

## Oxidation, reduction and sulfidation in ordinary and enstatite chondrites

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Enstatite chondrites are characterized by silicates with very low Fe/(Fe+Mg) and Si-bearing Fe,Ni-metal, both indicating formation under low oxygen fugacities. The occurrence of typically lithophile elements such as Mg, Ca, Mn, Cr and Ti in sulfide minerals shows that ECs formed under relatively sulfidizing conditions. However, the roles of sulfidation and reduction during the formation of ECs have seldom been compared. In this study we compare the extents of oxidation, reduction and sulfidation in a small set of equilibrated ordinary and enstatite chondrites (OCs and ECs). Initial goals of this work are to determine whether different OC and EC groups experienced different extents of sulfidation; and whether sulfidation occurred as a separate process, distinct from oxidation-reduction, in separating the ECs from the OCs.

In our approach, we first examine OCs and ECs as reacting systems, and try to understand mass balances that allow transfers of atoms between oxidized, reduced and sulfidized states. Then, we collect modes and determine mineral compositions for some type 5 and 6 chondrites, use those data to determine Fe-speciation and compare the extents of oxidation, reduction and sulfidation. Our samples are: Mt. Tazerzait (L5); Bensour (LL6); St. Marks (EH5); LEW 88180 (EH5); and NWA 974 (E6). X-ray elemental maps of polished thin sections of these samples were collected by wavelength dispersive spectroscopy (WDS) using a JEOL JXA-9800 electron probe micro-analyzer (EPMA). Step sizes for elemental mapping were from 7 to 12  $\mu\text{m}$  and 0.5 to 2.5  $\text{cm}^2$  per sample were mapped. Mineral modes were determined by overlaying grids on elemental maps and using the maps to identify minerals at each grid node. Compositions of low-Ca pyroxene, troilite, kamacite and (for the ordinary chondrites) olivine were also determined by EPMA (WDS). Multiple reactions must be considered to gain a complete understanding of the formation of diverse silicates, sulfides and metallic minerals in OCs and ECs. However, transfers of elements between these mineral groups can be described by only two independent reactions, such as: (R1)  $\text{FeMg}(-1) + \text{MgSiO}_3 + 0.5\text{S}_2 = \text{SiO}_2 + \text{FeS} + 0.5\text{O}_2$ ; and (R2)  $\text{FeMg}(-1) + \text{MgSiO}_3 = \text{Fe-metal} + \text{SiO}_2 + 0.5\text{O}_2$ . Reaction progress on (R1) describes sulfidation of silicate, and progress on (R2) describes reduction of silicate. Direct transfers of elements between sulfides and metallic minerals can be described by: (R3)  $\text{Fe-metal} + 0.5\text{S}_2 = \text{FeS}$ , which is equivalent to (R1) - (R2). Because (R3) can be described as a linear combination of (R1) and (R2), only two reactions are required to describe transfers of elements in this system. Variations in olivine:pyroxene can be described by an independent reaction:  $\text{Mg}_2\text{SiO}_4 + \text{SiO}_2 = 2\text{MgSiO}_3$ . Other elements that are transferred between mineral groups can be described by elemental substitutions for Fe in reactions (R1) and (R2). However, because Fe is the dominant element that occurs in all three mineral groups, an initial comparison of oxidation/reduction/sulfidation between samples can be accomplished by determining the speciation of Fe.

In the ECs, 2 to 4 mole % of the Fe occurs in silicate, 60 to 70% occurs in troilite, and most of the remainder occurs in Fe,Ni-metal. In contrast, in the OCs over 80% of the Fe occurs in silicates; more of the Fe in Mt. Tazerzait (L5) occurs in troilite (16% vs. 11%) and kamacite (3% vs. 0.7%) than in Bensour (LL6).

The high fraction of Fe in sulfide in the ECs indicates that the ECs are not simply the products of reduction of OC-like precursors. ECs are sulfidized as well as reduced. However, sulfidation might

not have occurred as an independent process. Instead, it is likely that removal of oxygen from the EC-forming region resulted in an increase in S/O ratio as well as a decrease in oxygen fugacity, simultaneously causing reduction and sulfidation.

Keywords: chondrites, oxidation, reduction, sulfidation, iron