtesy Michael E. Zolensky.

While there is much current activity related to the search for water on Mars, evidence continues to build for the presence of water elsewhere in the solar system. In 1998, the Lunar Prospector spacecraft discovered large quantities of hydrogen in craters near the lunar poles, presumably in the form of water ice. To confirm this interpretation, NASA decided to crash the probe into a crater near the South Pole upon completion of its project to map the lunar surface. The idea was that the crash would eject pieces of the ice-cemented regolith and water vapor into space, and these could be detected using various remote sensing instruments on Earth and in Earth orbit. On July 31, 1999, the probe completed a controlled crash, but no water vapor plume was detected, leaving the question of water on the Moon unanswered.

Other likely habitats for liquid water in the solar system are the icy moons of the giant planets. Jupiter's moon Europa shows evidence of tectonic activity in the form of ridges and troughs, and this has been interpreted to represent "ice tectonics" with a crust of ice overlying a liquid water "mantle" (McCord et al. 1998). Similarly, detectors on the Galileo spacecraft showed that the magnetic field on one of Jupiter's largest moons, Callisto, fluctuates. This has been interpreted to indicate a salt water ocean beneath the icy crust (Ruiz 2001).

The presence of hydrous phases and the analysis of isotopes in the carbonaceous chondrite meteorites provide convincing evidence for the presence of liquid water on the parent bodies in the asteroid belt. Direct evidence for liquid water on the asteroids was provided by the Monahans (1998) meteorite (Zolensky et al. 1999). This meteorite fell on a clear, dry day in the small West Texas town of Monahans, in March 1998, and was immediately collected. A sample of the meteorite was delivered to NASA's Johnson Space Center shortly thereafter, and microscopic examination revealed the presence of small amounts of bluish purple halite. Closer examination revealed that the halite contained aqueous fluid inclusions that could only have been trapped on the parent body, before ejection of the sample and its arrival on Earth.

In his contribution on extraterrestrial water, Zolensky summarizes the current state of understanding of the distribution of water in the solar system. The search for water in the solar system is an active area of research and is in a high state of flux, with abundant new information being returned to Earth daily from the numerous spacecraft and rovers involved in this search.

Water, or more generally, fluid, plays a critical role in many terrestrial and extraterrestrial processes. The more we learn about the distribution of fluids in our environment and the properties of these fluids, the better we will understand the world we live in. This inaugural issue of *Elements* is dedicated to fluids in planetary systems, and it is hoped that the summaries included here will inform readers of the importance of fluids and encourage the next generation of scientists to continue to "Follow the Water"

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