

**REDOX VARIATIONS IN EARLY SOLAR SYSTEM MATERIALS AND IMPLICATIONS FOR LATE STAGE PLANETARY ACCRETION AND PLANET FORMATION.** K. Righter<sup>1</sup>, <sup>1</sup> Mailcode XI2, NASA Johnson Space Center, Houston, TX 77058; kevin.righter-1@nasa.gov.

**Introduction:** Oxygen fugacity plays an important role in determining the detailed physical and chemical aspects of planets and their building blocks. Basic chemical properties such as the amount of oxidized Fe in a mantle (as FeO), the nature of alloying elements in the core (S, C, H, O, Si), and the solubility of various volatile elements in the silicate and metallic portions of embryos and planets can influence physical properties such as the size of the core, the liquidus and solidus of the mantle and core, and the speciation of volatile compounds contributing to atmospheres. This paper will provide an overview of the range of  $fO_2$  variation observed in primitive and differentiated materials that may have participated in accretion (cosmic dust, Stardust and meteorites), a comparison to observations of planetary  $fO_2$  (Mercury, Mars and Earth), and a discussion of timing of variation of  $fO_2$  within both early and later accreted materials. This overview is meant to promote discussion and interaction between students of these two stages of planet formation to identify areas where more work is needed.

**The record in primitive materials:** A wide range of  $fO_2$  is recorded in primitive materials ranging from the most reduced enstatite chondrites and CAIs both recording  $fO_2$  near IW-7, to the most oxidized IDPs and dust particles that record  $fO_2$  near or just above the IW buffer [1]. Between these two end members are a nearly continuous range of  $fO_2$  recorded in ordinary, R, and carbonaceous chondrites, Stardust particles, and chondrules (references in [1]; Figure 1).

**The record in planets:** All planets experienced reducing conditions that allowed a core to form, but do not necessarily retain that early reduced nature, as crustal and magmatic products on Mars and Earth are generally more oxidized than the conditions during core formation [2]. Mercury seems well defined between IW-7 and IW-4, the most reduced planet in our inner solar system [3]. Mars has a significant range of  $fO_2$  from IW to FMQ+1 [4]. Earth shows the largest variation in  $fO_2$  - nearly 10 log  $fO_2$  units - from near IW buffer to as high as the HM buffer [5,6]. The causes of variation in planetary materials is discussed further below.

**Processes that change  $fO_2$ :** Nebular processes, such as chemical gradients or variation in volatile speciation may cause early variations in  $fO_2$  in materials

[7]. Physical transport of materials from one part of the nebula to another may also cause redox variation [8]. Such early records can be modified by heating (thermal metamorphism) or fluid alteration (aqueous alteration on parent bodies) [9,10].

Pressure variation does not produce  $fO_2$  variation in most cases, but if graphite or diamond is present, the C phases and co-existing gas can cause large  $fO_2$  variation with small pressure changes compared to standard metal-oxide equilibria (e.g., ureilites and R-chondrites; [11,12]). High pressure equilibria in planetary interiors have potential to change  $fO_2$ , whether the equilibria involve solids [13,14] or liquids [15,16], but much work remains to understand multi-component rather than simple two or three component systems (e.g., Fe-S or Fe-S-C) or reduced peridotitic melts rather than evolved oxidized MgO-poor melts.

**Timing:** Variations in elemental valence of V and Ti have been observed in chondritic materials, and attributed to both oxidation and reduction processes. Transient behavior has been proposed for many of these, and such observations have been made in carbonaceous, ordinary, and enstatite chondrites indicating a widespread phenomenon [17-19]. A connection between oxygen isotopes, oxygen fugacity, and dust:gas ratios in the solar nebula has been proposed and argued based on measurements in CR chondrites, and constrained within the first several Ma of solar system [7].

Variations in  $fO_2$  have also been proposed for the later planet formation stage, but there is not consensus. Some argue for early reducing and later oxidized, as championed by early accretion models for Earth [20] and utilized more recently [21,22]. Early oxidized followed by later reduction was proposed by [23], and shown to be a possible consequence of deep metal-silicate equilibria [15,24]. However, the latter study also highlighted uncertainties in high pressure properties of silicate melts that allow for little to no change in  $fO_2$  resulting from deep metal-silicate equilibria [15,24].

**Outstanding questions:** There are plenty of outstanding questions and avenues for future research to help understand the chemical and physical environments and the causes of  $fO_2$  variation.

First, how oxidized was the early nebula – some matrix material has high Fe<sup>3+</sup> [25], but it is unclear what environment or how high  $fO_2$  was to generate this

material. Second, the role of pressure in Fe redox equilibria – both Fe-FeO in embryos and planets, and later FeO-Fe<sub>2</sub>O<sub>3</sub> equilibria in planets – is poorly constrained, as is the controlling role of volatiles and volatile speciation at pressure. To what extent do dust and sub-meter sized materials become completely transformed by higher temperature and pressure processes, thus erasing any nebular or primitive redox signature? Third, during oligarchic growth, the role of relative mass and volatiles in controlling redox equilibria needs to be better defined. For example, if there is an impact between two bodies with a target:impactor mass ratio of 7:3, involving a reduced target and oxidized impactor, what is the  $fO_2$  of the resulting body? Does the more massive body “win”, or is the resulting body simply a mix of the two? This is currently unknown. And fourth, what is the role of heliocentric distance? Was the inner solar system uniform from Mars inwards, or was there nonetheless variation? [26].

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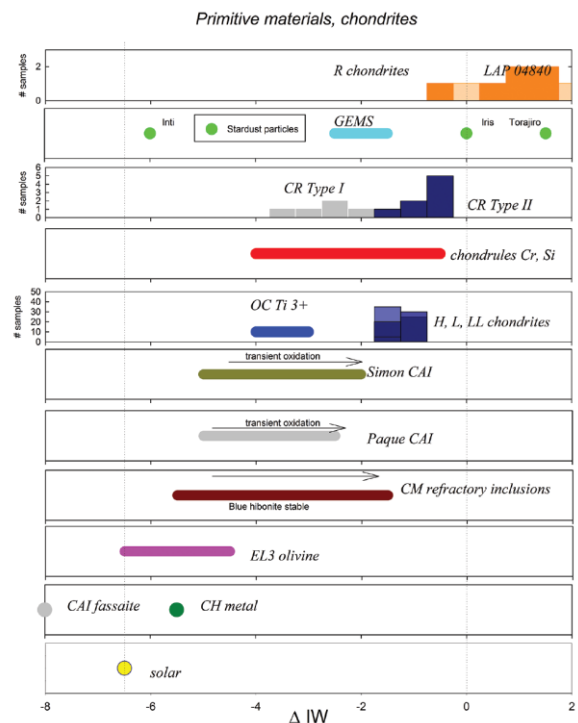


Figure 1: Range of oxygen fugacity ( $fO_2$  relative to the IW buffer) recorded in various primitive materials and chondrites. Total range of all materials is nearly 10 orders of magnitude, which makes  $fO_2$  an important intensive parameter for understanding the early solar system. Figure from [1].