THE AQUEOUS ALTERATION OF CR CHONDRITES: EXPERIMENTS AND GEOCHEMICAL MODELING.

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Introduction: CR carbonaceous chondrites are of major interest since they contain some of the most primitive organic matter known (e.g. [1], [2]). However, aqueous alteration has more or less overprinted their original features in a way that needs to be assessed. This study was initiated by comparing the mineralogy and modal abundances of the most altered CR1 chondrite, GRO 95577, to a less altered CR2, Renazzo [3, 4]. Calculated element distributions imply that GRO 95577 may result from aqueous alteration of Renazzo by an isochronal process on their parent asteroid, whose mineralogical composition was estimated (‘unaltered CR’ in Table 1).

Table 1. Modal abundances in Renazzo, GRO 95577, CRs and unaltered CR parent-body.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Renazzo</th>
<th>GRO 95577</th>
<th>CRs</th>
<th>Unaltered CR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kamacite</td>
<td>0.7</td>
<td>0.2</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Low-Ni kamacite</td>
<td>3.3</td>
<td>2.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Magnetite</td>
<td>0</td>
<td>1.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Pyrrhotite</td>
<td>0.7</td>
<td>0.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total opaque phases</td>
<td>9.9</td>
<td>5.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Matrix</td>
<td>4.9</td>
<td>9.7</td>
<td>4</td>
<td>8.4-10.2</td>
</tr>
<tr>
<td>Chondrules</td>
<td>47.9</td>
<td>45.6</td>
<td>50</td>
<td>29.7-63.3</td>
</tr>
<tr>
<td>Chondrules</td>
<td>47.9</td>
<td>45.6</td>
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<td>50</td>
<td>29.7-63.3</td>
</tr>
</tbody>
</table>

In the present study, laboratory alteration experiments were performed on mineralogical assemblages whose composition was as close as possible to that of the unaltered CR parent-body. The mineralogy of reaction products was compared to that of Renazzo and GRO 95577 in order to estimate the conditions under which alteration occurred. Experimental results were also compared to predictions of geochemical modeling.

Methods:

Images and chemical analyses. The composition of silicate minerals and opaque phases were determined before and after experiments using a JEOL JSM-5910LV Secondary Electron Microscope (SEM) and Cameca SX-100 electron microprobe in WDS mode. Appropriate silicate and metal standards were used and analyses were performed at 15 keV accelerating voltage, 20 nA beam current and 1 µm spot diameter.

Experiments of aqueous alteration. From oxygen isotopic data and the presence of serpentine/smectite in CRs, the temperature of aqueous alteration on the CR parent-body has been estimated to be between 0 and 300°C [5-8]. The abundance of FeNi metal and sulfides indicates a low fugacity in O2 and a high fugacity in S2. Preliminary experiments were performed at 250°C for a duration of 1 month using pure distilled water in anoxic Paar bombs (log fO2=-6). The system was closed such that the chemical conditions were buffered by the mineralogical assemblage. In order to identify the elementary reactions, six sub-assemblages were used (Table 2). The objectives were to understand the reactivity of silicates within chondrules (SA1); the influence of FeNi metal within chondrules (by comparing SA1 and SA2); the influence of FeNi metal-sulfides on the reaction within chondrules (by comparing SA2, SA3 and SA4); the reactivity of silicates and metals in the matrix (SA5); the influence of organic matter in the matrix (by comparing SA5 and SA6). Moreover the influence of water/rock ratio (W/R=1 or 40) was tested for whole “synthetic unaltered CR chondrites” (A7-3 and A7-4).

Table 2. Mineralogical assemblages.

