

REDUCTION, OXIDATION AND SULFIDATION IN THE SOLAR NEBULA DURING FORMATION OF ORDINARY, ENSTATITE AND RUMURUTI-LIKE CHONDRITES

T.J. Fagan¹ and Y. Tanimura¹ ¹Dept. Earth Sciences, Waseda University, Tokyo (fagan@waseda.jp)

Introduction: One of the fundamental observations of chondrites that can be used to infer conditions of the protoplanetary disk is the variation in oxidation state that occurs across all chondrite groups [e.g., 1-3]. Variations in oxidation state are revealed primarily by the speciation of iron between silicates and metals (see p. 217 of [4]). Fe#s (molar FeO/[MgO+FeO]) of mafic silicates rise and abundances of Fe-rich metal decrease in a sequence from enstatite (EH & EL) chondrites, to LL, L and H groups of the ordinary chondrites, and then to the Rumuruti-like (R) chondrites [1,3]. This variation in Fe-speciation reflects variable oxidation-reduction conditions in the part of the solar nebula where enstatite, ordinary and R chondrites formed.

Yet, iron also occurs as sulfide--often as troilite--in chondrites, raising the possibility that sulfidation might have operated as process independent of oxidation-reduction in the part of the solar nebula where enstatite, ordinary and R chondrites formed. In this project, we borrow a technique from terrestrial metamorphic petrology called reaction space (essentially, multi-dimensional reaction progress; see [5-7]) to investigate speciation of Fe among silicates, sulfides and metals, and thereby assess variations in sulfidation as well as oxidation/reduction in the ordinary, enstatite and R chondrites.

Methods: Three independent data sets were used to evaluate speciation of Fe in ordinary, enstatite and R chondrites. Data (1) is based on modes and mineral compositions in the following set of chondrites: Bencour (LL6, fall); Mt. Tazerzite (L5, fall); Tamdakht (H5, fall); St. Marks (EH5, fall); Lewis Cliff 88180 (EH5, find); Northwest Africa 974 (E6, find); Northwest Africa 753 (R3, find). Meteorite falls were emphasized in order to limit effects of terrestrial weathering, and high petrologic types were preferred because their coarser grain sizes are easier for determination of modes and their homogeneous mineral compositions are better suited for modal recombination. Modes were determined manually from grids overlain on elemental maps of thin sections. The elemental maps and quantitative analyses of minerals were conducted using a JEOL JXA electron microprobe analyzer (EPMA) at Waseda University (WU).

Data sets (2) and (3) are based on wet chemical analyses that determined concentrations of FeO, Fe₂O₃, FeS and metallic Fe of chondrite whole rocks. Data (2) were collected and compiled by E. Jarosewich at the Smithsonian Institution (SI) [8,9]. Data (3) were collected and compiled by K. Yanai, H. Kojima and H. Haramura at NIPR-Japan [10]. For Data (2), we used falls for ordinary chondrites in the SI data set, but because of the small number of enstatite chondrites (ECs) we used both falls and finds for the ECs. Data (3) are from Antarctic finds.

Results: Reaction space reduction of a matrix of the main phases and components in a reacting system involving ordinary (O), enstatite (E) and R chondrites yields four independent reactions: (R1) $\text{NaAlSi}_3\text{O}_8 = \text{NaAlSi}_2\text{O}_6 + \text{SiO}_2$; (R2) $\text{Mg}_2\text{SiO}_4 + \text{SiO}_2 = 2 \text{MgSiO}_3$; (R3) $\text{Mg}_2\text{SiO}_4 + 2 \text{FeMg}_{-1} = 2 \text{Fe} + \text{SiO}_2 + \text{O}_2$; and (R4) $\text{Mg}_2\text{SiO}_4 + 2 \text{FeMg}_{-1} + \text{S}_2 = 2 \text{FeS} + \text{SiO}_2 + \text{O}_2$. R1 does not appear to be important in most chondrites. R2 is very important as it describes variations in olivine vs. pyroxene, but it occurs entirely within the silicate subsystem. Reduction of FeO to Fe-metal occurs on R3, and sulfidation of FeO to FeS occurs on R4. So the variations in oxidation, reduction and sulfidation among O, E, R chondrites can be treated as a two-dimensional reaction space, where 0 progress on R3 and R4 represents a completely oxidized condition at the origin; 100% progress on R3 represents a completely reduced condition; 100% progress on R4 represents a completely sulfidized condition. Progress on R3 and R4 can be determined from speciation of Fe.

The three data sets show internally consistent distributions of Fe among silicates, sulfides and metals among ordinary and enstatite chondrites. For most ordinary chondrites, 10 to 25% of Fe occurs in sulfides, and the progression from LL to L to H chondrites shows a wide range in the extent of reduction of FeO to Fe-metal on R3. E and R chondrites plot at the reduced and oxidized ends, respectively, of the range of O chondrites. This approach shows little independent variation in sulfidation among the E, O, R chondrites, but a major variation in oxidation state, possibly controlled by H₂O vapor acting as an oxidant [e.g., 11].

References: [1] Van Schmus W.R. and Wood J.A. (1967) *GCA* 31:747-765. [2] McSween H.Y. (1977) *GCA* 41:1777-1790. [3] Weisberg M.K. et al (2006) in *MESS II*, p. 19-52. [4] McSween H.Y. and Huss G.R. (2010) *Cosmochemistry*, Cambridge Univ. Press, 549 p. [5] Thompson J.B. et al (1982) *Jour. Petrol.*, 23, 1-27. [6] Thompson J.B. (1991) *Canadian Mineralogist* 29, 615-632. [7] Fagan T.J. and Day H.W. (1997) *Geology*, 25, 395-398. [8] Jarosewich E. (1990) *MaPS* 31, 323-337. [9] Jarosewich E. (2006) *MaPS* 41, 1381-1382. [10] Yanai K. et al (1995) *Catalog of the Antarctic Meteorites*, NIPR, 230 p. [11] Cuzzi J.N. and Zahnle K.J. (2004) *ApJ* 614: 490-496.