COMPOSITIONS, GEOCHEMISTRY, AND ORIGINS OF RECRYSTALLIZED LL CHONDRITES: IMPLICATIONS FOR THE PRIMITIVE ACHONDRITES. J. M. Friedrich[1,2], M. Kimura[3,4], and G. C. Perrotta[1], [1]Department of Chemistry, Fordham University, Bronx, NY 10458 USA (friedrich@fordham.edu), [2]Department of Earth and Planetary Sciences, American Museum of Natural History, New York, NY 10024 USA, [3]Faculty of Science, Ibaraki University, Mito 310-8512, Japan, [4]National Institute of Polar Research, Tokyo 190-8518, Japan.

Introduction: Primitive achondrites known as the acapulcoites and lodranites have achondritic textures (recrystallization has eliminated most traces of chondrules). Of these, the acapulcoites are closest in both chemistry and mineralogy to their parent chondritic starting material. It is generally accepted that acapulcoites are essentially chondritic materials that have experienced temperatures higher than the equilibrated ordinary chondrites [1,2]. Most acapulcoites have probably experienced temperatures near those necessary for complete melting of the Fe(Ni)-FeS system (~980°C). There is limited evidence for partial melting of acapulcoite silicates [1-3].

When compared with equilibrated (petrographic types 4-6) ordinary chondrites, the majority of which experienced temperatures of only 600-900°C [4], the primitive achondrites are modified in composition and mineralogy because of the higher temperatures they experienced. However, some equilibrated ordinary chondrites have also seen higher sustained temperatures and these materials are the focus of this study. We used a classification of petrographic type 7 as a criterion for inclusion in this study. The idea of a type 7 chondrite is somewhat controversial. The scheme was partially based on the work of [4,5] on the Shaw L chondrite where they found textures and mineralogy that differed enough from those of typical type 6 chondrites to introduce a type 7 classification.

To investigate the nature of high degrees of thermal alteration in ordinary chondrites we selected six LL7 chondrites (EET 92013, Uden, Y-74160, Y-790144, Y-791067, Y-82067) for study. We point out that implicit in the 4-5-6-(7) equilibrated ordinary chondrite classification scheme is that each increasing petrographic grade is associated with increased metamorphic heating on the parent asteroid, generally accepted to be from heat generated by the decay of ^{26}Al. However, impacts on a porous parent asteroid can also heat a target [6,7] to a substantial degree, and others have shown that the heating and resulting composition and textures of the Shaw (L7) chondrite was due to impact heating [8,9].

Whether the heat necessary for the metamorphosis of a chondrite to type 7 was radiogenic or impact related, one thing that is clear about a type 7 classification is that complete melting or differentiation has not occurred – these materials are still largely identifiable as chondritic from mineralogical and bulk composition perspectives. We commenced our study to examine compositional changes in ordinary chondrites that have been identified as having experienced higher than typical thermal alteration and examine the nature of the heat source(s) involved. Our study may help to understand the origins of primitive achondrites whose chondritic planetary antecedents and origins are uncertain.

Methods: We used the method of [10] to quantify 45 trace elements by ICPMS in each of our samples. To correlate our compositional results with the petrology of our samples, we summarize previously published petrographic and mineral composition observations and augment them with our own petrographic section observations, including an assessment of shock stage [11].

Table 1. Samples and selected observations

sample	shock stage	highly recrystallized texture	brecciated	incipient Fe(Ni)-FeS removal
EET 92013	n.d.	+	-	+
Uden	n.d.	+	+	+
Y-74160	S1	+	+	-
Y-790144	S3	+	+	-
Y-791067	S1	+	+	+?
Y-82067	S1	+	-	-

Results and Discussion: Based on mineral compositions, each of the six chondrites investigated are clearly LL chondrites [12,13] and our bulk elemental analyses confirm an LL chondrite provenance.

Petrography. Table 1 summarizes petrographic observations. Each has been substantially recrystallized. These chondrites experienced a mild post-recrystallization shock history: shock stages are either S1 or S3. Three (EET 92013, Uden, Y-82067) of the six have occasional vestiges of chondrules remaining. In Y-82067 we observed triple junctions among the minerals and coarse-grained plagioclase, up to ~100 µm in size. With effort, a single relict barred olivine chondrule could be perceived within the Y-82067 section under cross polarized light.

