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 S3 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 ($\geq 850^\circ$C) and some at cold ($< 850^\circ$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.

2. Introduction

- Chondrites: Metamorphosed remnants from Early Solar System debris. They are primarily made up of dust and chondrules (Weisberg, 2006).
- Chondrules: Spheroidally sized silicate rocks 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 (Mätzler, 2012).
- Chondrules in cluster chondrules are highly deformed, and have been hypothesized to have accreted onto a planetesimal while still hot from formation (Mätzler, 2012).
- If it is the case that cluster chondrites chondrules were accreted hot, this establishes new constraints for chondrule formation models. So, were they hot?

3. Background

- Intracrystalline deformation in the form of dislocations can be measured using electron backscatter diffraction (EBSD) methods (Pashchev and Trout, 2005).
- EBSD works by diffusing electrons through crystal structures, allowing the exact orientation of a crystal 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 destroy dislocations (Ruzicka and Hugo, 2018).
- Thermal metamorphism can anneal crystals, obliterating dislocations (Ruzicka and Hugo, 2018).

4. Methods and Samples

- Samples
  - NWA 5205 (L3.2)
  - NWA 5421 (L3.7)
  - NWA 5781 (L3.3)
  - Tiesgch (V/IL 5.1-3)
- All are unmetamorphosed, preventing measurement of intracrystalline deformation evidence by thermal metamorphism.
- Shock Classification (Figure 1)
  - Samples were shock classified (Stöffler et al., 1991, 2018) and their weighted shock stage measured (Arino and Ruszczyk, 2010).
  - Low shock “L3” 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 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 (Mätzler, 2012; Ruzicka and Hugo, 2018).
  - Relations between these three categories of measurement in each sample were tested statistically.

5. Interpretation

- Tiesgch is an anomaly – it appears unmetamorphosed but cannot be as it is metamorphosed. This may be due to low water in the sample’s GO5 population.
- Intracrystalline deformation (GOS) and chondrule deformation (deformation parameter) are linked. Accordingly, temperature inferences of olivine grains reflect their host chondrules.
- All of all chondrules reflect high temperatures ($> 850^\circ$C), indicating that cluster chondrules chondrules are accreted hot.
- Presence of two cold chondrules implies cold and hot chondrules must be able to mix.

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 heterogeneous mixture of cold and hot chondrules accreting together to form the studied cluster chondrites, though most chondrules were hot during accretion, a 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 unmetamorphosed chondrules. This establishes two new constraints for chondrule formation mechanisms: 1) they must allow for 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 possibly meet these new constraints, whereas other models require modification to meet them, and potentials must be rejected if they cannot be so accommodated.