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Breakup and Structure of an *H*-Chondrite Parent Body: The *H*-Chondrite Flux over the Last Million Years

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Induced thermoluminescence (TL) measurements have identified a subset of Antarctic *H* chondrites which have significantly higher induced TL peak temperatures than other Antarctic *H* chondrites or modern falls. This group was not produced by weathering or shock, but appears to have been produced by differences in thermal history. This group also consists of meteorites with ~8-Myr cosmic ray exposure ages and relatively large $^{3}He/^{22}Ne$ and $^{21}Ne/^{22}Ne$ ratios suggestive of small degrees of shielding compared to other Antarctic and non-Antarctic *H*-chondrites. Metallographic cooling rate determinations confirm the unusual thermal history of this subset, *H*5 chondrites in this subset having cooling rates of ~100 °C/Myr, compared to ~10–20 °C/Myr for other H5 chondrites.

Possible origins for this unusual subset include formation in a near-surface layer on a *H*-chondrite parent body, formation on a more rapidly cooling parent body which was not directly related to the parent body currently dominating the *H*-chondrite meteorite flux, or by impact processing during the 8-Myr event. Thermoluminescence data from meteorites from six Antarctic collection sites indicate that this subset dominated the *H*-chondrite flux ~300,000 years ago, but ceased to be represented in the flux ~20,000 years ago. The generally smaller size of these meteoroid bodies may have allowed them to evolve more rapidly to Earth-crossing orbits but also resulted in their rapid destruction in space. These data show that the *H*-chondrite flux has changed over a relatively short period of time in terms of average meteoroid size and thermal history.

INTRODUCTION

Over 14,000 individual meteorite fragments have been gathered in the Antarctic since the start of systematic collection by Japanese, American, and European expeditions. While this large collection has already contributed greatly to our collection and study of unusual meteorites, especially the recent discovery of lunar meteorites (Yanai and Kojima 1991), research efforts have tended to neglect the more common types of meteorites. One important question is whether the Antarctic meteorites differ significantly from their non-Antarctic equivalents (Koeberl and Cassidy 1991). It has been suggested that there are significant differences in trace element abundances between groups of equivalent meteorites from the two collections (Dennison and Lipschutz 1987, Lipschutz and Samuels 1991) and it is clear that, at least at some sites (e.g., the Allan Hills Main field), there are large differences in the *H*:*L* chondrite abundance ratio (Huss 1991). However, it has been argued that these differences are largely the result of as yet unidentified pairing (i.e., fragmentation of meteorite falls during atmospheric entry and during weathering) in the Antarctic collection (Huss 1991) and weathering over the large terrestrial ages of these meteorites (Mittlefehldt and Lindstrom 1991). The existence and nature of any differences between the two collections, aside from those imposed by weathering and pairing, is important in exploring the nature of the meteorite flux over time. The Antarctic collection provides a unique window through which the nature of meteorite parent bodies and the delivery of meteorites to Earth can be examined.

The present study grew out of the discovery of a group of *H*5 chondrites with unusual induced thermoluminescence (TL) properties in a suite of Antarctic meteorites (Haq *et al.* 1988). The induced TL properties of ordinary chondrites are entirely determined by the abundance and nature of feldspar present (Sears 1988). Weathering and shock, while able to change certain induced TL properties, do not seem to be responsible for the creation of this group. Qualitative weathering estimates do not correlate with the group identification and the removal of weathering products from Antarctic meteorites by acid washing do not yield the requisite changes in the induced TL peak temperature–peak width (Benoit *et al.* 1991); this group is not present in a suite of modern falls representing a broad range of shock facies.

In this paper we summarize new data which further characterize this unusual subset of *H* chondrites. We then discuss the broader implications of these data in regard to parent body structure and to orbital delivery mechanisms of meteorites to Earth. A preliminary report of these results appeared in Benoit and Sears (1992).

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ANALYTICAL PROCEDURES

The induced TL procedures and apparatus are described in detail in Sears (1988). We report here new induced data derived from our continuing natural TL survey of Antarctic meteorites. These data are collected under slightly different procedures, but measurement of duplicate samples from Haq *et al.* (1988) under the same procedures showed no significant differences in induced TL parameters. All TL data reported here are from a minimum of 100 mg of homogenized bulk powder of a given meteorite. We use cosmogenic nuclide abundance data reported by Schultz *et al.* (1991). We report metallographic cooling rate data for a number of Antarctic meteorites. These rates were determined by electron microprobe analyses of taenite grains using the method of Wood (1967).

