THERMAL AND IMPACT HISTORIES OF ORDINARY CHONDRITES AND THEIR PARENT BODIES: CONSTRAINTS FROM METALLIC Fe-Ni IN TYPE 3 CHONDRITES.

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Introduction: Thermal histories of ordinary chondrites (OCs) when combined with radiometric ages provide valuable constraints on the size and impact histories of their parent bodies and insights into the evolution of the asteroid belt. Radiometric ages for ten H4-6 chondrites and thermal modeling provide strong support for the onion shell model, which assumes that parent bodies were heated by ^{26}Al and cooled as totally isolated bodies [1, 2]. However, metallographic cooling rates inferred for 22 unshocked or low-shock H4-6 chondrites are incompatible with this model as three H4s cooled through 600-500°C at rates of $>10^3$ °C/Myr that vastly exceed rates calculated for onion shell bodies [3]. Cooling rate ranges for the other type 4s, H5 and H6 chondrites are all 5-50°C/Myr, and do not decrease systematically with increasing type as the onion-shell model predicts [3, 4]. Compositional studies of adjacent orthopyroxene and clinopyroxene in four H5-6 chondrites and numerical modeling give cooling rates of 25-100°C/kyr between 800 and 700°C, 10^{3-4} × higher than predicted by the onion-shell model [5].

Type 3 ordinary chondrites should have resided in the surface layer of the parent bodies throughout metamorphism according to the onion shell model. However there are few data to constrain the ages or cooling rates of type 3 chondrites. Here we present metallographic cooling rate data for H3 and L3 chondrites and combine these constraints on asteroid surfaces and structure with those derived from studies of type 3-6 material in regolith breccias.

Methods: We have studied Ni zoning in taenite grains and cloudy taenite intergrowths in H3 chondrites that are unshocked or weakly shocked (largely S1/S2). Metallographic cooling rates at 450-600°C were determined using the Wood method by analyzing the central Ni contents of taenite grains in polished sections after X-ray mapping to select equant taenite grains that were free from inclusions and had symmetric Ni zoning. Cooling rates at ~350°C can be derived from measurements of the sizes of Ni-rich particles in cloudy taenite in etched sections [6] using a FEI field emission SEM with a resolution of 1-2 nm.

Results: Wood plots of central Ni *vs.* grain radius for taenite grains in the three H3 chondrites show that the central Ni contents of zoned taenite grains, which range from 20-40% Ni, closely follow theoretical curves calculated for cooling rates of 10-100°C/Myr. Table 1 lists the inferred metallographic cooling rates and mean cloudy taenite dimensions for these chondrites and Tieschitz (H/L3.6). Comparison with our data for 24 H4-6 chondrites [3] shows that H3 chondrites have a range of cooling rates (10-100°C/Myr) that is comparable to that shown by H4-6 chondrites (5-50°C/Myr). Cloudy taenite dimensions correlate inversely with cooling rates as for the H4-6 chondrites [3] and seven groups of iron and stony-iron meteorites [7]. Cooling rates calculated from cloudy taenite dimensions for three H3 chondrites using a relationship derived from the data for the seven meteorite groups [7] are within error of metallographic rates derived from Wood plots (Table 1).

Discussion: We infer that the Wood technique is valid for type 3 chondrites even though peak metamorphic temperatures were not high enough to convert all metal to taenite (>700°C for H chondrites with 10% Ni). Calculated Ni profiles for taenite grains in chondrites are not sensitive to bulk Ni or to assumed growth mechanism. Willis and Goldstein [8] showed that cooling rates inferred from central Ni concentrations in taenite grains are very similar for bulk Ni contents of 10-30%, which correspond to kamacite nucleation temperatures of 500-700°C. In addition, spherical taenite grains in kamacite have similar Ni zoning to spherical taenite grains of constant size. Thus the Wood technique only requires that slow cooling caused Ni zoning to develop in taenite grains that were initially homogeneous and contained ≤30% Ni. The consistency between metallographic cooling rates and cloudy taenite supports this conclusion.

Many type 3.6-3.9 OCs, like ALH 77299, are fragmental breccias composed of type 3 and type 4 material [9]. However, cloudy taenite rims show that central Ni concentrations were not modified by impact reheating as this would require Ni diffusion over several micrometers. Cloudy taenite, which consists of tetrataenite-kamacite intergrowths on scales of tens of nanometers, would have been completely erased by any reheating that caused micrometer-scale Ni diffusion.

