Thermodynamic constraints on the formation history of acapulcoites. G.K. Benedix and D.S. Lauretta,
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Introduction: Primitive achondrite meteorites (IAB irons/winonaites; acapulcoites/lodranites; and brachinites) exhibit chondritic (primitive) compositions, but non-chondritic textures (from metamorphic through partially melted) [1]. Because of this, they offer a unique insight into the first stages of the differentiation process on asteroids.

Acapulcoites and lodranites have textural and mineralogical evidence that they experienced varying amounts of partial melting during their history. They exhibit recrystallized textures. Acapulcoites typically have average grain sizes < 250µm, while lodranites are more coarse-grained (>300µm average grain size). The mineralogy is dominated by orthopyroxene and olivine followed by varying abundances of plagioclase, troilite, Fe-Ni metal, phosphates and chromite.

Minor partial melting has been proposed for the acapulcoites based on their approximately chondritic abundances of plagioclase and troilite, the smaller grain size [3], and trace element compositions [4, 5]. Similar textural and chemical evidence indicates that Lodranites experienced higher degrees of partial melting [3,4,5]. One of the main questions regarding the formation of the acapulcoites is whether they formed via reduction of H-chondrite starting compositions during partial melting.

In a previous study we examined the thermodynamic properties of the winonait/IAB group [2]. In this study we look at these properties (closure temperature and oxygen fugacity) for the acapulcoites.

Samples and Analytical Techniques: We examined three acapulcoites: Acapulco, MET 01195 (MET), and GRA 98028 (GRA). Acapulco is the type meteorite of the group. It is characterized by a fine-grained, recrystallized texture [3, 6] and mineral compositions (Table 1) at the higher FeO-end of the range for acapulcoites. MET has a medium-grained texture similar to EET 84302 [7]. The thin section we examined contains coarse phosphate and chromite as well as relatively large olivine and pyroxene. GRA is very fine-grained and has several relict chondrules; it has a texture that is similar to that of type 6 ordinary chondrites. On the basis of chemical and textural analyses, [5] suggested that GRA may be a very primitive acapulcoite. These samples were chosen because they exhibit a range of textures and mineral compositions.

Compositions. Mineral compositions (Table 1; olivine, chromite, orthopyroxene, and clinopyroxene) were acquired with a Cameca SX-50 at The Natural History Museum. Operating conditions were 20kV accelerating voltage and 20nA beam current. Well-known minerals were used as standards and a company-supplied ZAF correction scheme was applied.

Temperature and oxygen fugacity calculations. Closure temperature and oxygen fugacity were determined following the method described in [2]. In brief, we used the two-pyroxene thermometer devised by [8] that utilizes the Ca-exchange between low- and high-Ca pyroxenes. We also applied the olivine-chromite thermometer of [9]. Using these temperatures, oxygen fugacities were calculated based on the quartz-iron-fayalite and quartz-iron-ferrosilite buffers. The relevant buffers can be expressed as follows:

\[
\begin{align*}
2\text{Fe} + \text{SiO}_2 + \text{O}_2(g) &= \text{Fe}_2\text{Si}_2\text{O}_6 \quad (1) \\
2\text{Fe} + 2\text{SiO}_2 + \text{O}_2(g) &= \text{Fe}_2\text{Si}_2\text{O}_6 \quad (2)
\end{align*}
\]

Thermodynamic data are from the database incorporated into the HSC Chemistry Software package [10]. We set aFe = XFe in metal (0.91) and aSiO2, which is set to 0.9, since there is no quartz present in the rock.

Results and Discussion: The results for the meteorites studied are listed in Tables 1 and 2 and thermodynamic data are shown in Figure 1.

Mineral compositions. Olivines do not show evidence of zoning in any of the samples studied. The standard deviation for olivine in Acapulco indicates that olivine compositions are invariant, while for MET and GRA there is some variation. However, the majority of the variation is introduced by one grain having a slightly higher FeO content in both meteorites. Chromite composition is invariant in Acapulco and MET. In GRA, Al2O3 in chromite varies between 4.0 and 6.0 wt% (similar to that found by [5]), but does not appear to be associated with zoning. Orthopyroxene and clinopyroxene values are invariant within each meteorite.

Temperature. Two pyroxene temperatures range from ~950 to 1130°C. These are consistent with temperatures reported by [3] for acapulcoites. Olivine-chromite temperatures are lower, as expected during cooling due to the olivine-chromite thermometer staying open to lower temperatures, and fall between 700 and 800°C.
**Oxygen fugacity.** Oxygen fugacities average 2.2 log units below the Iron-Wustite (IW) oxygen buffer for pyroxene and 2.4 log units below for olivine. The data fall on a line ($R^2 = 0.9991$) that roughly parallels the IW buffer line, but lies approximately 2.3 log units below it.

