An Application of REE-in-Two-Pyroxene Thermometry to H Chondrites: Evidence for Early Fragmentation—Reassembly of the H chondrite Parent Body

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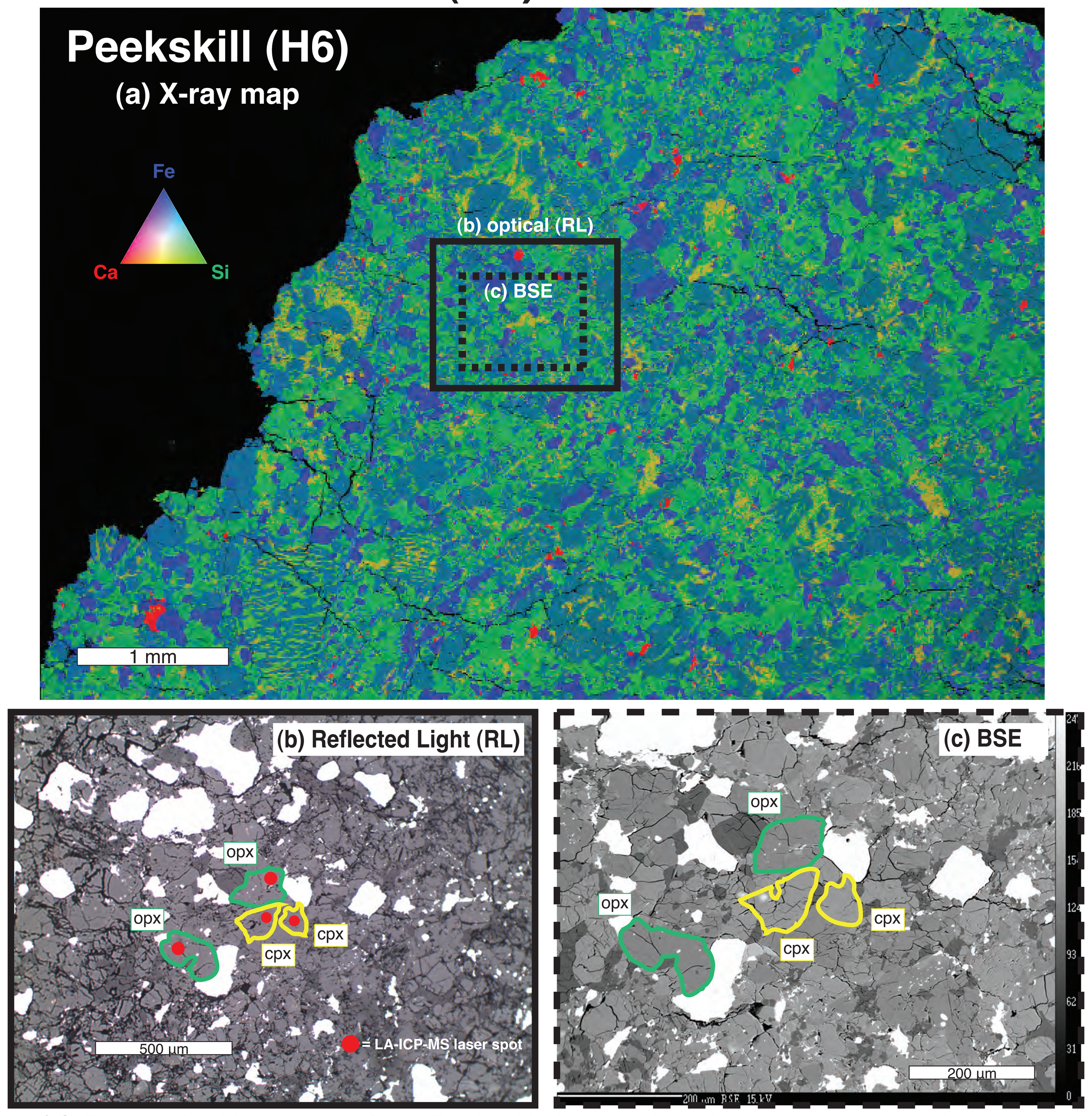
Introduction

