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Cluster Chondrite Accretion Temperatures Determined with Electron Backscatter Diffraction

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1. Abstract

We studied ordinary chondrites with cluster chondrite lithologies using electron backscatter diffraction to measure the temperatures of their olivine grains during deformation. Samples analyzed with the technique are shock classified as S1 and are type 3, so the deformation analyzed is inferred to represent the temperatures of the chondrules during accretional deformation. It was found that the studied samples are of a mixture of chondrules at mostly hot temperatures (>850°C) and some at cold (<850°C) temperatures during deformation. This is interpreted to represent a heterogeneous temperature of accretion, namely that the objects accreting were a mixture of cold and hot chondrules. This interpretation establishes two new constraints for chondrule formation models, requiring that they must allow for chondrule accretion shortly after the heating event and that they must allow for the mixing of hot and cold chondrules in the short time period prior to that accretion. These new constraints are most compatible with established protoplanetary bow shock and impact splash formation models, and other models are either wholly incompatible with the new constraints or require modification to be consistent with them.

3. Background

- Intracrystalline deformation in the form of dislocations can be measured using electron backscatter diffraction (EBSD) methods (Passchier and Trouw, 2005).
- EBSD works by diffracting electrons through crystal structures, allowing the exact orientation of a crystal at a point to be measured (Prior et al. 1999).
- Different dislocation types in olivine grains, a common mineral in chondrites, are strongly related to deformational temperature (Karato et al., 2008).
- Measurement of olivine dislocations can be used to infer deformation temperature (Ruzicka and Hugo, 2018).
- Hypervelocity impacts (shock metamorphism) can deform crystals and create dislocations (Ruzicka and Hugo, 2018).
- Thermal metamorphism can anneal crystals, obliterating dislocations (Ruzicka and Hugo, 2018).

4. Methods and Samples

- Samples
  - NWA 5205 (LL3.2)
  - NWA 5421 (LL3.7)
  - NWA 5781 (LL3.3)
  - Tieschitz (H/L3.6 S1-3)
  - All are unequilibrated, preventing erasure of intracrystalline deformation evidence by thermal metamorphism.
- Shock Classification (Figure 1)
  - Samples were shock classified (Stöffler et al. 1991, 2018) and their weighted shock stages measured (Jamsja and Ruzicka, 2010).
  - Low shock "S1" samples were selected for further analysis to avoid the interfering effects of shock metamorphism.
- Electron Backscatter Diffraction (Figures 2 and 3)
  - Two 2-4 µm step-size EBSD maps were made of each sample.
  - Equipment: Zeiss Sigma SEM at 20 kV accelerating voltage.
  - Whole map mean grain orientation spreads (GOS), average mean orientation spreads (MOS), annealing parameters, temperature parameters were measured (Ruzicka and Hugo, 2018).
- Chondrule Analysis (Figures 4-7)
  - Ten chondrules from each map were selected to represent the full range of population deformation.
  - Chondrule deformation parameters, grain orientation spreads, and temperature parameters were measured (Metzler, 2012; Ruzicka and Hugo, 2018).
  - Relations between these three categories of measurement in each sample were tested statistically.

2. Introduction

- Chondrites: Meteorites formed from Early Solar System debris. They are primarily made of dust and chondrules (Weisberg, 2006).
- Chondrules: Submillimeter sized spherules made from dust clumps and other small objects melted in the Solar nebula during Solar System formation (Hewins, 1997).
- How chondrules formed has been a mystery since 1877. Numerous models have been proposed, but none are confirmed (Hewins, 1997).
- Cluster Chondrite: A chondrite that is 88-92 vol% chondrules (Metzler, 2012).
- Chondrules in cluster chondrites are highly deformed, and have been hypothesized to have accreted onto a planetesimal while still hot from formation (Metzler, 2012).
- **<u>If it is the case that cluster chondrite chondrules were accreted hot, this establishes new constraints for chondrule formation models. So, were they hot?</u>**

