have overt balance defects and only a mild hearing impairment but have a malformed stapes, shortened cochlear duct, an enlarged internal auditory meatus, thin bone in parts of the otic capsule, a constricted superior semicircular canal, and loosely packed spiral ligament fibrocytes. This phenotype resembles that of deaf individuals with mutations in human *POU3F4*, but, apart from the spiral ligament defects, is not at all like the phenotype of the Minowa *Pou3f4* mouse mutant (perhaps owing to differences in genetic background between the two mouse strains). Some phenotype variability is also found among X-linked deafness patients with *POU3F4* mutations.

At least four other human deafness genes may affect the balance of ions in the cochlear duct. The Norrie disease gene (*NDP*)—expressed in the spiral ligament and stria vascularis (*4*)—encodes a mucin-like protein that when mutated leads to late-onset progressive hearing loss. The *COCH* gene (thought to encode an extracellular matrix protein) is mutated in a form of dominant, nonsyndromic progressive hearing impairment associated with a loss of fibrocytes and increased extracellular deposits in the spiral ligament, sites that correspond to the route of K^+ recycling (*4*). The *COCH* gene has recently been implicated in some cases of Ménière's disease, the symptoms of which include fluctuating balance and hearing disruption thought to result from a fluid imbalance in the inner ear (*9*). A chloride and iodide transporter—encoded by the *PDS* gene and expressed by epithelial cells between the stria vascularis and the sensory hair cell region—is mutated in Pendred's syndrome as well as a form of nonsyndromic deafness (*4*, *10*). Another gene, *ATP6B1*, is expressed in interdental cells, a group of epithelial cells on the other (inner) side of the hair cell region. This gene encodes a component of a proton pump thought to control the pH of the endolymph; mutation results in renal tubular acidosis and deafness (*11*).

The hair cells of the cochlea are exquisitely tuned sensory receptors that depend for their survival on maintenance of a suitable environment. Mutations in one of the many proteins that maintain this environment result in a gradual loss of hair cell function leading to progressive hearing loss and eventual hair cell death. Therapeutic intervention to bypass the dysfunctional protein and to restore a benevolent environment before the hair cells die might halt the progression of deafness.

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PERSPECTIVES: PLANETARY SCIENCE

Primordial Water

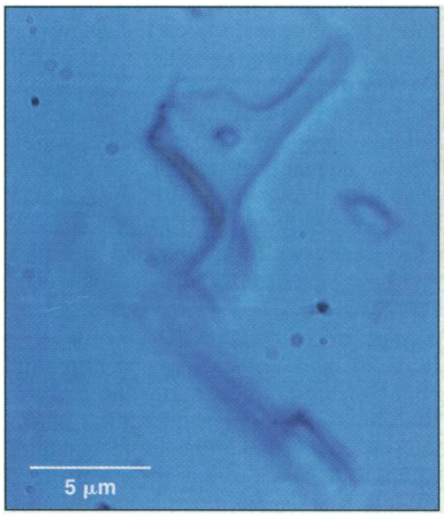
Robert N. Clayton

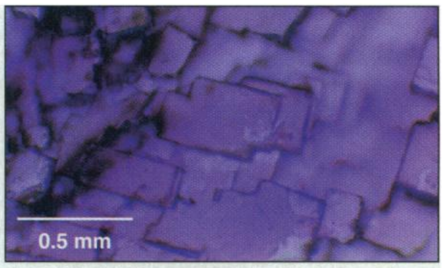
The most abundant element in the sun is hydrogen; the third most abundant element is oxygen. It therefore follows that water molecules must have been a major constituent of the solar nebula from which the planets formed. Most water condensed on the "giant" planets in the outer parts of the solar nebula, but some water remained in the inner regions of the solar nebula, where it was acquired by Earth and other rocky "terrestrial" planets, by processes that remain largely unknown.

Clues come from meteorites, which can provide evidence for the chemical behavior of water at the time when planetesimals—small rocky bodies from which planets accreted—grew in the early solar system. Two reports in this issue deal with chemical processes involving liquid water within asteroids or their planetesimal precursors. On page 1380, Brearley (*1*) presents transmission electron microscope evidence for the formation of iron-rich olivine at low temperatures and argues that these observations support an earlier proposal that this ubiquitous phase was formed by a hydration-dehydration sequence. And on page 1377, Zolensky *et al.* (*2*) present direct evidence for meteoritic water: tiny inclusions of brine within large crystals of halite (NaCl) inside a meteorite (see the figure). The existence of a water-soluble salt in this meteorite is astonishing. Also, this sample of aqueous solution trapped within the meteorite provides the first opportunity to study solar nebular water directly.

Ordinary chondrites and carbonaceous chondrites are two major classes of primitive stony meteorites. Both are characterized by abundant chondrules—millimeter-sized silicate spheroids that were once molten droplets in the solar nebula. In ordinary chondrites, the matrix between these chondrules is composed primarily of chondrule fragments. In contrast, in carbonaceous chondrites, the matrix is chemically and mineralogically distinct from chondrules and in many cases consists of hydroxyl-bearing clay minerals. Whether these hydrous minerals were formed in the nebula before accretion into a planetesimal, or within a planetesimal after accretion, remains controversial. It is generally assumed that the parent bodies of ordinary chondrites were dry and those of carbonaceous chondrites were wet.

Most ordinary chondrites are metamorphic rocks and show evidence of closed-system heating to temperatures of several hundred degrees Celsius. Under these conditions, nonvolatile element transport occurs only on a millimeter scale (*3*). Mobilization of water-soluble phases is well-





It just fell out of the sky. (Left) Fluid inclusions in halite crystals in the Monahans meteorite. The small bubble contains both a low-viscosity liquid and vapor and is mobile at room temperature. **(Right)** True color image of the halite crystals. The purple color may be caused by exposure to solar and galactic cosmic rays, exposure to decaying ^{40}K in small sylvite crystals within the halite, or both. See (*2*).