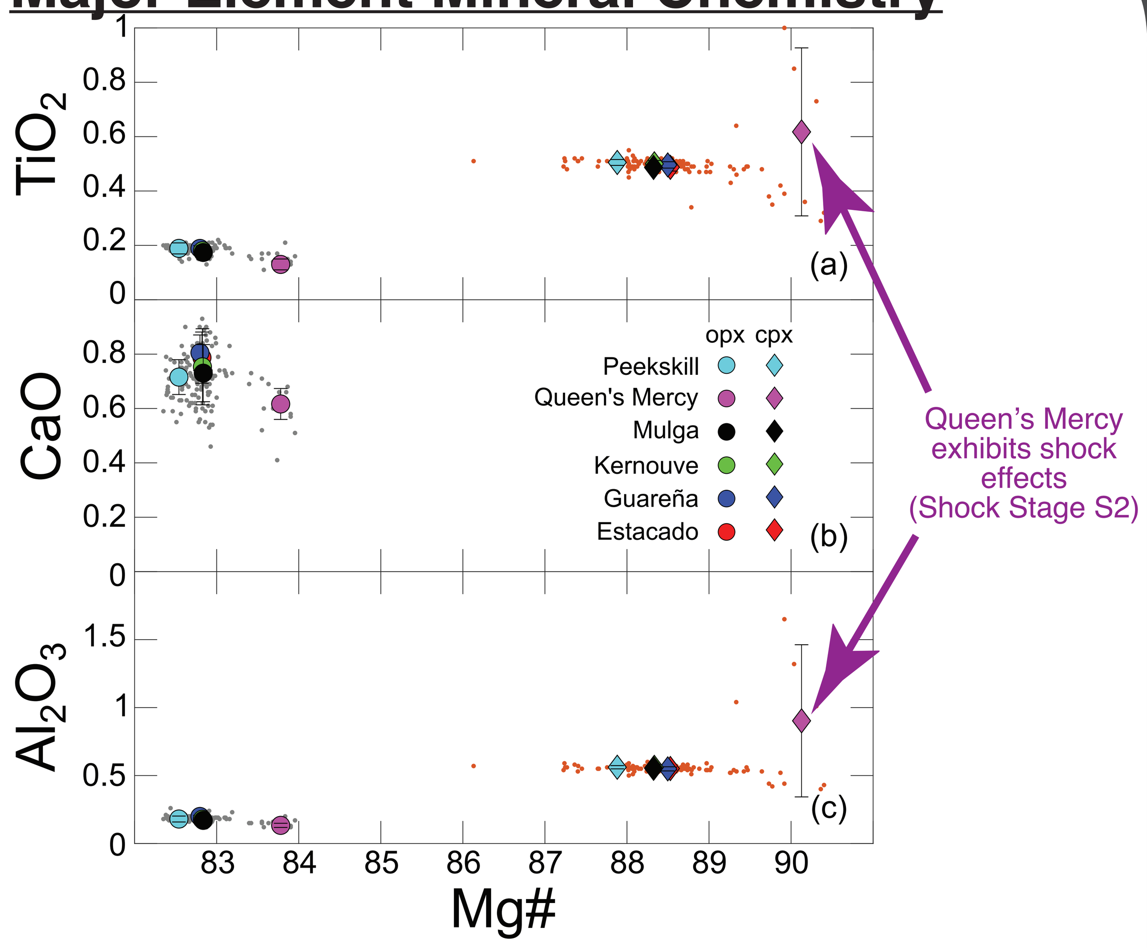
Thermal evolution models of asteroids are ground-truthed by estimates of temperatures and cooling rates from meteorite cosmochemical data [e.g., 1]. However, traditional geothermometers used to constrain the thermal evolution of meteorite parent bodies typically record blocking temperatures during cooling rather than peak or magmatic temperatures. Recently, a REE-in-two pyroxene thermometer was developed [2] that relies on the relatively slow diffusive exchange of REEs between coexisting pyroxenes. This method has been shown to record near-peak or magmatic temperatures for samples from a variety of geologic settings in the Earth's mantle and crust, and some samples from planetary environments [2-5]. Here, we apply the REE-in-two pyroxene thermometer to six H ordinary chondrites to provide key near-peak temp data. These data, accompanied by major element geothermometry, furnish new insights into the thermal histories of H chondrites. Accurate thermal histories in turn help to discriminate between competing models (e.g., onion-shell vs. fragmentation—reassembly) regarding the geologic evolution of the H chondrite parent body.