One problem in all studies of Antarctic meteorites is the degree of unknown "pairing" (i.e., fragmentation of individual meteorites during their terrestrial history). Extensive effort has been made to avoid paired meteorites in this analysis. Schultz *et al.* (1991) made a number of suggested pairings within our selected samples based on cosmogenic noble gas concentrations and petrologic classifications. These suggestions were largely confirmed by induced TL measurements (Sears *et al.* 1991). However, as noted by Scott (1984) and Benoit *et al.* (1992a), accurate pairing of ordinary chondrites, which tend to be very similar petrographically, requires careful analysis of all available data. We have gathered all the relevant data, including both natural and induced TL data, noble gas isotopic ratios, and cosmogenic ^{26}Al, ^{54}Mn, and ^{36}Cl concentrations, for the meteorites in our selective database (Table I). It should be noted that the relatively large amount of data from all sources makes this one of the best characterized groups of ordinary chondrites among the large Antarctic collection.

Among the meteorites of our database, Schultz *et al.* (1991) identified five pairing groups and an additional nine meteorites which appeared to be distinct individuals. The grouping of ALHA77012, 77177, and 78076 (pairing group 1), does not appear very strong. While ALHA77012 and 77177 are fairly similar in terms of induced TL, natural TL, and noble gas isotopic ratios, they have greatly different ^{26}Al concentrations and the third member of the group, ALHA78076, has significantly different induced and natural TL values. The pairing of ALHA77259 and 78108 (group 2) was discounted by Sears *et al.* (1991) on the basis of induced TL parameters and the large difference in natural TL (10 and 61 krad, respectively) supports this idea. Pairing group 3 is also suspect because of the wide range in ^{26}Al and natural TL values for these meteorites. We would, however, suggest that the pairing of ALHA79026 and 81039 from this group is likely. Groups 4 and 5 appear to hold up under rough inspection, although the former should be considered "possible" at best. Sears *et al.* (1991) suggested three additional groups based largely on induced TL and cosmogenic noble gas data; these groups also do not fare well in the present analysis. Two of these groups (A and C) show a very large range of natural TL values and the third (B) has a large range in ^{26}Al values. There do not appear to be any new suggested pairings based on the data in Table I. The accumulated data therefore indicate that there are only a few definite pairing groups within our selective database. This point is important for the purposes of our discussion; any trends observed in our database (Table I) are *not* caused by the inclusion of many fragments of a few unusual meteorite falls.

As noted previously, the amount of data for the meteorites in our database is unusually great by the standards of Antarctic ordinary chondrite studies. In comparison, only natural and induced TL data and petrologic classifications are available for most of the ordinary chondrites in our Antarctic survey database, which will be discussed in a later section of this paper. However, the large geographic separation and the very large number of meteorites included in the survey database would argue against pairing being the sole determining factor in the observed trends.

RESULTS

We here present data for two distinct suites of Antarctic meteorites. We start by presenting TL data for a selected suite of Antarctic meteorites which has been extensively examined to eliminate pairing (Table I) and we interpret these data in light of annealing experiments. We then discuss the relationship of these data with cosmogenic nuclide abundance data and metallographic cooling rate data on the same meteorites. Finally, we present data from our much larger survey database of Antarctic meteorites, which has not been corrected for pairing.

Induced TL and Thermal History

The unusual *H*5 group is readily apparent on a plot of induced TL peak temperature verses peak width (Fig. 1a). This group forms a tight cluster with an average peak width of ~138 °C and a peak temperature between 190 and 200 °C. In contrast, induced TL data for non-Antarctic falls (Fig. 1b) cover a broad range of peak widths. Among those with peak widths <150 °C, however, none have peak temperatures >185 °C. Thus, the Antarctic data form two distinct groups, one with unusually high peak temperatures (hereafter referred to as the >190 °C group) and the other with peak temperatures very similar

TABLE I

Natural TL, Induced TL Sensitivities (Relative to the Kernouve Meteorite), ^{26}Al Concentrations (in dpm/kg, Evans and Reeves 1987), Cosmogenic Noble Gas (Schultz *et al.* 1991) and ^{53}Mn and ^{36}Cl (in dpm/kg, Nishiizumi 1987) Concentrations for Antarctic Meteorites: Matched Fragments ("pairings") Suggested by Schultz *et al.* (1991) and Sears *et al.* (1991) Are Indicated.

