ON BUILDING AN EARTH-LIKE PLANET. Linda T. Elkins-Tanton, Department of Terrestrial Magnetism, Carnegie Institution, 5241 Broad Branch Road NW, Washington, DC 20015, USA (ltelkins@dtm.ciw.edu).

Introduction: Theory and observation point to the occurrence of magma ponds or oceans in the early evolution of all terrestrial planets and in many early-accreting planetesimals (Fig. 1) ([1] and refs therein). The apparent ubiquity of melting indicates that silicate and metallic material may be processed through multiple magma oceans before reaching solidity in a planet. The processes of magma ocean formation and solidification, therefore, control the earliest compositional differentiation and volatile content of the terrestrial planets, and form the starting point for cooling to clement, habitable conditions

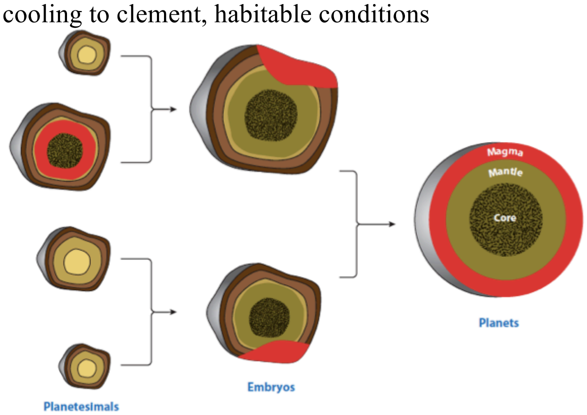

Fig. 1. Schematic of internal magma oceans in some planetesimals, magma ponds due to impact heating in planetary embryos, and magma oceans on planets due to giant accretionary impacts. After [1].

Melting in Planetesimals: If they accreted prior to about 2 Ma after the first solids in the solar system formed, significant and perhaps complete melting of planetesimals (10s to 100s of km radius) is expected due to radiogenic heat from short-lived radioisotopes [2-5]. This internal melting allows the dense metallic core to form. Because heating proceeds from the inside out, silicates may be dehydrated before melting, and a primitive undifferentiated crust may remain against the boundary condition of the cold of space [6, 7]. Lutetia may be one such partially differentiated body with a primitive crust [8]. Such a body is likely depleted in volatiles [9]; in bulk it may resemble an achondrite in volatile content. Complete solidification can take tens of millions of years, and thus planetesimals may be participating in planetary accretion while retaining molten zones internally [10] (Fig. 2).

Melting and Solidification in Planets: High extents of melting are expected in the large terrestrial planets due to the conversion of kinetic energy to heat during energetic accretionary impacts with planetary embryos (*e.g.,* [11-14]). Giant accretionary impacts likely occurred over as much as 100 Myr.

Freezing likely occurs from the bottom upward, and planets Mars-sized and larger likely solidified rapidly under a free radiative surface, without a conductive lid [15]. Even a modest insulating atmosphere will maintain the magma ocean surface above its liquidus initially, and above its solidus for much of solidification [1, 15-20]. Degassing from the magma ocean thus maintains the magma ocean's liquid surface. This critical conclusion means that a magma ocean beginning with as little as one hundred parts per million water will retain a free liquid magma ocean surface throughout the great majority of solidification.

The only likely way to form a relatively complete conductive lid on a planetary-scale magma ocean is by flotation of buoyant minerals, the most likely of which is plagioclase. Plagioclase formation is likely to occur only on small, dry planets like the Moon. On larger planets plagioclase does not become stable until the magma ocean has solidified to a high degree, close to the planetary surface, where high crystal fractions will prevent flotation. Additionally, water suppresses the crystallization of plagioclase, further delaying its appearance in the magma ocean (e.g., [21]).

Planetary-scale magma oceans are therefore highly unlikely to develop conductive lids, and will have high heat fluxes and rapid solidification, only tempered by any degassed atmosphere.

Initial atmospheres and oceans: The posited bulk water content of magma oceans on terrestrial planets is likely to be similar to or less than that of achondritic meteorites, on the assumption that planets are built from previously differentiated bodies. Most achondrites have a water content far less than 1 wt% [22]. At these low water abundances and particularly under any significant atmospheric pressure, bulk magma ocean liquids are not supersaturated in water. Fractional solidification is the most reasonable way to enrich the magma ocean liquids in water, which is incompatible in fractionating silicate minerals, to the point that the liquid is supersaturated and thus inclined to further degas [15, 19, 20].

Following solidification the young planet will be blanketed by a dense, possibly steam-dominated atmosphere that will cool toward the water critical point. Once sufficient cooling is complete the atmosphere will collapse into a water ocean. This cooling process requires millions to tens of millions of years [16, 19, 20, 23-25]. Terrestrial zircons indicate from their oxygen isotopes that water oceans on Earth predated 4.38 Ga ([26] and refs therein). The emergence of oceans on Earth forms another key part of the accretion timeline (Fig. 2).

Conclusions: A critical outcome of the likelihood of magma oceans on planetesimals, embryos, and planets is that from their earliest days, terrestrial planets are differentiated not only between core and mantle but throughout their silicate regions as well. No terrestrial planet retains a sample of its pure bulk composition. Even the earliest crusts are likely to be at their simplest partial melts of pre-differentiated mantles.

With just hundreds of ppm water in the bulk magma ocean, the Earth would retain sufficient water in its mantle to hasten convection and volcanism, and it would degas a steam atmosphere that would collapse upon cooling to a water ocean kilometers deep over the whole planetary surface (Fig. 3). An implication is that any rocky planet that accretes with traces of water is likely to produce an early water ocean. Though later accretion of hydrous chondritic and cometary material is inevitable, it may be unnecessary to explain the water budget of Earth.