H Chondrite (H6) Characterization



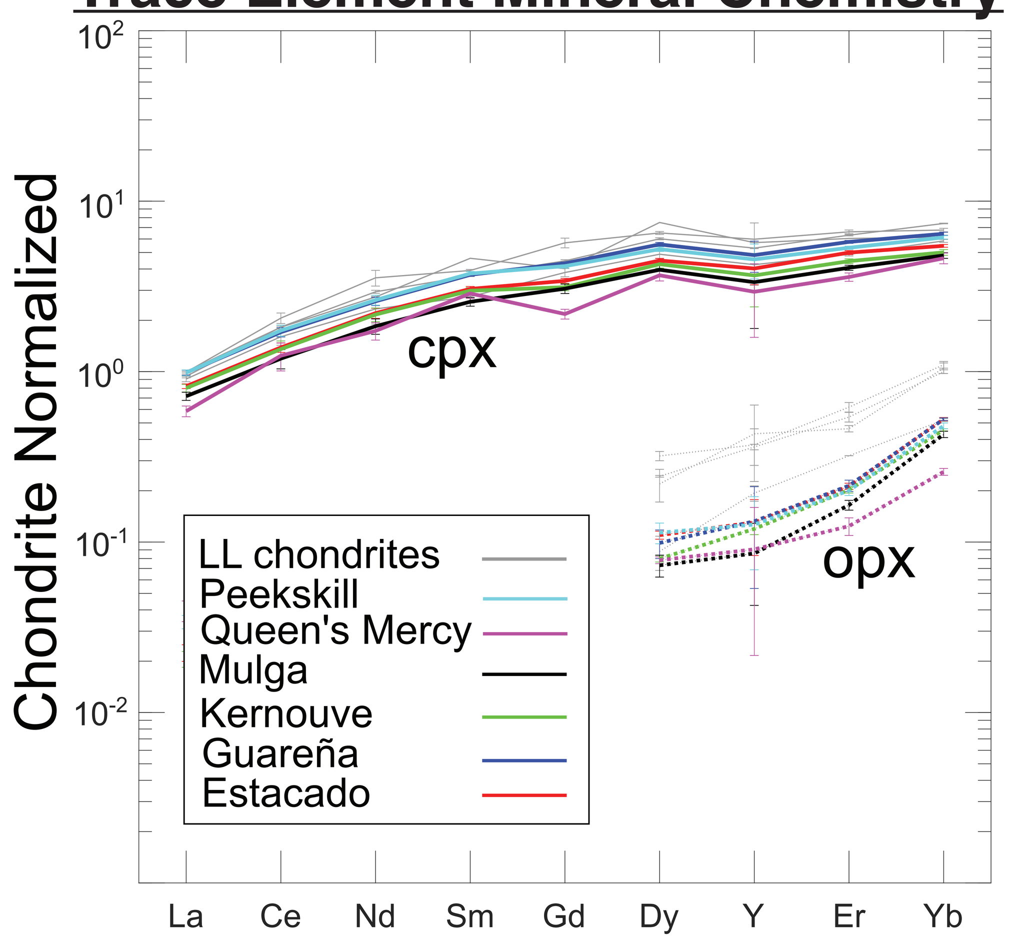
(a) False-color X-ray map of the Peekskill H chondrite; phases characterized are cpx (yellow), opx (light green), olivine (blue-green), FeNi metal (blue), and phosphates (red).
(b) RL photomicrograph (grains selected for LA-ICP-MS analysis outlined).
(c) BSE image of dashed region in (a).