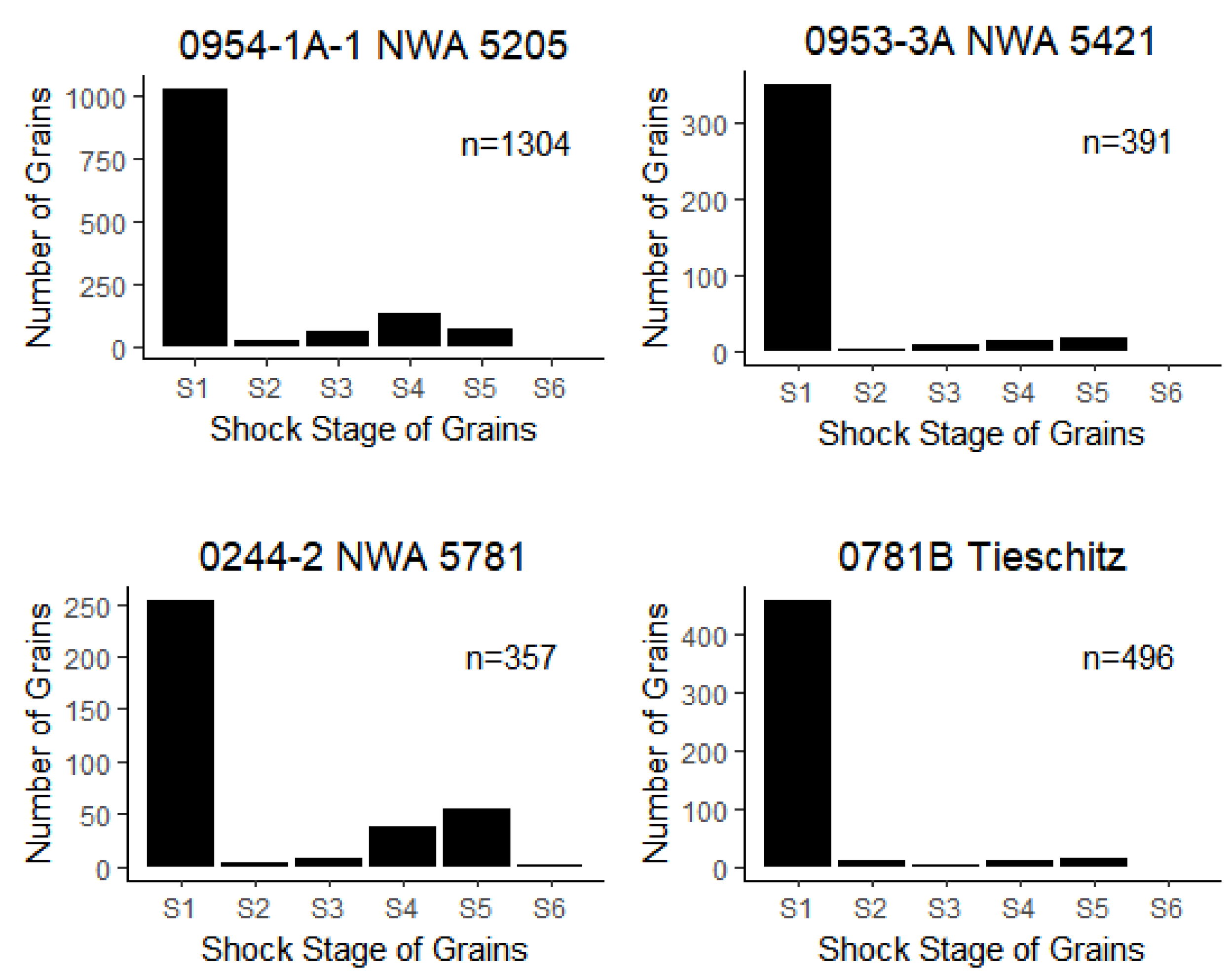

Figure 1. Shock Stage Data for the Samples. All are S1. Graphs are histograms of olivine grains displaying characteristics typical of given shock stages.

5. Interpretation

- Tieschitz is an anomaly – it appears annealed but cannot be as it is unmetamorphosed. This may be a result of skew in the sample's GOS population.
- Intracrystalline deformation (GOS) and chondrule deformation (deformation parameter) are linked. Accordingly, temperature inferences of olivine grains reflect their host chondrules.
- Almost all chondrules reflect high temperatures (>850°C), indicating that cluster chondrite chondrules are accreted hot.
- Presence of two cold chondrules implies cold and hot chondrules must be able to mix.

