Thermodynamic constraints on the formation history of lodranites.
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Introduction: Primitive achondrites (IAB irons/winonaites; acapulcoites/lodranites; and brachinites) have chondritic 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 [2], and trace element compositions [3, 4]. Similar textural and chemical evidence indicates that Lodranites experienced higher degrees of partial melting [2,3,4].

The petrogenesis and formation history of the acapulcoite/lodranite parent body has been the topic of a number of recent abstracts and papers [5-9]. One of the main questions regarding the formation of the acapulcoites/lodranites is whether they experienced reduction during partial melting.

In previous studies, we examined the thermodynamic properties of the winonaite/IAB group [10] and the acapulcoites [11]. In this study we look at these properties (closure temperature and oxygen fugacity) for the lodranites.

Samples and Analytical Techniques: We examined two thin sections of Lodran (USNM 481-1, USNM 481-2), the type meteorite of the group. It is characterized by a course-grained, recrystallized texture [2, 12] and mineral compositions (Table 1) at the higher FeO-end of the range for acapulcoites.

Minerals. Because of a lack of high-Ca pyroxene in the available sections, for this study we used chromite and olivine to determine oxygen fugacity. Chromite, although rare, exhibits two different morphologies that have different compositions (see below), as noted in a previous study of Lodran [13]. One type of chromite is found in association with metal and olivine and exhibits subhedral textures, while the other type of chromite is found as rounded blebs within olivine grains.

Compositions. Mineral compositions for olivine and chromite (Table 1) were acquired with a Cameca SX-100 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 [10]. In brief, we applied the olivine-chromite thermometer of [14]. Using these temperatures, oxygen fugacities were calculated based on the quartz-iron-fayalite buffer. The relevant buffer is expressed as follows:

$$2Fe + SiO_2 + O_2(g) = Fe_2SiO_4 \qquad (1)$$

Thermodynamic data are from the database incorporated into the HSC Chemistry Software package [15]. We set aFe = XFe in metal (0.91) and $aSiO_2$, 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 Table 1 and thermodynamic data are shown in Figure 1.

Mineral compositions. Olivine ranges from Fa_{12}-Fa_{14} and displays some slight zoning in the thin sections studied. Because of this, temperatures were determined for nine specific olivine-chromite pairs.

Rounded chromite found within silicate grains is within error of the chromite compositions of acapulcoites with Cr/Cr+Al of ~0.86. Chromite associated with metal contains almost no Al leading to a Cr/Cr+Al of ~0.99, similar to chromite in type 3 ordinary chondrites [16]. Both types of chromite have Fe/Fe+Mg of 0.68, which is well within error for acapulcoites. Because the temperature calculations are based on the Fe-Mg diffusion systematics, the difference in Al abundance does not effect the calculations presented here (as can be seen in Fig. 2).

Temperature. Olivine-chromite temperatures range from ~740˚C to ~900˚C and, except for the temperature determined from the high-Al chromite (~740˚C), are higher than those reported for acapulcoites.

Oxygen fugacity. Oxygen fugacities average 2.0 log units below the iron-wustite (IW) buffer for olivine. The data fall on a line (R^2 = 0.9990) that roughly parallels the IW buffer line.

Comparison to Acapulcoites and IAB/Winonaites. Comparison of these data to both the previously determined data for the acapulcoite group and IAB/winonaite group [10, 11; Figure 1] shows that olivine-chromite closure temperatures are higher on average for Lodran than for the acapulcoites or IAB/Winonaites. The oxidation state of Lodran, based on olivine, is slightly more oxidized than either the acapulcoites (IW-2.4) or IAB/Win (IW-3.0). This may indicate that the acapulcoite-lodranite parent body cooled relatively quickly, although without the corresponding two-pyroxene temperatures, this is difficult to assess.