<table>
<thead>
<tr>
<th>Assemblage</th>
<th>Minerals</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>Forsterite + Pyrrhotite + FeNi metal</td>
</tr>
<tr>
<td>S2</td>
<td>Forsterite + Pyrrhotite + FeNi metal</td>
</tr>
<tr>
<td>S3</td>
<td>Forsterite + Pyrrhotite + FeNi metal</td>
</tr>
<tr>
<td>S4</td>
<td>Forsterite + Pyrrhotite + FeNi metal</td>
</tr>
<tr>
<td>S5</td>
<td>Fayalite + FeNi metal + Pyrrhotite</td>
</tr>
<tr>
<td>S6</td>
<td>Fayalite + FeNi metal + Pyrrhotite</td>
</tr>
<tr>
<td>S7</td>
<td>Fayalite + FeNi metal + Pyrrhotite</td>
</tr>
<tr>
<td>S8</td>
<td>Fayalite + FeNi metal + Pyrrhotite</td>
</tr>
<tr>
<td>S9</td>
<td>Fayalite + FeNi metal + Pyrrhotite</td>
</tr>
<tr>
<td>S10</td>
<td>Fayalite + FeNi metal + Pyrrhotite</td>
</tr>
<tr>
<td>S11</td>
<td>Fayalite + FeNi metal + Pyrrhotite</td>
</tr>
<tr>
<td>S12</td>
<td>Fayalite + FeNi metal + Pyrrhotite</td>
</tr>
</tbody>
</table>

We used pure minerals (forsterite Fo, fayalite Fa, clinoxyroxene CPx, anorthite An, FeNi metal from Chinga, pyrrhotite Po), whose compositions were checked by EMPA. Maillard products were used as an analogue of CR Organic Matter (O.M.) because they share similar functional groups [10].

Geochemical modeling. The Geochemist Workbench software was used to model the reactivity of unaltered CR parent-body and sub-assemblages (Table 2) after 1 month at 250°C for the same conditions as the laboratory experiments. Thermodynamic data from thermo.dat database were computed. Using the EQ 3/6 software, the data on kamacite 83 and pentlandite were calculated. O.M. was tentatively described by benzeneaq, phenolaq, tolueneaq and CH3COOHaq. The kinetic laws for non-oxidative dissolution of minerals were defined.

Results:

Experiments of aqueous alteration. The silicates within the chondrule assemblage (SA1) are altered to
clinochlore, An being completely eliminated (Figure 1). The alteration of FeNi metal or Po liberates Fe which is incorporated into clinochlore (SA2 and SA3). Po favors the alteration of Fo but this is no longer true when FeNi metal and Po are both present (SA4). On the contrary, for the matrix assemblage, formation of clays is very limited (SA5). This may be due to the absence of An in the matrix assemblage, such that no Al is available. When O.M. is present in the matrix, no clay formation is observed (SA6). On the contrary, when the constituents of matrix and chondrule are in contact, clays are formed and their formation is favored by an increase in the W/R ratio (A7-3 and A7-4).

Figure 1. SEM observation of the SA1 polished section.

The reaction products in chondrule (SA1 to SA4) are TOT O’ clays whose composition is characterized by Si>Al>Mg>Fe. These products are quite similar to the alteration products found in GRO 95577 chondrules, which are vermiculite in the core (Si>Mg>Fe>Al) and clinochlore in the mesostasis (Si>Mg>Fe,Mg>Al). It was not possible to get good chemical analyses of the experimental phyllosilicates formed in the matrix assemblages, and therefore not possible to compare them to the phyllosilicates in the matrix of GRO 95577.

The slight difference in composition between the experimental alteration products of the chondrule assemblage and those in chondrules of GRO 95577 may result from the short duration of the experiments. During the initial stages of the experiment, alteration of An dominates that of Fo or CPX, explaining why experimental clays are richer in Al than natural samples, which experienced longer term alteration. The low level of clay formation in the presence of O.M. indicates that organics may inhibit silicate alteration. However, despite the slower alteration of silicates in the presence of O.M., for the longer durations and smaller grain sizes typical of the alteration of natural matrix, transformations of the silicate phases may take place.

**Geochemical modeling.** Only the results for the chondrule assemblage are presented since it is the system for which there is the best match between the natural sample and the reaction products. GWB predicts the consumption of An and Fo, the alteration of CPX and the neoformation of clinochlore in chondrule.