Major Element Mineral Chemistry



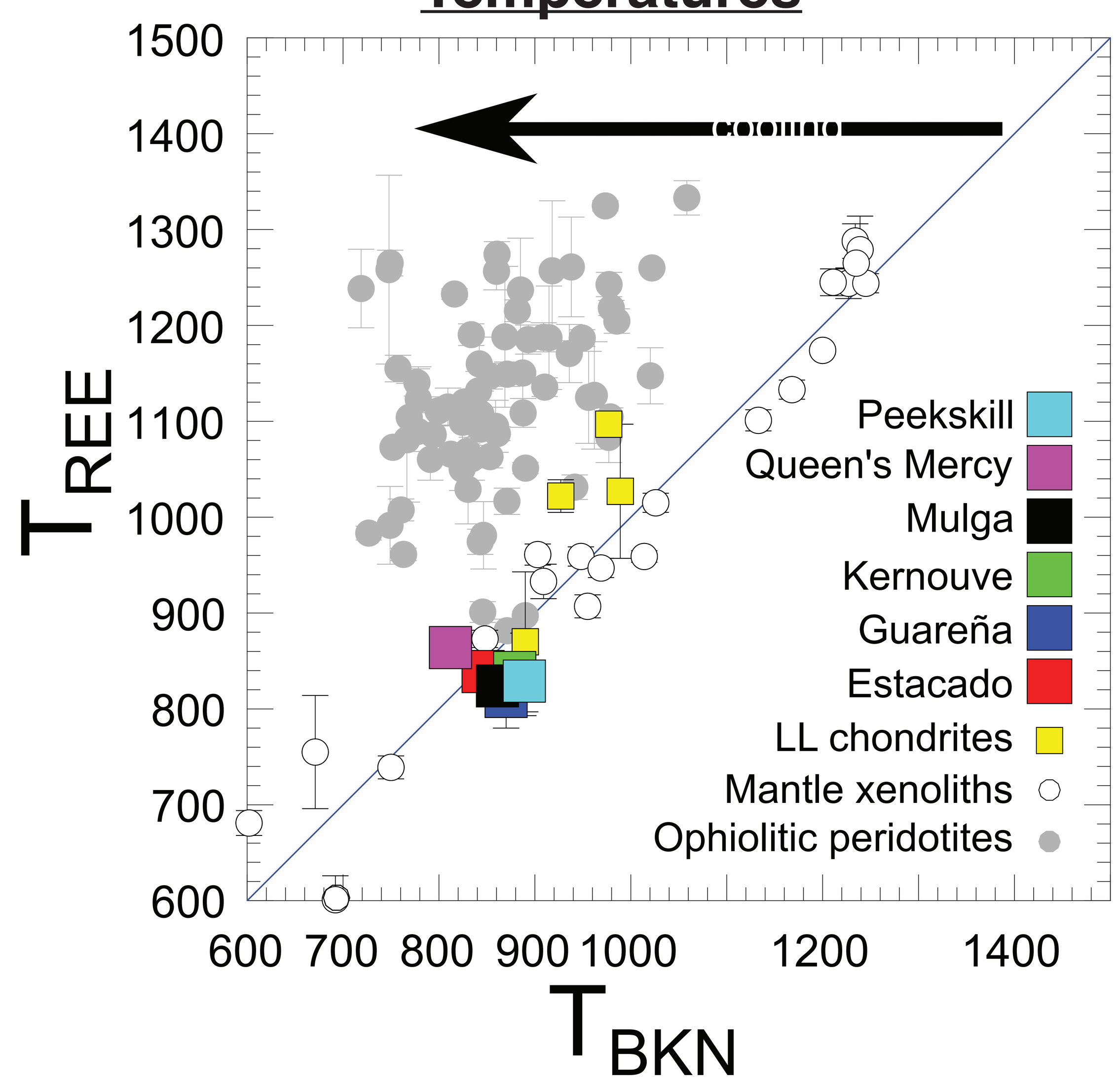
Major element variations in six H chondrites (H6) from this study. Small gray (opx) and orange (cpx) dots show the range of mineral compositions among all samples; large symbols are averaged compositions of grains analyzed by LA-ICP-MS.
Takeaway: Homogeneous compositions suggest thermally equilibrated samples.

