The origin, history and role of water in the evolution of the inner Solar System

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Water, as the oxide of the most abundant element in the universe, is widespread in the galaxy. On Earth it plays a fundamentally important role in both Earth and life sciences. Water controls the rheology of the deep Earth and its ability to convect,affects igneous processes by increasing the viscosity of melts, and this role in changing the behaviour of igneous systems is required for plate tectonics to occur. Water has a controlling influence on the composition of our atmosphere, on climatic processes and is essential for all forms of life.

The last few years has seen a quiet revolution in our understanding of water in the inner solar system. Liquid water was once considered essentially the preserve only of the planet Earth, placed in the "Goldilocks zone": not too close to the Sun to allow surface water to evaporate by heating, and not so far away as to be cold and barren- as Mars was assumed to be. Early work on the samples returned from the Apollo missions reported them to be "as dry as a bone (Taylor, 1979) leading to models of moon formation involving loss of all its volatiles (reference). Recent discoveries have challenged these views. The exploration of Mars, combined with work on martian meteorites, have shown that this planet contains rocks that have been altered by aqueous processes, and its surface has been moulded by the action of solid and liquid water (references: Gupta, Bridges?). Remote sensing missions to the Moon have indicated the presence of OH^- deposits on its poles. In parallel, studies of samples returned from the Moon, combined with studies of lunar meteorites, have shown that lunar water is stored in apatite and other minerals (e.g. Anand et al. 2014).

While we have data for water on several solar system bodies (Earth, Moon, Mars and Vesta) its~~the~~ exact abundance ~~of water in these~~in planets, even the Earth, is poorly constrained. Generally, the inner solar system in general is depleted in all volatile components including water~~.~~— (Wanke and Gold 1981) but planetary and asteroidal bodies show huge bulk variations in volatile element abundance. ~~While the abundance of volatiles show huge variations among terrestrial bodies, these bodies show approximately similar interior levels of volatile abundances and similar volatile element ratios (S/H_2O, F/H_2O and Cl/H_2O; Hauri et al), perhaps pointing to similar processes by which these bodies obtained their volatile elements.~~ The cause of this depletion is not clear: it may be inherited, or due to loss during impacts, or a mixture of the two processes (e.g. Sarafian et al ; –2017).

Water in the terrestrial planets may be either exogenous or indigenous. Modelling by Elkins-Tanton et al. (2011) has shown that the terrestrial planets can retain water on accretion at levels that may not require further addition post-accretion. Furthermore, as they outline in their paper in this issue, this primordial water may facilitate the early onset of plate tectonics on Earth. A low D/H component recently identified from the deep mantle suggests that some of Earth's water was derived from the primordial protosolar nebular (Hallis et al., 2015; 2017).

If water on the terrestrial planets were instead acquired by impact after their formation, then watery comets and rocky asteroids are both potential suspects for delivering volatiles. Comets have a good potential in this role, as they are composed mainly of water, carbon monoxide, carbon dioxide along with organic material, silicates and oxides. The Rosetta mission approached the nucleus of the comet 67P/Churyumov-Gerasimenko and delivered the Philae lander to the surface in 2014 (e.g. Taylor et al. 2015). This mission showed that comets are highly heterogeneous in their composition, resulting from their diurnal cycles (Wright et al. this issue). Although having planets pelted with cometary snowballs is an appealing model to deliver volatiles, the C, N, and O isotopic evidence rule out most comets as the source of most inner solar system water. Terrestrial Kr isotopic compositions nevertheless show that later comet addition, while not contributing significantly to the C,N,H_2O,may have played an important role in sourcing the noble gas budget of the Earth's atmosphere (Holland et al., 2009).

Instead, the isotopic evidence points to the main source of water in the inner solar system being asteroids. The isotopic composition of the inner solar system (terrestrial planets and the asteroid belt) is clearly distinct from the outer solar system (comets). While a minority of comets do have a D/H ratio, for example, similar to the Earth, the majority have highly enriched D/H, ruling them out as major sources of Earth's water. Carbonaceous chondrites, especially CI chondrites, are the best match (Alexander et al. 2017). Water in chondrites is contained within clay minerals, with H_2O accounting for up to 10 weight percent of the bulk meteorite. Water is also stored in chondrites in direct liquid form (Zolensky 2017) as inclusions within salt and other minerals.

Water on the Moon may also provide insights into the origin of water on the Earth and other planets, since the Moon is a much simpler geological system, with an ancient surface providing a geological record back to its earliest stages of its history. Remote sensing measurements have detected hydroxyl molecules, that may originate in a number of ways- it could be indigenous, from impacts or from solar wind implantation (Klima and Petro, 2017). Modelling of D/H data from water contained within igneous lunar samples points to a source similar to carbonaceous chondrites (Barnes et al., 2016) and so the origin of water in the Earth and moon are likely to be the same.

How water on the Earth evolved was also discussed at our meeting. Ancient (up to ~2 billion years old) water trapped in crystalline rock fracture networks have recently been discovered (Holland et al., 2013; Sherwood Lollar et al., 2014).. Water-rock reactions in mafic systems generate hydrogen, methane and light hydrocarbons which are bio-available. The discovery of bio-friendly terrestrial subsurface fluid systems which are stable on planetary timescales demonstrate the capacity for other planets' near surface to support life irrespective of the present day planetary surface conditions. .

From discussions at the meeting, a consensus emerged that volatiles were likely incorporated into the terrestrial planets both during planetary accretion and later by asteroidal impacts. The discussion also threw up some unsolved problems. Given its immense importance on Earth, an important issue is whether surface and subsurface water is an expected consequence of the formation of any Earth-like planet. Would the hydrosphere in terrestrial exo-planets be compatible with them being habitable? Understanding the origin, evolution and role of inner solar system water is critical to our understanding of the geological and biological evolution of planets in our solar system and beyond.

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