Conclusions and future studies. The difference in chromite morphology and composition offers a unique view of the oxidation state of Lodran, both prior to and post melting. The chromite found within olivine has the same composition (high in aluminum) as that found in acapulcoites and likely represents the relict composition, while the chromite found in association with metal has suffered a depletion of Al, most likely due to removal of a plagioclase-enriched partial melt. The closure temperature calculated from the olivine-high-al chromite pair is the lowest calculated for Lodran. The aassociated oxygen fugacity is IW-2.1. Although the temperatures calculated from the low-Al chromite are ~100°C higher, the calculated oxygen fugacities are identical within error (IW-2.0) to that determined for the high-Al chromite. This implies that there is no change in fO_2 during partial melting.

In future studies, we will explore two-pyroxene closure temperatures and related fO_2 in a suite of lodranites.

References: [1] Prinz M. et al. (1983) *LPS XIV*, 616-617. [2] McCoy T.J. et al. (1996) *GCA* 60, 2681-2708. [3] Floss C. (2000) *Meteoritics and Planet. Sci.* 35, 1073-1085. [4] Patzer A. et al. (2004) *Meteoritics and Planet. Sci.* 39, 61-85. [5]Irving A.J. *et al.* (2007) *LPS XXXVIII* Abstract #2254. [6]Irving A.J. *et al.,* (2007) *Meteoritics and Planet. Sci*. 42, A74. [7]Patzer et al., (2008) *GCA* 72, A728. [8]McCoy T.J. et al., (2006) *GCA* 70, 516-531. [9]Rubin (2007) *GCA* 71, 2283-2401. [10] Benedix G.K. et al. (2005) *GCA* 69, 5123-5131. [11] Benedix G.K. et al., (2006) *LPS XXXVII* Abstract# 2129. [12] Palme H. et al. (1981) *GCA* 45, 727-752. [13] Bild R.W. and Wasson J.T. (1976) *Mineral Mag.,* 40 721-735. [14] Sack R.O. and Ghiorso M.S. (1991) *Am. Min., 76,* 827-847. [15] Eriksson G. and Hack K. (1990) *Metall. Trans., 21B*, 1013-1023. [16] Bunch et al. (1967) *GCA* 31, 1569-1582.

Table 1. Average mineral compositions for Lodran.

Olivine	
Fa[1]	12.6±*1.2*
Chromite[*]	
Cr/Cr+Al	0.99±*0.000*
Fe/Fe+Mg	0.69±*0.019*
Chromite_r[§]	
Cr/Cr+Al	0.86±*0.005*
Fe/Fe+Mg	0.69±*0.004*

[1]Fa = Fe/Fe+Mg in olivine in mol%; [*]Chromite associated with metal; [§]Chromite associated with silicate

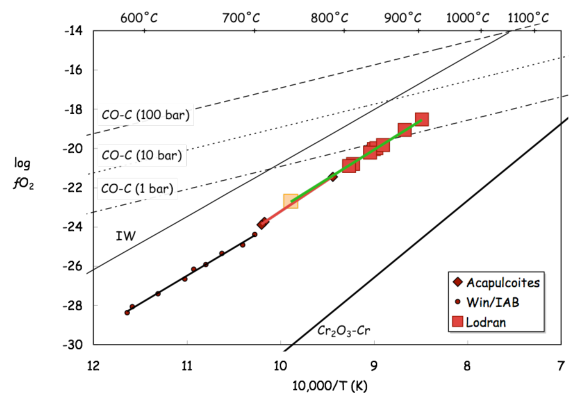

Figure 1. *Plot of oxygen fugacity (log fO_2) vs temperature (10,000/T(K)) for Lodran (squares) compared to the acapulcoites analyzed in [2] (diamonds) and the IAB/Winonaite (circles). Oxygen fugacity was determined from olivine (reaction 1). Green line is regression through lodran data (R^2=0.9990). Red line indicates regression through acapulcoite data (R^2=0.9996). Black line through circles is regression line for IAB/Win data (R^2=0.9959). The yellow square is the temperature and oxygen fugacity determined for high-aluminum chromite. It is interesting to note that this point falls within the acapulcoite temperature range. Also shown in this plot are the Iron-Wustite, Cr-Cr_2O_3, and three CO-C (1, 10 and 100 bars) fugacity buffers for reference.*