This is in good agreement with the SA1 reaction products and chondrule mineralogy of GRO 95577. Nevertheless the modeling predicts complete elimination of Fo, whereas this mineral remains in the experiments. The poor agreement in terms of reaction kinetics (despite good agreement in terms of mineralogy) may be due to the formation of a protective nanometric layer at the surface of Fo. Moreover GWB uses the Transition State Theory law, which does not take into account the influence of surface properties of minerals (defects, energetic heterogeneities) on kinetic laws [11].

**Conclusions:**

This work shows that the aqueous alteration of CR parent asteroid may have occurred at 250°C in an anoxic medium without any S₂ flow and in the presence of pure water. It also illustrates the great influence of Al, produced by breakdown of the feldspathic mesostasis, of Po and of O.M. on the crystallization of clinochlore. Al seems to be necessary while Po favors the formation of these clays on Fo unlike O.M. This latter point may be due to the kind of O.M. used. Maillard products seem to have been decomposed into oil which wet the surfaces of silicates and thus inhibited their alteration. New alteration tests with other organics will start in March 2007. Moreover, the geochemical modeling gives good prediction of the evolution of the system from a thermodynamic point of view whereas the kinetic aspect needs to be refined. As future work, other experiments will be conducted at different temperatures, longer term and under CO₂ and H₂S fluxes. Modeling work will be refined to constrain long-term predictions.

**References:**

The aqueous alteration of CR chondrites: experiments and geochemical modeling.

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Objectives

The aqueous alteration of CRs

- mineralogical transformations?
- original composition of CRs?
- influential mineral phases?
- physico-chemical conditions?
1. Characterization of CR chondrites

- SEM images
- EMPA chemical analyses
- Modal analysis using X-Ray elemental mapping and IDL image treatment software

on Renazzo (CR2) and GRO 95577 (CR1)

- Images, composition, abundance of each phase
- Estimation of the composition of the unaltered CR body
1. New data on the mineralogy of Renazzo and GRO 95577.

2. Phenomenological information on the aqueous alteration process
   - unusual petrologic type 1: limits of chondrule are still visible in GRO 95577
     → chemical alteration without major mechanical process
   - olivine + pyroxene \(\rightarrow\) vermiculite
     \[
     \begin{array}{c}
     \text{Fd mesostasis} \\
     \text{Aqueous alteration} \\
     \text{Fe olivine-rich matrix} \\
     \end{array}
     \]
     \[
     \begin{array}{c}
     \text{vermiculite} \\
     \text{chamosite} \\
     \end{array}
     \]

3. Modal analysis
1. Characterization of CR chondrites

vol% = area% for prismatic crystals

<table>
<thead>
<tr>
<th></th>
<th>R</th>
<th>G</th>
<th>CR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chondrules</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Olivine</td>
<td>19.2</td>
<td>0</td>
<td>19.5</td>
</tr>
<tr>
<td>Pyroxene</td>
<td>23</td>
<td>0</td>
<td>23</td>
</tr>
<tr>
<td>Vermiculite</td>
<td>0</td>
<td>25.2</td>
<td>3.5</td>
</tr>
<tr>
<td>Feldspatic meso.</td>
<td>2.8</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Chamosite meso.</td>
<td>1.4</td>
<td>13.2</td>
<td></td>
</tr>
<tr>
<td><strong>Opaque phases</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kamacite</td>
<td>0.7</td>
<td>0.2</td>
<td>4</td>
</tr>
<tr>
<td>Low-Ni kamacite</td>
<td>3.3</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>Pyrrhotite</td>
<td>0</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>S inter. phases</td>
<td>0.9</td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td>Magnetite</td>
<td>0</td>
<td>1.1</td>
<td>4.9</td>
</tr>
<tr>
<td><strong>Matrix</strong></td>
<td></td>
<td></td>
<td>50</td>
</tr>
<tr>
<td>Matrix</td>
<td>47.9</td>
<td>45.6</td>
<td></td>
</tr>
</tbody>
</table>