Meteorite	Class.	Nat. TL (krad)	Induced TL (Kernouve = 1)	3He/ 21Ne	22Ne/ 21Ne	^{26}Al	CRE* (Ma)	Pair[a]	^{53}Mn	^{36}Cl
<190 °C group:										
ALHA76008	H6	10.3+-0.1	0.16+-0.02	3.76	1.08	11+-1	1.94		24+3	
ALHA77004	H4	35.5+-0.3	0.048+-0.008	--	--	52+-5	--		326+13	15.2+-0.5
ALHA77012	H5	14.7+-0.1	0.15+-0.03	4.48	1.10	78+-3	50.7	1		
ALHA77014	H5	6.5+-0.1	0.037+-0.004	4.00	1.07	55+-3	22.8			
ALHA77177	H5	9.3+-0.1	0.12+-0.03	4.05	1.07	54+-3	48.1	1		
ALHA77258	H6	48+-1	0.150+-0.006	--	--	29+-2	--		434+18	12.2+-0.4
ALHA77294	H5	32.3+-0.3	0.29+-0.04	4.20	1.09	63+-2	28.8	A	433+17	20.8+-0.6
ALHA78076	H5	58+-2	0.37+-0.01	4.15	1.07	52+-4	53.4	1+		16.9+-0.5
ALHA78102	H5	23.4+-0.4	0.31+-0.05	--	--	35+-3	--		327+37	14.0+-0.6
ALHA78111	H5	0.8+-0.1	0.20+-0.05	4.57	1.08	53+-3	29.3	A		
ALHA78115	H6	48+-2	0.60+-0.06	5.77	1.12	43+-3	52.9		334+14	21.6+-0.6
RKPA79004	H5	35+-2	0.23+-0.05	--	--	45+-3	--	B		
RKPA80233	H5	15.3+-0.1	0.13+-0.03	--	--	67+-4	--	B		
>190 °C group:										
ALHA77182	H5	0.6+-0.1	0.23+-0.02	6.15	1.18	44+-9	17.9			12.9+-0.6
ALHA77259	H5	9.9+-0.1	0.065+-0.007	6.34	1.22	49+-2	10.5	2+		
ALHA77262	H5	65+-3	0.14+-0.02	4.86	1.11	47+-5	8.5		353+-19	22+-2
ALHA77274	H5	27+-0.4	0.20+-0.04	4.23	1.08	53+-2	4.7			
ALHA78075	H5	10.6+-0.1	0.08+-0.01	5.90	1.13	49+-3	8.5	3		
ALHA78108	H5	60.6+-0.3	0.056+-0.012	5.19	1.40	55+-3	7.2	2+		
ALHA79026	H5	< 1	0.32+-0.04	5.81	1.13	60+-4	8.3	3		
ALHA79029	H5	67.0+-0.4	0.068+-0.008	5.33	1.13	49+-3	6.6	4		
ALHA79046	H5	37.9+-0.1	0.33+-0.05	**	**	50+-3	8.7	5		
ALHA80132	H5	1.2+-0.1	0.34+-0.08	5.50	1.19	58+-3	7.1			
ALHA81015	H5	35+-3	0.045+-0.006	**	**	--	9.4	5		
ALHA81039	H5	2.5+-0.1	0.27+-0.05	5.59	1.14	56+-2	8.7	3		
ALHA82102	H5	119+-2	0.25+-0.05	6.01	1.16	39+-2	6.6	4		
EETA79007	H5	72+-1	0.074+-0.024	--	--	47+-3	--			
RKPA80220	H5	130+-2	0.15+-0.02	--	--	--	--	C		
RKPA80230	H5	32.5+-0.1	0.20+-0.03	--	--	--	--	C		

[a] Suggested pairings based on cosmogenic noble gas contents (numbers, Schultz *et al.* 1991) and on induced TL measurements (letters, Sears *et al.* 1991).

* Cosmic ray exposure ages based on ^{3}He, ^{21}Ne, and ^{38}Ar concentrations (Schultz *et al.* 1991).

\+ The TL data of Sears *et al.* (1991) do not support pairing of ALHA77012 and 78076 or ALHA78108 and 77259.

** These meteorites contain solar gases. Cosmogenic nuclide ratios cannot be calculated.

to non-Antarctic *H* chondrites[1] (<190 °C group). Dennison and Lipschutz (1987) have documented differences in trace element concentrations between Antarctic and non-Antarctic *H* chondrites which might be related to the above groups. It is clear from our non-Antarctic data that shock does not increase peak temperatures among those meteorites with peak widths <150 °C. Petrographic observations on a subset of meteorites from Fig. 1a (Table II) indicate that there is no tendency for meteorites which have experienced higher degrees of shock to be found preferentially in one group. In addition, it is apparent from the induced TL data (Table I) that very heavy shock is not responsible for the creation of the >190 °C group. Very large degrees of shock convert the feldspar phosphors to nonluminescent glass and thus significantly lower TL sensitivity (Haq *et al.* 1988). The average TL

[1] The non-Antarctic meteorites or "modern falls" are defined in this paper to include only observed historical falls. Non-Antarctic finds are not included in this database.

