CONSTRAINTS ON THE THERMAL AND IMPACT HISTORY OF ORDINARY CHONDRITES FROM TWO-PYROXENE EQUILIBRATION TEMPERATURES.

Deon van Niekerk, Edward R. D. Scott, and G. Jeffrey Taylor, Hawai‘i Institute of Geophysics and Planetology, University of Hawai‘i at Manoa, Honolulu, HI 96822, USA dionysos@higp.hawaii.edu.

Introduction: If the parent bodies of the ordinary chondrites (OCs) had been metamorphosed by ^{26}Al and cooled without major impact disturbance they would have developed an “onion shell” structure. Radiometric ages of nine H chondrites are consistent with this model [1], whereas metallographic cooling rates of ~30 OCs are not [2, 3]. Ganguly et al. [4] used two-pyroxene (pyx) and spinel-olivine/opx equilibration temperatures, as well as modeling of Fe-Mg diffusion profiles across these phases, to argue that five H4-6 chondrites cooled at 25-100°C/kyr from peak metamorphic temperatures down to 700°C. These cooling rates are ~10^{3-4} times faster than the cooling rates derived from “onion shell” models and metallographic cooling rates at 500°C for H5-6 chondrites [3, 4]. Ganguly et al. [4] inferred that the parent body of the H chondrites was disrupted soon after peak temperatures were reached and then reaccreted after the fragments had cooled rapidly to ~700°C. All unshocked or low-shock H chondrites, except a few H4 chondrites like Forest Vale, cooled slowly at 10-100°C/Myr below ~700°C [2-4].

To further constrain the impact and thermal histories of the OC parent bodies, we have analyzed adjacent low-Ca and high-Ca pyroxene in seven H5 and H6 chondrites to determine equilibration temperatures and search for chemical zoning in high-Ca pyx that would indicate slow cooling at high temperatures at rates comparable to those recorded by metal at 500°C. We also derived approximate cooling rates directly from two-pyx equilibration temperatures using measured diffusion rates.

Methods and Results: We studied polished thin sections of seven unshocked and low-shock (S1-S3) H chondrites (Table 1). We identified co-existing low-Ca and high-Ca pyx in each, from energy-dispersive x-ray maps collected on a scanning electron microscope. We then obtained quantitative elemental analyses of pyx chemistry by using a JEOL JXA-8500F electron microprobe with 13 kV accelerating potential, a 20 nA beam current, and a 1 µm beam size. We measured 10-30 µm long compositional profiles across the contact between high and low-Ca pyx. Equilibration temperatures were determined using mean compositions of the two phases. We used the two-pyx geothermometer of Lindsley [5] applied with the improved software formulation QUILF95, by [6]. We assumed that Fe^{3+} was absent.

Table 1 lists our results. Like Ganguly et al. [4], we found uniform major element concentrations in pyroxenes. H6’s have equilibration temperatures of 870-920°C similar to those found in other H6s by [4] and [7]. Our data also support the findings of [8] and [4] that temperatures for types 5 and 6 OCs overlap.

Table 1. Two-pyroxene equilibration temperatures (°C) that were determined for seven H chondrites.

Guarena (H6)	896; 877
Mount Browne (H6)	888; 889
Butsura (H6)	873; 921
Estacado (H6)	883; 883
PortalesValley (H6)	907
Forest City (H5)	882
Ambapur Nagla (H5)	903; 943

Discussion: The Lindsley geothermometer [5] depends on the temperature sensitivity of the equilibrium compositions of coexisting high-Ca and low-Ca pyroxene. Ca concentrations of high-Ca and low-Ca pyroxene increase and decrease, respectively, with falling temperature. The calculated temperature corresponds to the lowest temperature at which equilibrium was established on cooling. Note that equilibrium temperatures were once questioned because temperatures determined from high and low-Ca pyx differed considerably. However, the improved QUILF formulation of [6], which was also used by [7], gives more consistent temperatures. Spinel-ol/opx temperatures of OCs are 150-200°C lower than nearly all two–pyx temperatures because diffusion rates are faster in these phases.

Concerns have been raised about possible effects of relict igneous zoning and submicroscopic exolution on the two-pyx temperatures temperatures of chondrites [9, 10]. However, these concerns are not relevant to type 5-6 and some type 4 chondrites, because they have homogeneous major element compositions that give consistent temperatures [4, 7].