Compositions. At first glance, our elemental analyses indicate that the high degree of thermal alteration experienced by our samples was, for the most part, isochemical in nature. However, more detailed indicators show some experienced very low degrees of partial melting and occasional Fe(Ni)-FeS mobilization (Fig. 1). Se/Co values, a proxy for troilite/metal ratios, and Rb/Sc, a plagioclase/pyroxene surrogate indicator, also suggest some evidence for mineralogical mobilization. This is akin to the incipient partial melting reported in the acapulcoites [2].

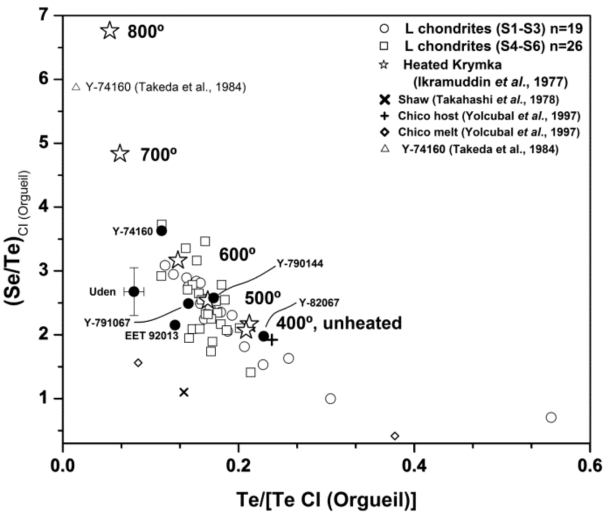

Figure 1. CI normalized Se/Te ratio versus CI normalized Te abundance in the six chondrites included in this study with literature data for mildly-shocked (S1-S3) and strongly-shocked (S4-S6) L chondrites [14] and artificially heated Krymka (LL3.2) shown for comparison. The indicated temperatures of heated Krymka are not to calibrate temperatures experienced by the chondrites in this study, only to show the effects of increasing temperature on the material. Te has a greater volatility than Se, so simple heating of chondritic material should move the Se/Te ratio to higher values with modest depletion of Te. Simultaneous removal of Te and Se reduce both Te and Se/Te values and defines a trend interpreted as Fe(Ni)-FeS eutectic mobilization or loss. Uden and EET 92013 lie to the left of the simple heating trend, indicating some extraction of Fe(Ni)-FeS material, like the impact generated materials found in the L chondrites Chico and Shaw (see above) and hinted at with some of the more strongly shocked L chondrites. Using this metric, the Yamato chondrites in this study show little to no evidence of Fe(Ni)-FeS eutectic mobilization.

Impact-related thermal alteration. ^{40}Ar-^{39}Ar ages for some of the samples in our suite allow us to reflect on the source of the heat responsible for the high degrees of thermal alteration. [15] found an ^{40}Ar-^{39}Ar age of 4.2 ± 0.1 Ga for Uden. This corresponds to an increasingly acknowledged large ~4.2 Ga impact event on the LL parent body [e.g. 16], giving some evidence for an impact origin for Uden's hyper-metamorphosed nature. [17] found a ^{40}Ar-^{39}Ar plateaus at 4.30 Ga and 4.00-4.25Ga in Y-74160. They attributed the 4.3Ga age as the time of recrystallization. [17] did not find a well-defined release plateau in Y-791067. Eighty percent of integrated ^{39}Ar was released at variously ill-defined ages of <4.26 Ga.

Conclusions: The six chondrites in our investigated suite are of LL provenance, but each experienced temperatures high enough for them to have been recrystallized in the solid state and/or some experienced very low degrees of partial melting. These LL chondrites display a variety of compositions, reflecting localized phenomena related to temperatures enough to initiate exceedingly low degrees of partial silicate melting and Fe(Ni)-FeS eutectic mobilization. This scenario is akin to the incipient partial melting recorded by McCoy et al. (1996) in the acapulcoites; however our samples, in general, have somewhat more limited compositional changes than the acapulcoites.

Uden, Y-74160, and Y-791067 have ^{40}Ar-^{39}Ar ages that are late enough that radionuclide decay (^{26}Al) could not have been responsible for the high degree of thermal alteration exhibited by these samples since ^{26}Al was largely exhausted by the K-Ar closure dates (~4.2-4.3 Ga) measured in these samples. The heat source responsible for the thermal alteration in the recrystallized LL chondrites was likely impact related.

The origins of highly metamorphosed LL chondrites appear to be impact related, but we cannot explicitly extrapolate the same scenario to the acapulcoites. Acapulcoite K-Ar systems show ~4.5Ga crystallization ages , a time when ^{26}Al was still abundant. However, because of the localized, heterogeneous heating experienced on the acapulcoite parent body [1] an impact-heating contribution cannot be ruled out.

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