Metallographic cooling rates for H3 chondrites are not faster than the cooling rates for H4-6 chondrites, contrary to the predictions of the onion-shell model. Each type shows a range of cooling rates with little systematic difference between types. Data for Tieschitz and Mezö-Madaras show that many type 3 OCs cooled at ~2-20°C/Myr. Cloudy taenite data confirm that cooling rates at 350°C for type 3 ordinary chondrites are not consistent with onion shell models.

The onion shell model is also inconsistent with numerous other data and observations: 1) ancient impact melts like H6 Portales Valley and L chondrite impact melts, Shaw, PAT 91501, and MIL 05029 with Ar-Ar ages of 4.4-4.5 Gyr [see 10]; 2) Ar-Ar ages of unshocked or low-shock OCs apart from those studied by [1] do not correlate with petrologic type [e.g., 11]; 3) evidence for prior shock heating in S1 and S2 chondrites [12]; and 4) cooling rates of 25-100°C/kyr above 700°C inferred from compositional zoning in opx-cpx and opx-spinel [5]. Either impact heating was more important than ^{26}Al heating [13], or else impacts excavated and mixed material during metamorphism, contrary to onion-model assumptions.

Davison et al. [13] find that large projectiles would create km-sized, hot (1200-1400 K) plugs of impact material beneath impact craters in porous asteroids causing adjacent target material to cool at 1-1000 °C/Myr. Three arguments suggest that ordinary chondrites were not significantly heated by such impacts. 1) The few ancient, impact-melted chondrites crystallized rapidly. 2) H, L, and LL chondrites lack foreign impact melt clasts aside from those formed from small projectiles which cooled quickly. 3) Slowly cooled chondrites with ages of ~4 Gyr that should have been generated by major impacts during the late-heavy bombardment are not known.

We conclude that numerous impacts during metamorphism at 4.4-4.5 Gyr caused fragmentation and mixing of material from different depths in the ordinary chondrite parent bodies.

Regolith breccias: Most ordinary chondrite regolith breccias are classed as H4 or H5 chondrites but are actually composed of type 4-6 clasts in a fragmental matrix that contains a small fraction of isolated unequilibrated chondrules [e.g., 14]. A few regolith breccias have type 3 matrices and type 4 clasts (e.g., Ngawi, ALH 77299 [9]). We infer that type 3 regolith breccias formed during a brief early period when the surface layers of the parent bodies were predominantly composed of cold, loosely consolidated type 3 material with minor equilibrated material. Impacts eroded and thoroughly mixed this material throughout the asteroid, so that the surfaces of ordinary chondrite parent bodies became predominantly composed of type 4-6 material.

Studies of cooling rates of taenite grains in ordinary chondrite regolith breccias that have cloudy rims confirm that these breccias are composed of material from diverse depths [4, 15]. The total range of cooling rates in matrix grains is comparable to that observed in all petrologic types and clasts in regolith breccias. Thus impacts thoroughly scrambled the parent bodies of OCs after they cooled, possibly via catastrophic impacts that caused break-up and reassembly [4, 15]. Additional evidence for post-metamorphic impact scrambling comes from cosmic-ray exposure ages of regolith breccias [16] and the Itokawa sample, which consists largely of equilibrated LL4-6 grains with a small fraction of unequilibrated LL3 material [17]. Given that the mass of the asteroid belt was much higher during metamorphism, we should expect major impacts at that time.

Conclusion: Our studies of metal in types 3-6 OCs, those by Ganguly et al. [5], the properties of OC regolith breccias, and the thermal histories of iron and stony-iron meteorites all suggest that OC parent bodies experienced numerous impacts during metamorphism. The onion-shell model for ordinary chondrites should be abandoned.

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Table 1. Metallographic data for H3, H4-6, and other ordinary chondrites.

Chondrite	Class	Cooling rate °C/Myr	Cloudy taenite size, nm	Calc. Cooling rate[+] °C/Myr
ALH 77299	H3.7	10	90.9±2.5	13
Dhajala	H3.8	100	41.9±2.0	135
OTT 80301	H3.8	15	79.4±2.5	20
Tieschitz	H/L3.6		82.2±3.5	18
Mezö-Madaras	L3-4 br	2*		
22 chondrites	H4-6[#]	5-50	60-120	

[+] Calculated from cloudy taenite particle size and best fit to data from 7 meteorite groups [Goldstein].

[#] Excluding three H4 chondrites that cooled at >10^3 °C/Myr. * Data from Scott and Rajan (1981).