THERMAL HISTORY OF H-CHONDRITE PARENT ASTEROID: AN INTEGRATED MODEL SATISFYING THERMOMETRIC, DIFFUSION KINETIC AND THERMOCHRONOMETRIC DATA. J. Ganguly[1] and S. Chakraborty[2], [1]Department of Geosciences, University of Arizona, Tucson, AZ 85721 (ganguly@email.arizona.edu), [2]Institut für Geologie, Mineralogie und Geophysik, Ruhr-Universität Bochum, D-44780 Bochum, Germany (sumit.chakraborty@rub.de).

Introduction: The structure (onion-shell vs. rubble-pile) and thermal history of the parent body of the undifferentiated chondritic meteorites have been controversial. Modeling of Pb-Pb ages of phosphates [1], metallographic cooling rates [2] and thermochronometric studies [3] of samples from different metamorphic types (4-6) of unshocked H-chondrites suggest a layered or onion-shell structure of an Asteroidal parent body with a negative correlation between metamorphic grade and cooling rate. Furthermore, the cooling age vs. closure temperature (T_c) relations suggested by the thermochronometric data of the different metamorphic types seem to be compatible with the cooling limbs of the T-t paths at different depths resulting from the internal heating from ^{26}Al decay followed by conductive cooling. In this work, we have carried out detailed thermometric studies, grain-scale compositional mapping and diffusion kinetic modeling of selected samples of H4-H6 chondrite. These results reveal new features about the cooling history in the high temperature regime. We integrate these data with other constraints on cooling rates and discuss the implications for parent body prcesses.

Samples and Methods: The samples studied in this work are: Guarena (H6), Kernouvé (H6), Allegan (H5) and Forest Vale (H4). Each sample was analyzed to determine the compositions of the coexisting orthopyroxene(Opx)-clinopyroxene(Cpx),Opx-Spinel(Spnl) and olivine(Ol)-Spnl pairs and checked for the compositional zoning by step scanning at ~ 1-2 μm steps and compositional mapping in an electron microprobe. All mineral grains in each meteorite have been found to be completely homogeneous in composition. An example of compositional homogeneity is illustrated in Fig. 1. Optical examination failed to reveal any Cpx grain in any sample, but very small Cpx grains, usually a few tens of microns, have been found by careful elemental mapping in a microprobe. The "equilibration" temperatures of the Cpx-Opx, Opx-Spnl and Opx-Ol pairs have been determined using available thermometric calibrations [4.5.6] that we judged to be careful modern studies.

Results of Thermometric Studies & Diffusion Modeling: The results of thermometric studies are illustrated in Fig. 2 in terms of a plot of "equilibration" temperatures vs. metamorphic grades. The 2-pyroxene (2-Px) temperatures show a positive correlation with metamorphic grade, but Opx-Spnl and Ol-Spnl temperatures show reverse trends!

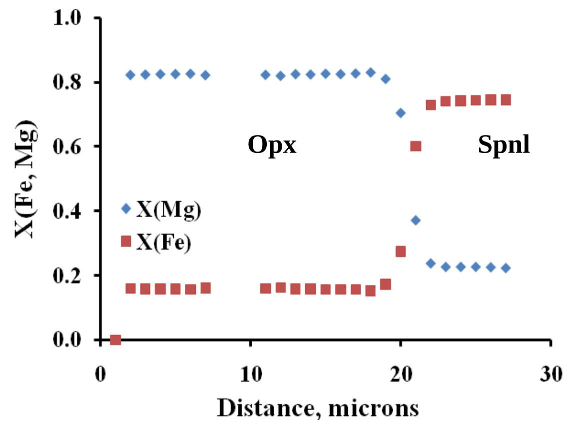

Fig. 1. Compositional profiles in coexisting Opx and Spnl in Forest Vale (H4). The apparent zoning near the interface is an artifact of convolution effect in microprobe analyses.

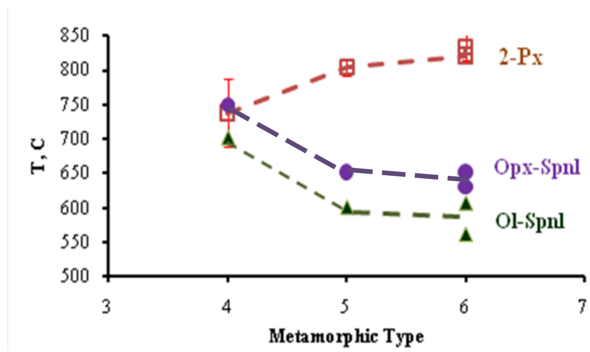

Fig. 2. Thermometric data vs. metamorphic grades of selected H-chondrites. Vertical lines: ± 1σ.

In H4 chondrite (Forest Vale), the 2-Px, Opx-Spnl and Ol-Spnl thermometric temperatures are in agreement with one another. This is expected if H4 chondrites represent near surface samples in a layered parent body and hence were cooled very rapidly. The positive trend of 2-Px temperatures vs. metamorphic grade is compatible with a layered parent body structure, but the Opx/Ol-Spnl temperatures and the homogeneity of the mineral grains cannot be explained in terms of resetting of the temperatures during cooling since there is no cooling rate that leads to the preservation of 2-Px temperatures and homgeneous pyroxene compositions and at the same time to complete resetting of the Opx/Ol-Spnl compositions. Lacking a better alternative, we tentatively suggest that the Spnl grains have recrystallized during cooling.