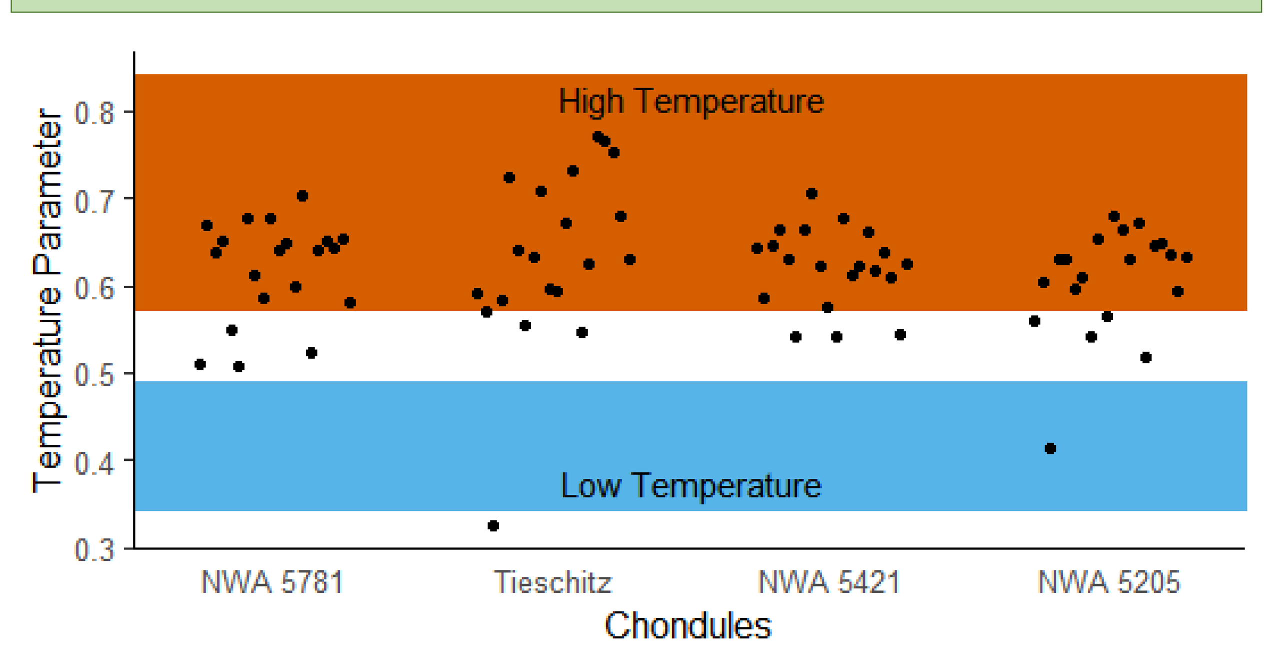

Figure 4. Graph of Chondrule Temperature Parameters. Points are chondrules, grouped by sample. Lower colored region represents the range observed temperature parameters in cold shocked chondrites in Ruzicka and Hugo (2018). Upper colored region represents the range observed temperature parameters in hot shocked chondrites in Ruzicka and Hugo (2018).