Cooling rates. Cooling rates can be estimated from equilibration or closure temperatures using Dodson’s relationship [11] provided that diffusion rates, grain sizes and shapes are known. Ca diffuses slower than Fe and Mg in pyx, and diffusion rates are slower for high-Ca than low-Ca pyx. We therefore use the Ca diffusion rate in diopside for the fastest direction (c-axis) [12] to relate cooling rates with two-pyx closure temperatures (Fig. 1). We assumed spherical grains 15 µm in radius. Doubling or halving the radius reduces or increases the corresponding cooling rate by a factor of 2-4.

Figure 1 shows that for chondrites with equilibrated pyx compositions, cooling at 5-100°C/Myr should generate two-pyx closure temperatures in the range ~600-700°C. Closure temperatures of 850-950°C (as in Table 1) correspond to cooling rates of ~10-100°C/kyr.

In the case of undisturbed cooling, as in the "onion shell" model, we expect to find that the most metamorphosed type 6 chondrites have the slowest cooling rates and lowest equilibration temperatures. Onion shell thermal models for H OC parent bodies predict that most material will cool through 500°C at rates of 5-100°C/Myr with the slowest cooled type 6 materials located at the greatest depth [e.g. 3]. Therefore types 4 to 6 in such bodies should have two-pyx closure temperatures that are inversely correlated with type: ~700°C for type 4 and ~600°C for type 6.

As a rough check on the plausibility of our conversion of two-pyx equilibration temperatures into cooling rates, we looked at eucrite data. Two-pyx temperatures for metamorphosed eucrites range from 650-1100 °C [13, 14]. The eucrite with the highest temperature, EET 90020, cooled rapidly at more than several °C/day [14]. Eucrites that preserved their basaltic textures have equilibration temperatures of 650-800°C [13]. In addition, the unshocked cumulate eucrite Serra de Mage which appears to have cooled very slowly, has a two-pyroxene temperature of 750-800°C [13, 15]. Thus eucrite data seem roughly consistent with our conversion relationship.

Slowly cooled H5-6 chondrites should have chemically zoned pyroxene. Ganguly et al. [4] showed that Mg# values in the outermost 10 µm of high-Ca pyx grains should be up to 2% higher than core values for a cooling rate of 20°C/Myr. However, such Mg# zoning was absent in our samples, consistent with the data of [4].

The uniformly high two-pyx temperatures of 850-950°C, which we and others [4, 7] have determined for type 5 and 6 H, L, and LL chondrites, imply that they cooled at rates of ≈10-100°C/kyr from peak temperatures. These rates far exceed those attainable in a body that was heated by ^{26}Al and remained undisturbed [3][4].

Impact histories of OC parent bodies. The cooling rates of 25-100°C/kyr determined for five H chondrites from Mg# zoning in adjacent pyroxenes [4], the two-pyx equilibration temperatures of 850-950°C for ~50 type 5-6 OCs [4, 7 and this work], and the cooling rates of ≈10-100°C/kyr that we infer from these temperatures provide strong evidence that the OC parent bodies were disrupted during metamorphism into sub-km fragments. These fragments cooled in space so that temperatures did not exceed 700°C after reaccretion. All equilibrated OCs except for a few H4s were then cooled slowly at 10-100°C/Myr. If OCs are representative samples, their parent bodies were totally disrupted in the first ≈10 Myr. This history resembles that of the ureilites except that OCs were not heavily shocked during disruption. Further studies are needed to better understand these impact events and to reconcile this history with younger radiometric ages for OCs with corresponding closure ages of ~800°C [see 16].

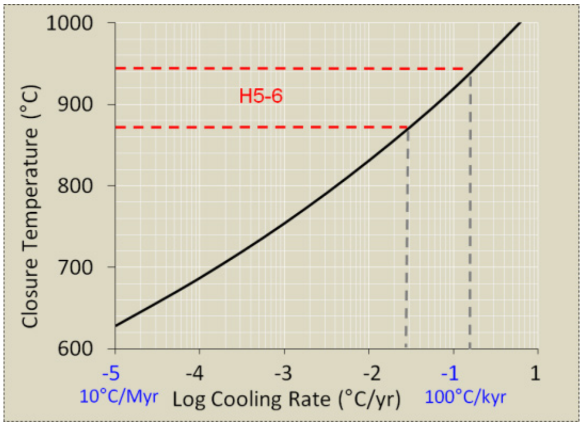

Figure 1. Relationship between closure temperature for Ca diffusion in diopside and cooling rate for grains with a radius of 15 µm derived from Dodson's equation [11]. The dashed red lines show the range of two-pyx equilibration temperatures from Table 1.

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