The preservation of high 2-Px temperatures and homogeneity of the very small Cpx grains require very rapid cooling at high temperatures, as illustrated in Fig. 3. The calculations are based on diffusion kinetic data for Mg parallel to the b-axis [7], which is the slowest diffusion direction in Cpx, and average grain radius/half-length of 50 and 100 μm. The maximum observed grain radius/half-length is ~50 μm in the plane of the thin section (some grains are even smaller).

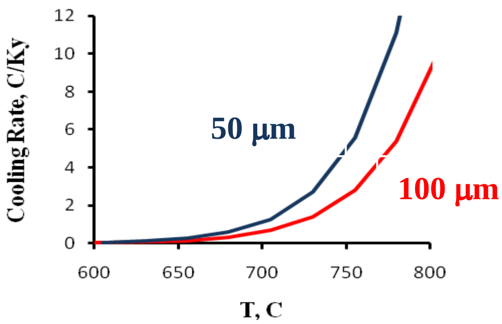

Fig. 3. High-temperature cooling rate as function of temperature required to preserve the homogeneity of Cpx of 50 and 100 μm radius/half-length.

Integration and Comparison with Other Data and Implications: Figure 4 shows the limiting T-t paths of H4 (Forest Vale) and H6 chondrites (Guarena and Kernouvé) that define the **minimum** cooling rates required to preserve the homogeneity of Spnl and Cpx compostions, resepectively, in these meteorites (the Spnl diffusion data are from [8]). These T-t paths are compared with the Pb-Pb and ^{40}Ar-^{39}Ar ages of the meteorites along with their assumed closure temperatures [3]. The dashed line shows an adjusted lower temperature limb of the T-t path that satsfy all constraints for the H6 chondrites, especially considering the uncertainties in the assumed (cooling rate independent) values of the clsoure temperatures of the thermochronometers and Ar-ages [3]. The inferred T-t paths characterized by a very rapidly cooling high temperature limb and a very slowly cooling low-temperature limb are analogous to that of mesosiderites [9]. A cooling model of this form cannot develop solely by internal heating due to ^{26}Al decay followed by static conductive cooling, as assumed earlier to construct thermal history model of the Asteroidal parent body of H-chondrites [3]. The high temperature limb of the T-t path requires a physical mechanism for rapid dispersal of heat from near the core of a mechanically coherent Asteroidal parent body.

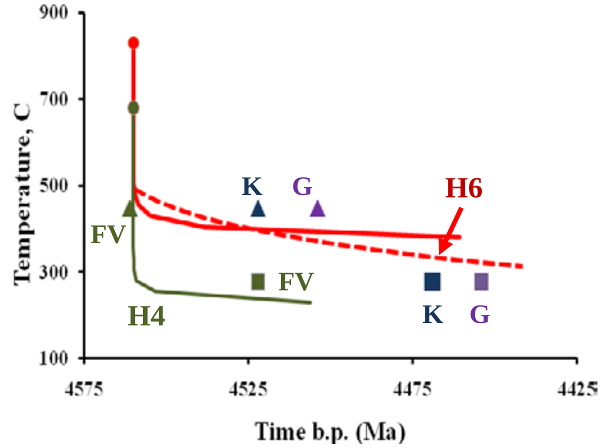

Fig. 4. Cooling models (solid lines) of H4 (Forest Vale: FV) and H6 chondrites (Kernouve: K, and Guarena: G) satisfying 2-Px temperatures (filled circles) and homogeneity of Spnl and Cpx compositions in H4 and H6, respectively. The Pb-Pb age of phosphates (triangles) and ^{40}Ar-^{39}Ar ages ages (squares), along with their assumed closure temperatures [3] are shown for comparison. The dashed line shows an adjusted lower temperature limb of the T-t path that satsfy all constraints for the H6 chondrites (see text).

A validation of the inferred rapid cooling rate at high temperature comes from the obeserved Fe-Mg **ordering state** of Opx in H-chondrites. Opx grains from the different metamorphic types (4-6) have been found to have similar closure temperatures of cation ordering that suggest similar cooling rate through the observed closure temperatures of 480-580 °C [10]. Preliminary calculations suggest cooling rates of several degrees/Kyr between T_o and T_c(ord), which is in agreement with the cooling rate in Fig. 3, but cannot be reconciled with the model of internal heating from ^{26}Al decay, followed by static conductive cooling [3].

References: [1] Ganguly J. and Tirone M. (2001) *Meteoritics & Planet. Sci.*, *36*, 167-175 [2] Lipschutz M.E. (1989) In: *Asteroids* (eds. Brinzel et al.) pp. 740-778. [3] Trieloff M. (2003) *Nature*, 422, 502-506. [4]Anderson D.J. et al. (1993) Comp in Geosciences 19, 1333-1350 [5] Liermann H-P and Ganguly J. (2003) *CMP*, 145, 217-227. Erratum (2007) *CMP*, 154, 491. [6] Ballhaus C. (1991) *CMP*, 107, 27-40. [7] Zhang X-Y et al. (2010) *CMP*, 159, 175-186. [8] Liermann H-P and Ganguly J (2002) *GCA* 66, 2903-2913. [9] Ganguly J. et al. (1994) *GCA*, 58, 2711-2723. [10] Folco et al. (1996) *MAPS.*, *36*,388-393.