References: [1] Elkins-Tanton (2012) *Ann. Rev. EPS*, 40, 363. [2] Urey (1955) *PNAS* 41, 127. [3] Fish (1960) *ApJ* 132, 243. [4] Lee (1975) *Bull. APS*, 20. [5] LaTourrette (1998) *EPSL*, 158, 91. [6] Fu. (2012) *LPSC* 44, 1173. [7] Elkins-Tanton (2011) *EPSL*, 305, 1. [8] Weiss (2011) *PSS*. [9] Young (2003) *EPSL*, 213, 249. [10] Hevey (2006) *MAPS*, 41, 95. [11] Hustoft (2006) G^3, 7. [12] Wetherill (1980) *Ann. Rev. Ast. Astroph.*, 18, 77. [13] Tonks. (1993) *JGR*, 98, 5319. [14] Halliday (2001) *SS Rev.*, 96, 1. [15] Abe (1985) *JGR*, 90, 545. [16] Matsui (1986) *Nature*, 319, 303. [17] Abe (1993) *Lithos*, 30, 223. [18] Abe (1997) *PEPI*, 100, 27. [19] Zahnle (1988) *Icarus*, 74, 62. [20] Elkins-Tanton. (2008) *EPSL*, 271, 181. [21] Goldsmith (1982) *Am. Min.* 67, 653. [22] Jarosewich (1990) *MAPS*, 25, 323. [23] Abe (1986) *JGR*, 91, E291. [24] Kasting (1988) *Icarus*, 74, 472. [25] Elkins-Tanton (2011) *Astroph. Sp. Sci.*, 302, 359. [26] Harrison (2009) *Ann. Rev. EPS Sciences*, 37, 479

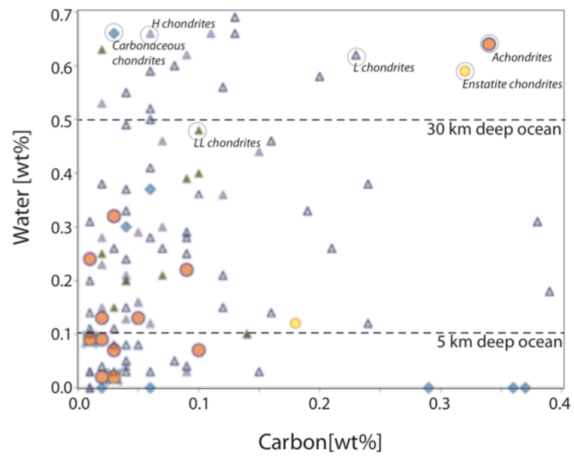

Fig. 3. Water and carbon contents of achonddites and chondrites from [22]. The depths of water oceans formed on collapse of the degassed water from a magma ocean are shown for two initial bulk water contents.

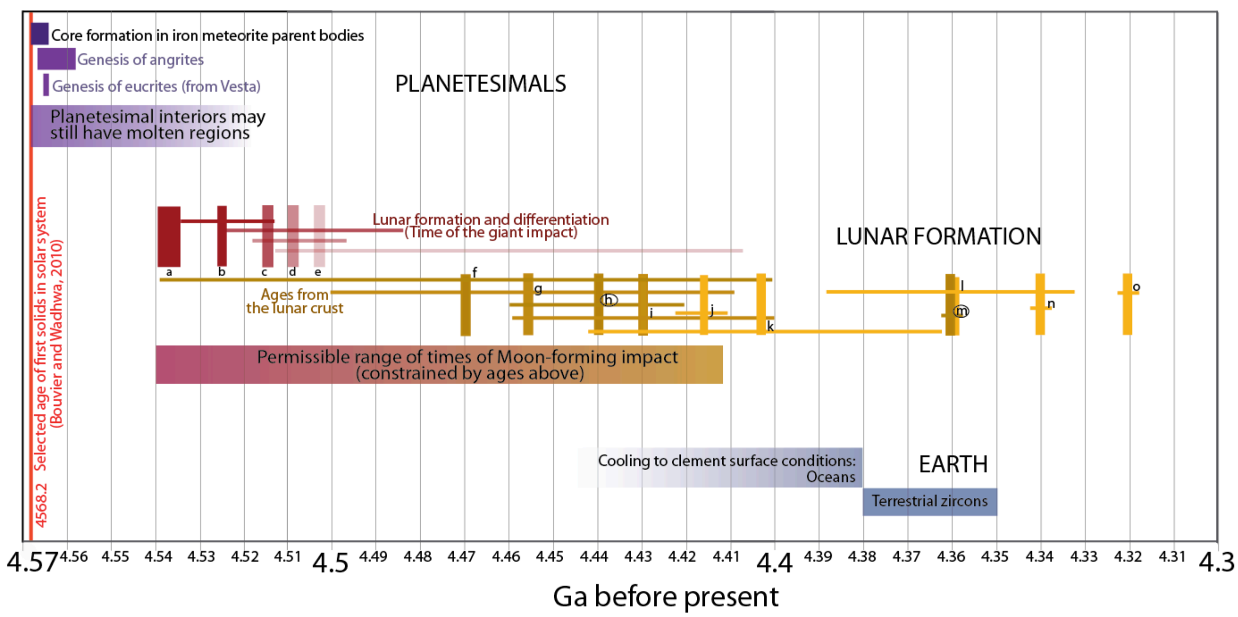

Fig. 2. Timeline of early solar system processes related to magma oceans, demonstrating that planetesimals may accrete while still partially molten, constraining the age of the Moon-forming impact and showing the long period of lunar crustal formation from the magma ocean, and showing that the Earth may have cooled to clement conditions while a shall of magma ocean remained on the Moon. After Fig. 8 [1]; references therein.