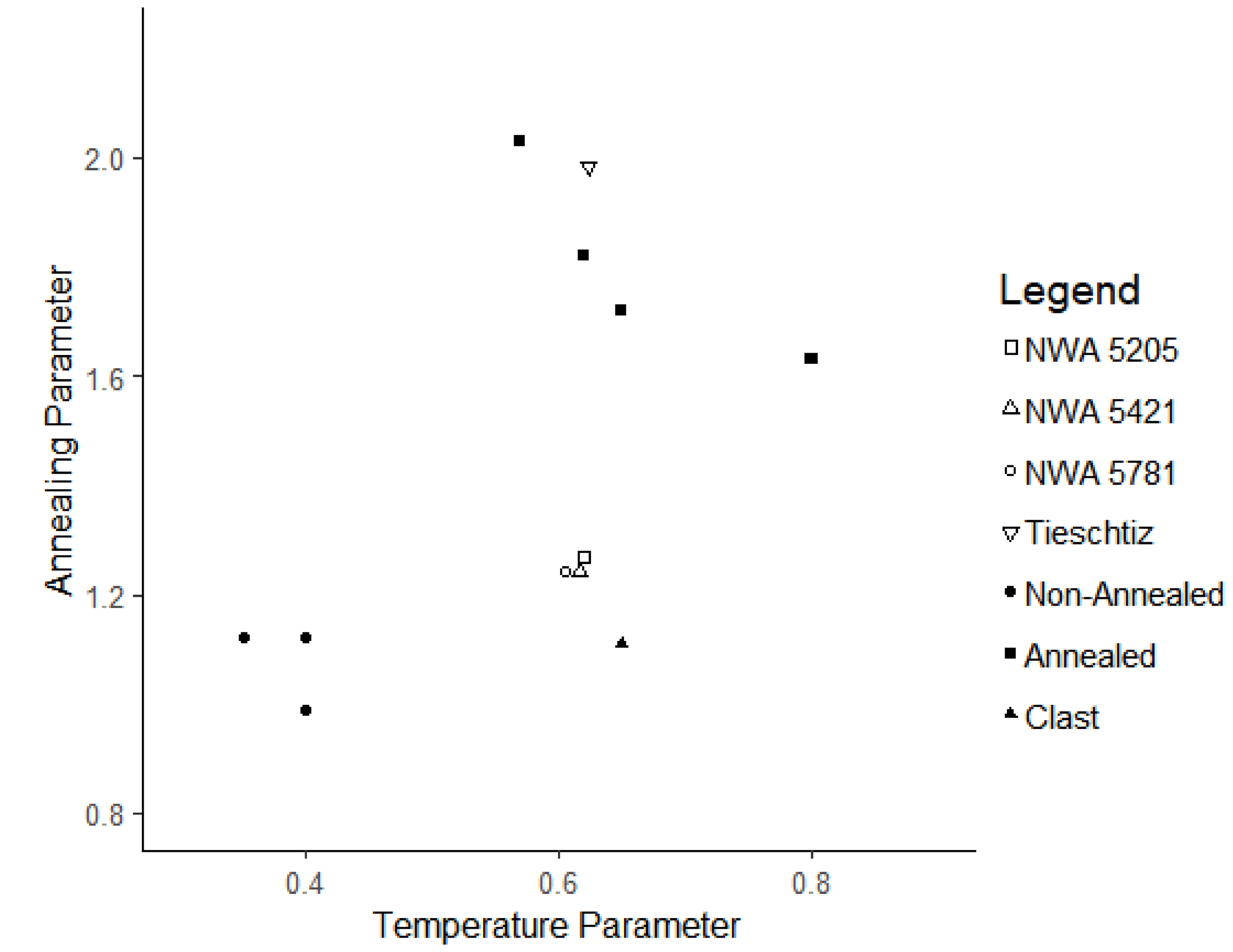

Figure 2. Graph Comparing Annealing and Temperature Parameters. Black points represent data from Ruzicka and Hugo (2018) shocked samples. Most samples analyzed in this study form a tight cluster distinct from the clusters of the Ruzicka and Hugo (2018) study. Tieschitz plots with the annealed samples, but unlike them, is unequilibrated.