Computation of chemical composition

- isochemical alteration
- composition of the unaltered CR
2. Experimental study

Experiments of aqueous alteration

- on a synthetic *unaltered* CR composition
- on 6 sub-assemblages (chondrule, matrix…)

Comparison with GRO 95577

- Test the relevancy of *one set of* physico-chemical conditions
- Show the *influential* mineral phases
- Understand the *alteration mechanisms*
2. Experimental study

Experimental conditions

- **Temperature**: 250°C (see Clayton et al. 1977, Weisberg et al. 1993)
- **Duration**: 1 month
- **Solution**: pure distilled water (fusion of accreted ices)
- **Gaz fugacity**: the mineralogical assemblages set the physico-chemical conditions
  = CLOSED SYSTEM
- **R/solution**: 1 or 1/40
- **System**: - preparation in an anoxic glove box
  - hydrothermal Parr bomb
  - initial injection of N2 → anoxic
2. Experimental study

**Experimental conditions**

- Different systems

<table>
<thead>
<tr>
<th>System</th>
<th>Reagents</th>
</tr>
</thead>
<tbody>
<tr>
<td>SA-1</td>
<td>Silicates chondrule</td>
</tr>
<tr>
<td></td>
<td>Fo + CPX + An</td>
</tr>
<tr>
<td>SA-2</td>
<td>Silicates chondrule + FeNi</td>
</tr>
<tr>
<td></td>
<td>Fo + CPX + An + FeNi</td>
</tr>
<tr>
<td>SA-3</td>
<td>Silicates chondrule + sulfides</td>
</tr>
<tr>
<td></td>
<td>Fo + CPX + An + Po</td>
</tr>
<tr>
<td>SA-4</td>
<td>Silicates chondrule + FeNi + sulfides</td>
</tr>
<tr>
<td></td>
<td>Fo + CPX + An + FeNi + Po</td>
</tr>
<tr>
<td>SA-5</td>
<td>Matrix</td>
</tr>
<tr>
<td></td>
<td>Fo + Fa + FeNi + Po</td>
</tr>
<tr>
<td>SA-6</td>
<td>Matrix with organic matter</td>
</tr>
<tr>
<td></td>
<td>Fo + Fa + FeNi + Po + O.M.</td>
</tr>
<tr>
<td></td>
<td>= Maillard product, Kolb et al. 2005</td>
</tr>
<tr>
<td>A7-3</td>
<td>« Unaltered CR », R/sol°=1</td>
</tr>
<tr>
<td></td>
<td>Fo + CPX + An + FeNi + Po</td>
</tr>
<tr>
<td>A7-4</td>
<td>« Unaltered CR », R/sol°=1/40</td>
</tr>
<tr>
<td></td>
<td>Fa + O.M.</td>
</tr>
</tbody>
</table>
2. Experimental study

(1) Alteration within chondrule

- SA1 : Fo + CPX + An
2. Experimental study

(1) Alteration within chondrule

- Formation of a crust of phyllosilicates

Fo + CPX + An

SA-1-I

<table>
<thead>
<tr>
<th>Percentage (%)</th>
<th>Fo</th>
<th>CPX</th>
<th>An</th>
</tr>
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<tbody>
<tr>
<td>Thick</td>
<td>80</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>Medium</td>
<td>30</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>Thin</td>
<td>10</td>
<td>10</td>
<td>80</td>
</tr>
<tr>
<td>None</td>
<td>5</td>
<td>45</td>
<td>50</td>
</tr>
</tbody>
</table>

Forsterite | Pyroxene
2. Experimental study

(1) Alteration within chondrule

- Formation of a crust of phyllosilicates

\[ Fo + CPX + An + \text{FeNi} \approx Fo + CPX + An \]