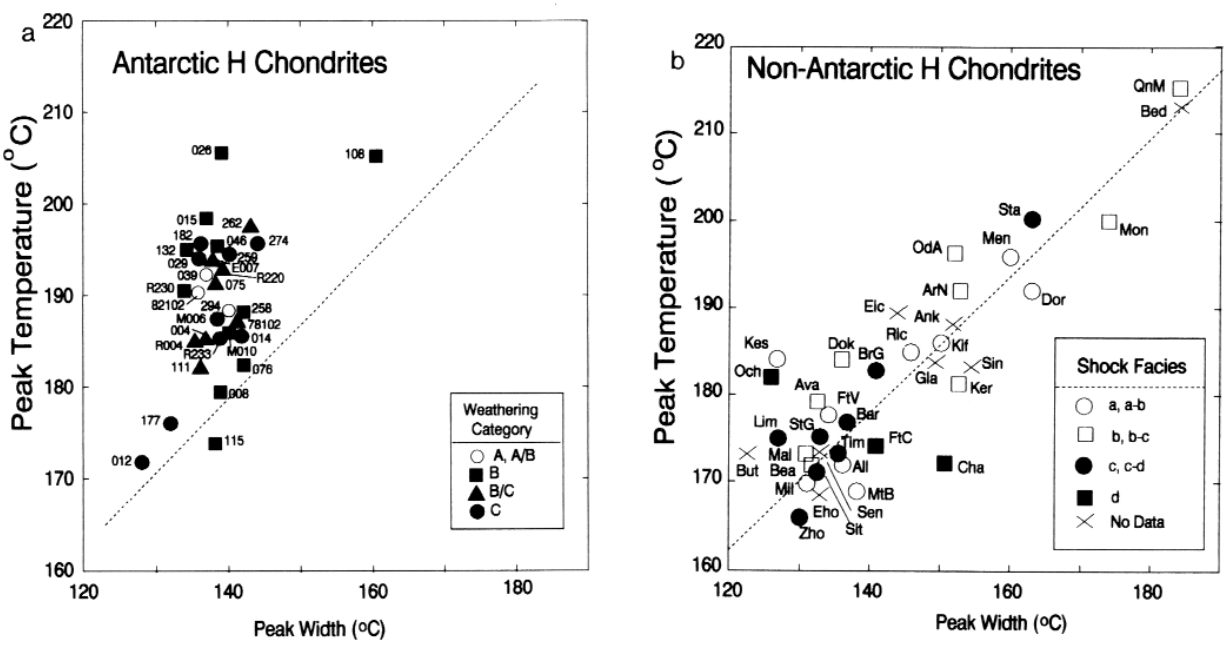

FIG. 1. (a) Induced TL peak temperature vs peak width for a suite of 31 Antarctic *H* chondrites. Data are from Haq *et al.* (1988). Data are coded according to weathering category (A = least weathered) as determined by naked eye assessment. (b) Equivalent data for 37 non-Antarctic (i.e., modern falls) *H* chondrites. Data are coded according to shock facies determined from petrographic criteria (Dodd and Jarosewich 1979). Dashed line is regression line through the non-Antarctic data. Note presence of cluster of Antarctic meteorites with peak temperatures >190 °C which do not appear to be the result of either weathering or shock.

TABLE II

Induced Thermoluminescence Peak Temperatures and Widths and Metallographic Cooling Rates for 13 Antarctic Meteorites

Name, Class., Weathering Cat.*			Shock Type§	---Induced TL+---- Peak Temp.(C)	Peak Width(C)	Metal. Cooling Rate(K/My)**
ALHA76008	H6	B	S3	180+-2	140+-2	5
ALHA77012	H5	C	S3	172+-3	128+-3	10
ALHA77014	H5	C	S4-5	186+-5	139+-2	2
ALHA77182	H5	C	S2	195+-11	136+-2	n.d.
ALHA77262	H4	BC	S3	197+-3	143+-2	~100
ALHA77274	H5	C	S3	195+-4	144+-4	100-200
ALHA77294	H5	A	S3	188+-2	140+-3	20-30
ALHA78076	H6	B	S3	182+-2	142+-3	~10
ALHA78111	H5	B	S2	182+-3	136+-2	30-50
ALHA78115	H5	BC	S2	174+-2	138+-2	10
ALHA79026	H5	B	S4	205+-4	139+-2	200
ALHA81015	H5	B	S3	198+-2	137+-2	100
ALH 82102	H5	BC	S3	190+-6	136+-2	100

* Source for all samples: Meteorite Working Group of NASA. Classifications and weathering categories from Score and Lindstrom (1990).