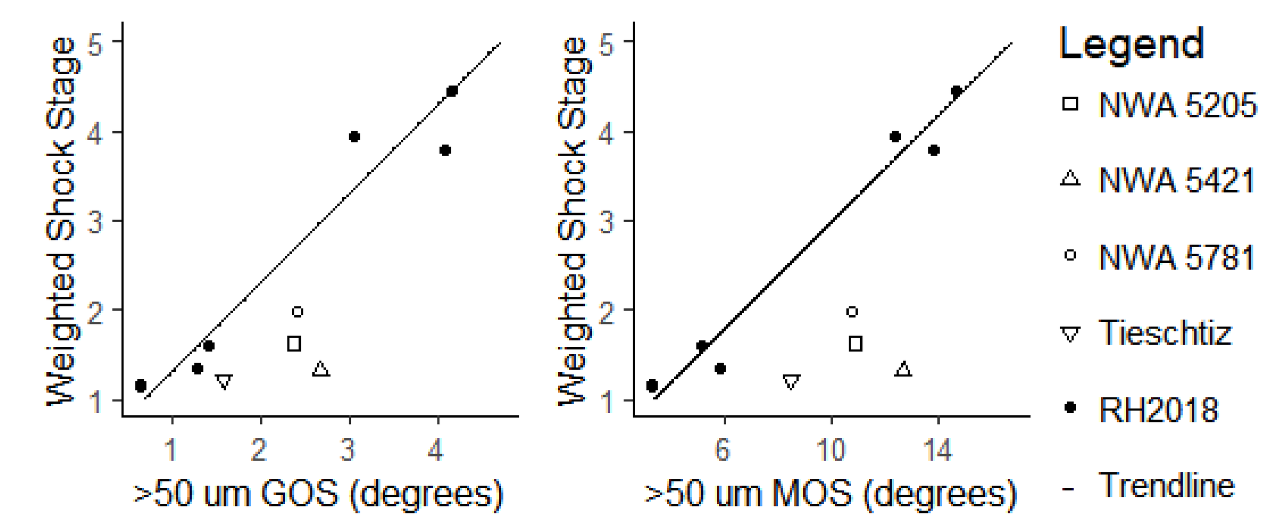

Figure 3. Diagrams Comparing GOS and MOS to Weighted Shock Stages. Data of this study depart from the trend established in Ruzicka and Hugo (2018), but are in regions of GOS, MOS, and weighted shock stages outside those of that study. "RH2018" is an abbreviation representing data from Ruzicka and Hugo (2018)

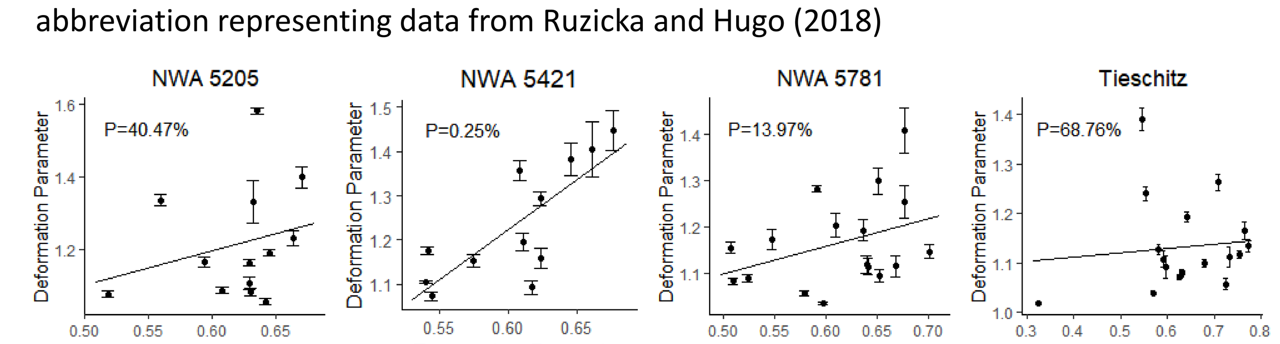

Figure 5. Graphs Comparing Chondrule Temperature and Deformation Parameters. "P" is the probability of no significant correlation between the two parameters in the sample, as determined by ANOVA. Points are individual chondrules.