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known in carbonaceous chondrites, but not in ordinary chondrites. It is thus very surprising that Zolensky *et al.* found coarsely crystalline halite (NaCl), not ordinarily known as an igneous or metamorphic mineral, inside a metamorphosed ordinary chondrite, Monahans, which fell on 22 March 1998 in Monahans, Texas. Evidence that the halite was deposited from aqueous solution is provided by the presence of tiny (5 μm long) inclusions of brine. The meteorite was recovered rapidly after its fall and examined under clean-laboratory conditions, ensuring that the halite and its fluid inclusions are not terrestrial contaminants.

Zolensky *et al.* recognize two alternative explanations for their unique observation. Water-deposited minerals may actually be common in ordinary chondrites but are usually dissolved away before examination. Alternatively, Monahans may be an exceptional meteorite, bearing minerals deposited by solutions from an exotic source, such as a cometary impact on the surface of the parent body. In the former case, the authors are rewarded for their prompt action and careful study; in the latter case, they are lucky that a one-of-a-kind meteorite happened to fall in Texas, where their laboratories are located.

Even when actual samples of nebular water are not available, its influence on the formation of planetary materials may leave recognizable features in the rocks. Interaction between nebular gas and condensed phases may be revealed by variations in abundances of isotopes of the light elements. Isotopic exchange between nebular water vapor and the molten precursors of chondrules and refractory inclusions leaves an isotopic imprint on these meteoritic components. Quantitative interpretation of the exchange processes requires knowledge of the isotopic composition of the water vapor in the solar nebula, which can be estimated from the isotopic compositions of clay minerals and carbonates formed by aqueous reactions within parent bodies (*4*). A direct sampling of the solar wind is planned for the Genesis spacecraft mission (*5*). Isotopic analysis of the sun or comets by remote spectroscopy is not sufficiently accurate for this purpose. The brine inclusions discovered by Zolensky *et al.* provide the first opportunity for the direct isotopic analysis of a meteoritic water sample, but such an analysis is difficult because of the small size of the inclusions. Each inclusion contains on the order of a picomole of water, which is beyond the capability of existing high-precision mass spectrometers by about a factor of a thousand.

Brearley finds that the matrix olivine of the famous carbonaceous chondrite Allende contains nanometer-sized grains of a sulfide and of poorly graphitized carbon, which could not have survived a high-temperature crystallization of the olivine. This is taken to support the proposal of Krot *et al.* (*6*) that iron-rich olivine (in Allende and elsewhere) was produced in a two-stage process consisting of hydration within the parent body to form iron-bearing clay minerals, followed by thermal dehydration to produce iron-rich olivine. As noted by Brearley, a stumbling block for the hydration-dehydration hypothesis is the absence of the expected signature in the oxygen isotopic composition of the Allende matrix. On the three-isotope plot that records the high-temperature interaction between nebular gas and solid minerals, the matrix composition does not show heavy-isotope enrichment, which is readily observed in other meteoritic components with unambiguous evidence for low-temperature processes.

These two reports provide an interesting contrast. Brearley, dealing with a carbonaceous chondrite, infers the transient presence of water from the absence of high-temperature reactions with trace phases. Zolensky *et al.* have actual samples of meteoritic water, found in a meteorite where it is not expected. It is analogous to the contrast between the Cheshire Cat and Goldilocks. By following a well-marked trail of water long gone and fortuitously finding a sample of primordial water, the studies fill in some of the gaps in the story of aqueous alteration of meteorite parent bodies.

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PERSPECTIVES: GEOPHYSICS

A Seismic Look Under the Continents

Karen M. Fischer and Rob D. van der Hilst

Even a casual glance at topographical and geological maps reveals striking differences between continents and oceans. The continents stand on average 4.6 km higher than the ocean floor. And at up to 4 billion years in age, their crusts are much older than the oceanic crust, which is at maximum 200 million years old (Ma). Seismic studies have shown that these differences continue below Earth's surface. Continental crust is thicker and more chemically buoyant. Also, the lithosphere—the rigid outer layer of Earth including the crust and part of the upper mantle that sustains plate tectonics—reaches depths of no more than 100 to 125 km under the oceans, whereas lithospheric "keels" extend to depths of 250 km or more beneath most stable continental interiors. Seismic, gravity, and geochemical data have shown that these continental keels are both cool and chemically buoyant (*1*, *2*) and that they have been mechanically coupled to the overlying cratonic (*3*) crust for billions of years (*4*), keel and crust moving together in the plate tectonic cycle. However, many aspects of keel composition, formation, and subsequent modification by flow in the surrounding mantle and by continental collision and rifting have remained enigmatic (*5*). Extensive seismic array studies are now shedding new light on continental keels.

Enhanced online at www.sciencemag.org/cgi/content/full/285/5432/1365

Restricted by sparse data, studies of the continental mantle long relied on broad correlations between geological and geophysical data sets, which assumed that processes underlying keel formation and evolution were uniform from region to region. In the last decade, however, higher resolution analyses of data from dense arrays of broadband seismometers have demonstrated that continents are extremely complex assemblages and that the relations between the composition and seismic signature of the continental keels and their age and geodynamic history are more variable than previously assumed.

The speed at which seismic waves travel through different parts of the mantle is indicative of the properties of local materials. Global models of mantle wave speeds have suggested that keels beneath stable cratons reach depths of 400 km or more (*6*). But recent seismic imaging of cratonic regions in southern Africa (*7*), Tanzania (*8*), Australia (*9*), North America (*10*), and Brazil (*11*) has shown that the

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