![Graph showing phyllosilicates crust quality](chart.png)
2. Experimental study

(1) Alteration within chondrule

- Formation of a crust of phyllosilicates

\[ \text{Fo + CPX + An} \]

[Graph showing phyllosilicates crust quality with bars for thick, medium, thin, and none.]
(1) Alteration within chondrule
- Formation of a crust of phyllosilicates

\[ \text{Fo} + \text{CPX} + \text{An} + \text{FeNi} + \text{Po} \approx \text{Fo} + \text{CPX} + \text{An} \]

**Experimental study**

![Bar chart showing phyllosilicates crust quality](chart.png)
2. Experimental study

chondrule

Fo $\rightarrow$ Si, Mg

CPX $\rightarrow$ Si, Mg, Ca $\rightarrow$ clinochlore

An $\rightarrow$ Si, Al, Ca
2. Experimental study

FeNi

Fe

clinohlore

Si, Mg
Si, Mg, Ca
Si, Al, Ca

Fo  CPX  An

chondrule
2. Experimental study

chondrule e.g. Takatori et al. 1993

FeNi

Fe

Fe

CPX Si, Mg, Ca clinochlore

Fo Si, Mg

Po

An Si, Al, Ca

Po

e.g. Ohnishi and Tomeoka 2007
2. Experimental study

chondrule

Fo  Si, Mg
FeNi  Po
CPX  Si, Mg, Ca
An  Si, Al, Ca

FeNi → clinochlore

Fe → Fe
Po
2. Experimental study

(2) Alteration within matrix
• SA-5 : Fo + Fa + FeNi + Po

Few crusts!

![Image of Fo, Fa, and other minerals]
2. Experimental study

(2) Alteration within matrix

- Formation of a crust of phyllosilicates

\[ \text{Fo} + \text{CPX} + \text{An} + \text{FeNi} + \text{Po} \]

- Formation of a crust of phyllosilicates

\[ \text{Fo} + \text{Fa} + \text{FeNi} + \text{Po} \]
2. Experimental study

(2) Alteration within matrix

- Formation of a crust of phyllosilicates

\[ \text{Fo} + \text{Fa} + \text{FeNi} + \text{Po} + \text{M.O.} \]

---

**Diagram:**

- **SA-6-I**

**Bar Chart:**

- Forsterite
- Fayalite

- Phyllosilicates crust quality:
  - Thick
  - Medium
  - Thin
  - None

---

**Graph:**

- Percentage (%)

---

**Legend:**

- Forsterite
- Fayalite

---
2. Experimental study

matrix

Fo ➔ Si, Mg
Fa ➔ Si, Fe
FeNi ➔ Limited clay formation
Po ➔
2. Experimental study

matrix

Fo  →  Si, Mg
Fa  →  Si, Fe
FeNi
Po

Al is missing

Limited clay formation
## 2. Experimental study

- **Fo** → **Si, Mg**
- **Fa** → **Si, Fe**
- **FeNi**
- **Po**

- Al is missing
- Limited clay formation
- Acid pH without Al → dissolution only
(3) Alteration within the synthetic chondrite

- A7-3: Fo + CPX + An + Fa + FeNi + Po + O.M., R/sol° = 1

Few crusts!
2. Experimental study

(3) Alteration within the synthetic chondrite
- Few crusts

R/sol°=1
Fo + CPX + An + Fa + FeNi + Po + O.M.

Phyllosilicates crust quality

<table>
<thead>
<tr>
<th>Phyllosilicates crust quality</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thick</td>
<td>20</td>
</tr>
<tr>
<td>Medium</td>
<td>10</td>
</tr>
<tr>
<td>Thin</td>
<td>5</td>
</tr>
<tr>
<td>None</td>
<td>90</td>
</tr>
</tbody>
</table>