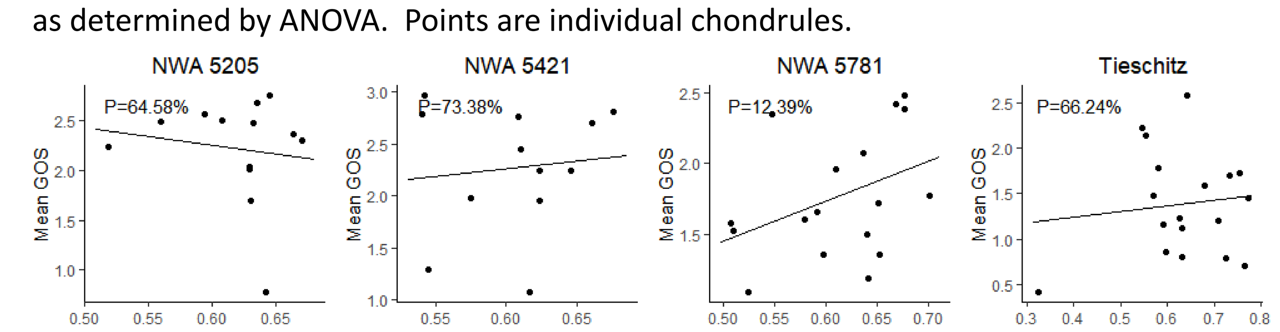

Figure 6. Graphs Comparing Chondrule Temperature Parameters and Mean GOS. "P" is the probability of no significant correlation between the two parameters in the sample, as determined by ANOVA. Points are individual chondrules.

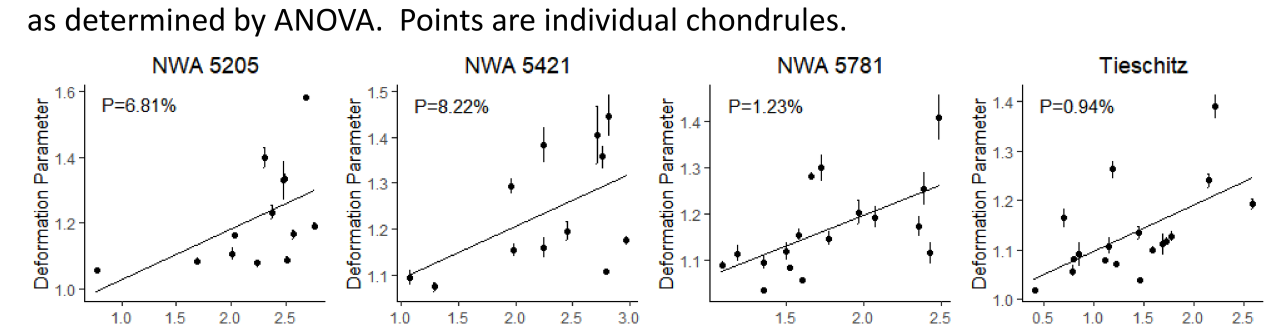

Figure 7. Graphs Comparing Chondrule Mean GOS and Deformation Parameters. "P" is the probability of no significant correlation between the two parameters in the sample, as determined by ANOVA. Points are individual chondrules.

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6. Model Implications

- Two new constraints:
  - Chondrules must form near planetesimals to enable hot accretion.
  - Hot and cold chondrules must be able to mix.
- Of existing chondrule formation models, bow shockwave and impact splashing models can best meet these two new constraints.
- Density shockwave models could be adapted to meet these constraints if modified to incorporate gravitationally-bound clouds of dust and chondrules.

7. Conclusions

In an analysis of four unshocked type 3 ordinary chondrites with cluster chondrite lithologies, evidence for temperature at accretion was found from the temperature-dependent activation of olivine dislocation slip systems that accommodate the deformation observed in these rocks. A mixture of temperature signals is observed, indicating a heterogenous mixture of cold and hot chondrules accreting together to form the studied cluster chondrites, though most chondrules were hot during accretion. Temperature of the chondrules is not well correlated with their degree of deformation, however their intracrystalline and whole-chondrule deformation are linked. The most plausible source of heating for the accreted hot chondrules is the unknown chondrule formation mechanism, as these objects could not have been heated by thermal metamorphism or shock metamorphism in these unshocked and unequilibrated chondrites. This establishes two new constraints for chondrule formation mechanisms: 1) they must allow the mixing of hot and cold chondrules and 2) they must allow for chondrule accretion to be spatially and temporally proximal to chondrule formation. Bow shock and impact models for chondrule formation can most plausibly meet these new constraints, whereas other models require modification to meet them, and potentially must be rejected if they cannot be so accommodated.