**Comparison to IAB/Winonaites.** It is interesting to compare these data to that of the IAB/winonaites group [2; Figure 1]. Both sets of closure temperatures are higher in the acapulcoite data, although the two-pyroxene data overlap the IAB/winonaites data. Although graphite was not found in any of the thin sections studied here, [11] reported its presence in Acapulco and thus graphite may indicate that reduction plays a role in the reduction of these meteorites similar to that found for IAB/winonaites [2].

Olivine-chromite temperatures of the acapulcoites are slightly higher than those of IAB/winonaites (fig. 1). This may indicate that the acapulcoite parent body cooled relatively quickly from peak temperatures in the regions where the acapulcoites were located.

**Conclusions and future studies:** Olivine-chromite and two-pyroxene temperatures together with olivine and orthopyroxene compositions reveal oxygen fugacities of acapulcoites to fall on a line that parallels and falls between the IW and the IAB/Win buffers. Two-pyroxene temperatures were likely the peak temperatures reached in these meteorites.

Future work will include lodranites to track the thermal history of the acapulcoite/lodranite parent body.


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**Table 1.** Relevant mineral compositions for samples in this study.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Acapulco</th>
<th>MET 01195</th>
<th>GRA 98028</th>
</tr>
</thead>
<tbody>
<tr>
<td>Olivine</td>
<td>Fa&lt;sup&gt;1&lt;/sup&gt; 11.3±0.1</td>
<td>8.2±1.0</td>
<td>7.8±1.0</td>
</tr>
<tr>
<td>Chromite</td>
<td>Cr/Cr+Al 0.88±0.00</td>
<td>0.86±0.01</td>
<td>0.90±0.03</td>
</tr>
<tr>
<td></td>
<td>Fe/Fe+Mg 0.63±0.02</td>
<td>0.56±0.03</td>
<td>0.59±0.02</td>
</tr>
<tr>
<td>OPX</td>
<td>Fs&lt;sup&gt;2&lt;/sup&gt; 10.6±0.2</td>
<td>8.5±0.4</td>
<td>9.0±0.4</td>
</tr>
<tr>
<td>CPX</td>
<td>Fs&lt;sup&gt;3&lt;/sup&gt; 4.7±0.1</td>
<td>3.8±0.3</td>
<td>3.9±0.4</td>
</tr>
<tr>
<td></td>
<td>Wo&lt;sup&gt;4&lt;/sup&gt; 34.2±0.3</td>
<td>33.9±1.0</td>
<td>35.4±0.3</td>
</tr>
</tbody>
</table>

<sup>1</sup>Fa = Fe/Fe+Mg in olivine in mol%; <sup>2</sup>Fs = Fe/Fe+Mg in orthopyroxene; <sup>3</sup>Fs = Fe/Fe+Mg+Ca in clinopyroxene; <sup>4</sup>Wo = Ca/Fe+Mg+Ca in clinopyroxene.

**Table 2.** Temperature (in °C) and oxygen fugacity determined in this study.

<table>
<thead>
<tr>
<th>Meteorite</th>
<th>Oliv-Chr&lt;sup&gt;5&lt;/sup&gt;</th>
<th>ΔW&lt;sup&gt;6&lt;/sup&gt;</th>
<th>2-pyx&lt;sup&gt;7&lt;/sup&gt;</th>
<th>ΔW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acapulco</td>
<td>786</td>
<td>-2.3</td>
<td>1126</td>
<td>-2.0</td>
</tr>
<tr>
<td>MET 01195</td>
<td>710</td>
<td>-2.5</td>
<td>1127</td>
<td>-2.2</td>
</tr>
<tr>
<td>GRA 98028</td>
<td>707</td>
<td>-2.6</td>
<td>952</td>
<td>-2.3</td>
</tr>
</tbody>
</table>

Oliv-Chr = Olivine-chromite temperature; ΔW is the deviation in oxygen fugacity from the IW buffer in log units; 2-pyx = Two-pyroxene temperature.

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**Figure 1.** Plot of oxygen fugacity (log fO<sub>2</sub>) vs temperature (10,000/T(K)) for the 3 acapulcoites analyzed in this study (diamonds) compared to IAB/Winonaites (circles). Oxygen fugacity determined from orthopyroxene (reaction 2) is shown in blue, and that determined from olivine (reaction 1) in red. Individual points are labeled with abbreviations for the meteorite names: ACA – Acapulco; MET – MET 01195; GRA – GRA 98028. Red line indicates regression through acapulcoite data ($R^2 = 0.9991$). Black line through circles is regression line for IAB/Win data ($R^2 = 0.9997$). Also shown in this plot are the Iron-Wustite, Cr-Cr<sub>2</sub>O<sub>3</sub>, and three CO-C (1, 10 and 100 bars) fugacity buffers for reference.