SA-6-I
Faydita
Faydita

A7-3-I

(3) **Alteration within the synthetic chondrite**

- A7-4 : Fo + CPX + An + Fa + FeNi + Po + O.M., $R/sol^o = 1/40$

2. **Experimental study**
2. Experimental study

(3) Alteration within the synthetic chondrite

Formation of a crust of pseudo phyllosilicates

$$\text{R/sol}^\circ = 1/40$$

$$\text{Fo} + \text{CPX} + \text{An} + \text{Fa} + \text{FeNi} + \text{Po} + \text{O.M.}$$
2. Experimental study

Low R/Sol° ratio favors the clay formation

Synthetic chondrite
2. Experimental study

chondrule

Clinochlore
TOT O’ Si-Al-Mg-Fe
Limited clay formation
Al is missing

Vermiculite
TOT Si-Mg-Fe-Al

Chamosite
TOT O’ Si-Mg-Fe-Al

matrix

Experiments
GRO 95577
2. Experimental study

Why is there any differences between experiments and GRO 95577?

- **Limited duration** of tests → limited alteration of Mg-bearing minerals (Fo, CPX) et Fe-bearing ones (Fa) compared to Al-bearing ones (An)
- **O.M.**
- **Porosity of the matrix** not well reproduced

How to deal with this …

- **Long-duration tests** on synthetic chondrites
- **Analysis of the O.M.** - before and after experiments
  - vs. O.M. in Renazzo and GRO 95577
- **Analysis of the matrix of Renazzo and other CRs**
3. Geochemical modeling

Geochemical modeling using Geochemist Workbench (GWB)

- on an unaltered CR composition
- on the 6 sub-assemblages (chondrule, matrix...)

Comparison with reaction products (Step 2)

- Does the model predict what happened in the experiments?

Long-term predictions?

Application to other carbonaceous chondrite groups?
### 3. Geochemical modeling

#### Systems

<table>
<thead>
<tr>
<th>System</th>
<th>Phases</th>
</tr>
</thead>
<tbody>
<tr>
<td>SA-1</td>
<td>Silicates chondrule</td>
</tr>
<tr>
<td></td>
<td>Fo + CPX + An</td>
</tr>
<tr>
<td>SA-2</td>
<td>Silicates chondrule + FeNi</td>
</tr>
<tr>
<td></td>
<td>Fo + CPX + An + FeNi</td>
</tr>
<tr>
<td>SA-3</td>
<td>Silicates chondrule + sulfides</td>
</tr>
<tr>
<td></td>
<td>Fo + CPX + An + Po</td>
</tr>
<tr>
<td>SA-4</td>
<td>Silicates chondrule + FeNi + sulfides</td>
</tr>
<tr>
<td></td>
<td>Fo + CPX + An + FeNi + Po</td>
</tr>
<tr>
<td>SA-5</td>
<td>Matrix</td>
</tr>
<tr>
<td></td>
<td>Fo + Fa + FeNi + Po</td>
</tr>
<tr>
<td>SA-6</td>
<td>Matrix with organic matter</td>
</tr>
<tr>
<td></td>
<td>Fo + Fa + FeNi + Po + O.M.</td>
</tr>
<tr>
<td>A7-3</td>
<td>« Unaltered CR », S/sol°=1</td>
</tr>
<tr>
<td></td>
<td>Fo + CPX + An + FeNi + Po</td>
</tr>
<tr>
<td>A7-4</td>
<td>« Unaltered CR », S/sol°=1/40</td>
</tr>
<tr>
<td></td>
<td>Fo + CPX + An + FeNi + Po + Fa + O.M.</td>
</tr>
</tbody>
</table>

Systems of the experiments (Step 2)
3. Geochemical modeling

**Physico-chemical conditions**

<table>
<thead>
<tr>
<th>Condition</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Temperature</strong></td>
<td>250°C</td>
</tr>
<tr>
<td><strong>Solution</strong></td>
<td>pure deionized water (1 \times 10^{-9}) mol Ca(^{2+}), Fe(^{2+}), Mg(^{2+}), SiO(_2) aq, Al(^{3+}), Ni(^{2+}), SO(_4^{2-})</td>
</tr>
<tr>
<td><strong>Fugacity in gas</strong></td>
<td>the mineralogical assemblages set the physico-chemical conditions = closed system (\log fO_{2g} = -6)</td>
</tr>
<tr>
<td><strong>Rock/solution</strong></td>
<td>1 or 1/40</td>
</tr>
<tr>
<td><strong>1 month</strong></td>
<td></td>
</tr>
</tbody>
</table>