Trace Element Mineral Chemistry



Chondrite normalized REE+Y abundances in cpx (solid lines) and opx (dotted lines). Error bars are 1σ SD of replicate analyses. Shown for comparison are the range of values in four LL chondrites [6] (light gray lines).
Takeaway: Trace elements are homogeneous and reproducible among px grain pairs.

Temperatures



T_{REE} vs. T_{BKN} (Brey and Köhler two-solvus px thermometer [7]) for H chondrites (large squares) and LL chondrites (yellow squares) [6]. The difference between T_{REE} and T_{BKN} (ΔT) can be used to infer the cooling rate of the sample:
$T_{REE} \approx T_{BKN}$ ==> fast cooling
$T_{REE} > T_{BKN}$ ==> slow cooling

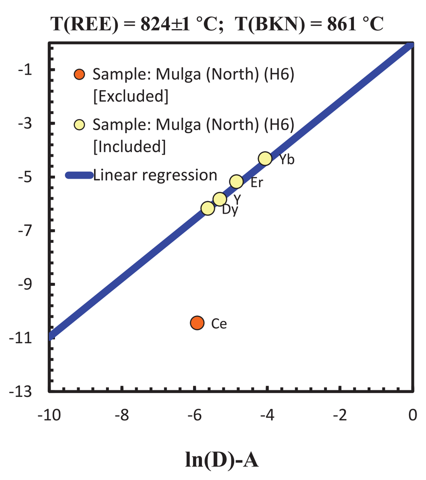
Table - Temperatures recorded for six H chondrites (H6).

Sample	Shock[a]	T_{REE}	T_{BKN}	ΔT	2-Px[b]	T_{Ca-Ol}
Estacado	S1	839±18	846	-7	—	728
Guareña	S1	813±33	870	-57	848	717
Kernouve	S1	838±14	879	-41	848	712
Mulga (north)	—	824±1	861	-37	—	706
Peekskill	—	829±18	889	-60	—	712
Queen's Mercy	S2	864±5	812	52	—	733

[a] Shock Stage from [8]; [b] temperature data from [7]; all temperatures given in °C

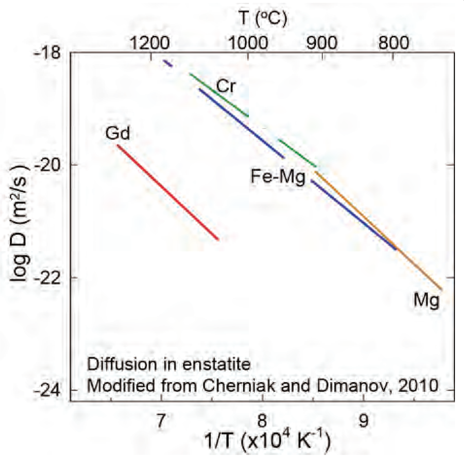
Takeaway: The agreement of T_{REE} and T_{BKN} among the H chondrites implies that these samples were rapidly cooled from peak temperatures of >800 °C.

Methods



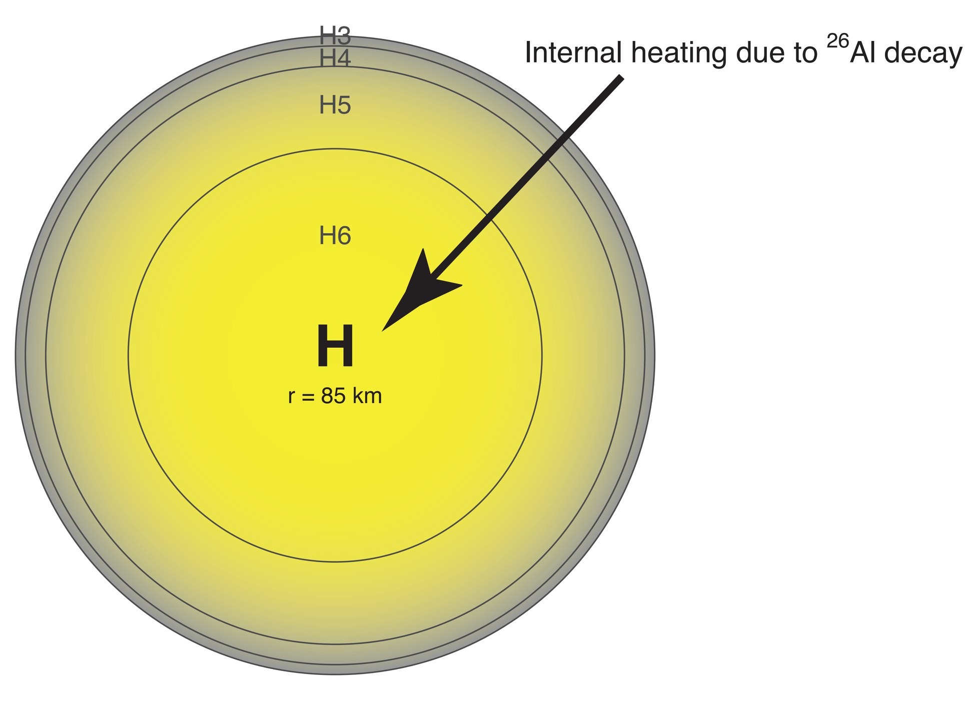
(Left) T_{REE} inversion diagram for Mulga (North). A linear regression through REE+Y defines T_{REE}. T_{REE} cannot be determined in cases where REE+Y fail to align linearly.

(Right) In pyroxene, REE (3+ cation) diffusion is one to two orders of magnitude slower than for major elements (2+ cation).



Competing Parent Body Models

Onion-Shell

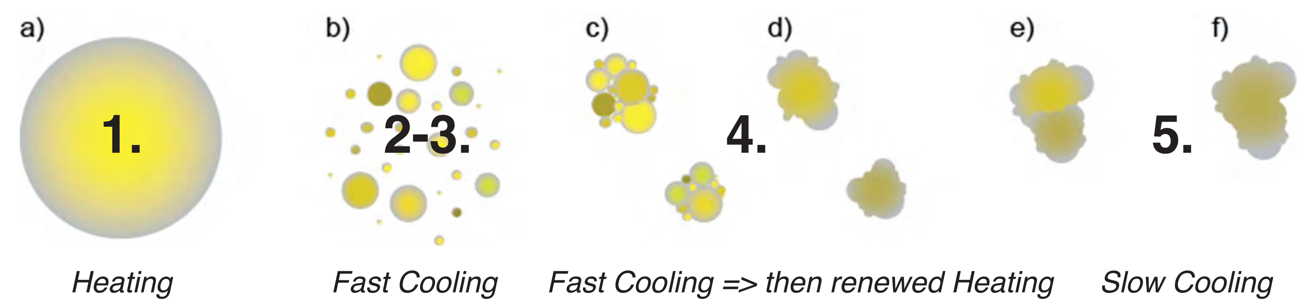


An onion-shell model for the thermal evolution of the H chondrite parent body (after [9] Miyamoto et al.,1981).

Fragmentation—Reassembly

A proposed five stage fragmentation—reassembly model for the thermal evolution of the H chondrite parent body (numerical modeling forthcoming).