Conditions of the experiments (Step 2)
3. Geochemical modeling

Work on thermodynamic data

Use data from thermo.dat = thermodynamic database of GWB

Use EQ 3/6 software

Compute $\log K$ for
- **Kamacite83** : $\text{Fe}_{0.83}\text{Ni}_{0.17}$
  considering it as a solid solution between Fe$^0$ and Ni$^0$

- **Pentlandite** : $\text{Fe}_{0.5}\text{Ni}_{0.5}\text{S}$
  considering it as a solid solution between FeS and NiS

- **Organic matter** :
  - benzene (aq)
  - phenol (aq)
  - toluene (aq)
  - $\text{CH}_3\text{COOH}$ (aq) but mostly IOM in chondrites!
3. Geochemical modeling

Non oxidative kinetic laws for dissolution

Law = $S \times k \times (1-Q/K)$

<table>
<thead>
<tr>
<th>Mineral</th>
<th>$S$ (cm$^2$/g)</th>
<th>$k$ (mol/cm$^2$.s)</th>
<th>$E_a$ (J/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>diopside</td>
<td>87</td>
<td>$10^{-14.15}$</td>
<td>62760</td>
</tr>
<tr>
<td>forsterite</td>
<td>87</td>
<td>$10^{-13.5}$</td>
<td>62760</td>
</tr>
<tr>
<td>fayalite</td>
<td>66</td>
<td>$10^{-14}$</td>
<td>62760*</td>
</tr>
<tr>
<td>anorthite</td>
<td>98</td>
<td>$10^{-12.55}$</td>
<td>62760</td>
</tr>
<tr>
<td>pyrrhotite</td>
<td>31</td>
<td>$10^{-14}$</td>
<td>63000</td>
</tr>
<tr>
<td>kamacite 83</td>
<td>41</td>
<td>$10^{-15}$</td>
<td>63000*</td>
</tr>
</tbody>
</table>

Sources: Lasaga et al. (1994), Janzen et al. (2000)

*Approximated
3. Geochemical modeling

(1) Alteration within chondrule

SA-1 : Fo + CPX + An

Modeling

Experiment

YES

An altered

Kinetic over-estimation for Fo$_{36}$
3. Geochemical modeling

Agreement between modeling and experiments

• crystallization of clinochlore
• alteration of anorthite

Discrepancy between modeling and experiments

• over-estimation of the kinetic law of dissolution for Fo (nanometric protective layer)
• Transition State Theory used by GWB ➤ surface properties no taken into account

Work on kinetic laws + add info on surfaces + add info on I.O.M.

Agreement modeling vs. experiments for the other systems

Long-term predictions
Application to other carbonaceous chondrite groups
Conclusions and perspective studies

- Mostly isochemical process during alteration from Renazzo → GRO 95577
  - heat given by radiogenic decay of $^{26}$Al (not accretion)
- Composition of the unaltered CR body estimated

- $T=250\,^\circ\text{C}$ and anoxic conditions are likely
- Importance of the feldspathic mesostasis (Al)
- Importance of the O.M. (wet silicate surfaces)
- Importance of sulfides (acid medium which favors Fo dissolution)
- Importance of the interaction between kamacite-sulfides (high affinity)
  - SOON, tests at 100 $^\circ\text{C}$ and at with various I.O.M.

- GWB modeling is nearly consistent with natural alteration
  - SOON, long-term modeling and application to other CCs
Thanks to

Loan, Craig, Georg Ann at JSC
Thierry and Philippe at LMTG
Brigitte and Matthieu at MNHN Paris
MWG for GRO 95577’ loan

&

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