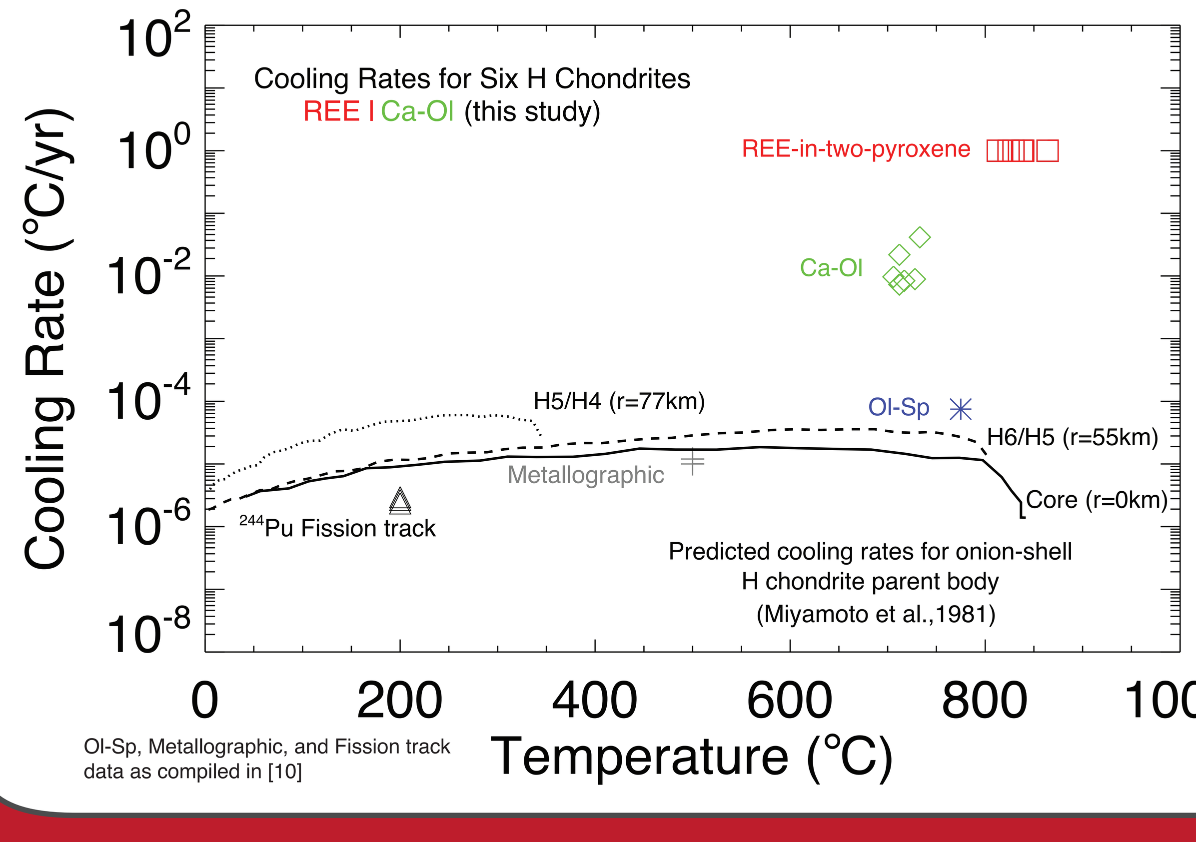
Stages:
1. Radially symmetric evolution of the initial asteroid due to heating by ^{26}Al decay
2. Collisional breakup of fragments follow scaling laws for collisional populations
3. Short cooling period (<1 yr) for collisional fragments => random reassembly
4. Post-reassembly thermal evolution and compaction of rubble pile asteroids
5. Further reassembly of small rubble piles into a larger rubble pile parent body



Takeaway: A challenge for modelers is to reconcile slow, low temperature cooling rates correlated with metamorphic grade (suggesting an onion-shell) with fast rates obtained for high temperature cooling intervals, which suggest catastrophic fragmentation of the H chondrite parent body.

Conclusions

=> Samples have equilibrated major+trace element compositions; suitable for our method.
=> REE-in-two-pyroxene method provides key near-peak temperature data.
=> T_{REE}, T_{BKN}, and Ca-Ol temperatures suggest fast cooling rates (see below).
=> **Our results suggest an early fragmentation—reassembly event, rather than** ***in situ*** **cooling at different depths in an onion-shell parent asteroid.**



Ol-Sp, Metallographic, and Fission track data as compiled in [10]

References & Funding

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