+ Induced TL data from Haq *et al.* (1988).

§ Based on petrographic observations using the classification scheme of Stoffler *et al.* (1991). This system runs from S1 (unshocked) to S6 (very strongly shocked).

** Estimated from Fig. 5.

sensitivity values for the two groups are approximately the same, being somewhat lower than for non-Antarctic meteorites as would be expected for weathered meteorites (Benoit *et al.* 1991), and none of the meteorites in either group has extremely low TL sensitivity. In the subset we have examined in detail (Table II) only one meteorite, ALHA77014, has a relatively low TL sensitivity which might be partly related to shock. Meteorites with similarly low TL sensitivities are found in both groups (Table I). Finally, as will be discussed below, meteorites of both groups show concordance on metallographic cooling rate diagrams, which is not the case for heavily shocked meteorites.

Given that weathering and shock are not likely to have been responsible for the creation of the >190 °C group of Antarctic *H* chondrites, the next most likely agent is thermal history. To a first approximation, induced TL curves of ordinary chondrites can be deconvoluted into two individual curves at peak temperatures of ~150 °C and ~220 °C, which represent the low- and high-temperature forms of albitic feldspar, respectively (Fig. 2a; Guimon *et al.* 1985). By mixing these curves in various proportions, it is possible to calculate a mixing line which is fairly linear until the curve is dominated by the high-temperature (disordered) feldspar end-member (Fig. 2b). The exact place-

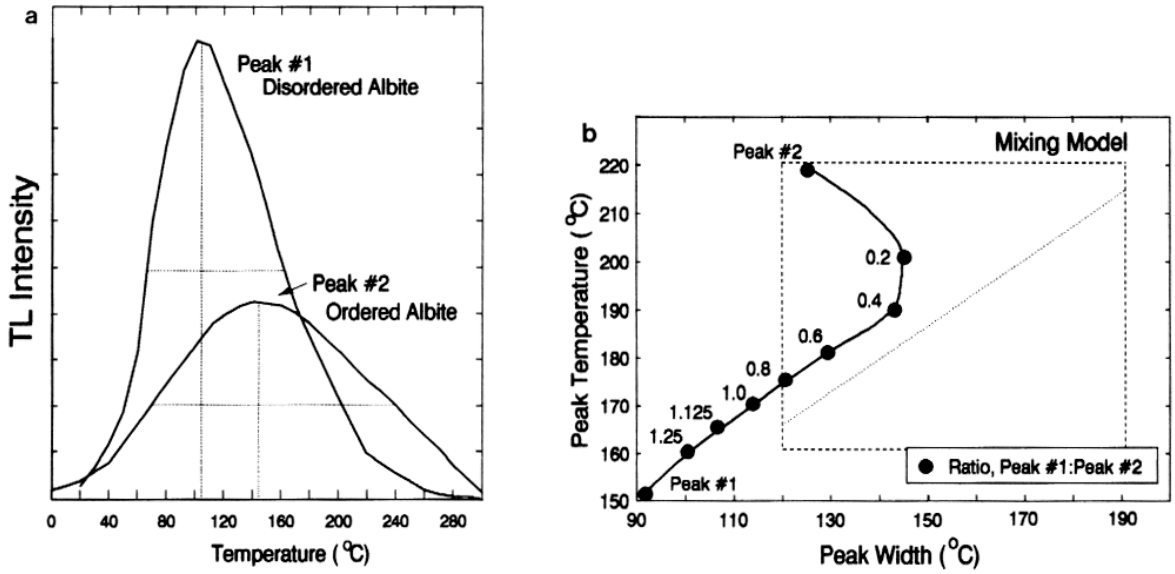

FIG. 2. (a) Induced TL glow curves used to model mixing of feldspar phosphors. Curves are based on the data of Guimon *et al.* (1985). The curves represent low (ordered) and high (disordered) temperature feldspar. Induced TL glow curves of ordinary chondrites can be modeled as mixes of these two curves. (b) Mixing line for the two phosphor end-members shown in Fig. 2a. Note that, at a high ratio of disordered to ordered feldspar, the line leaves the linear trend. Dashed box is range shown in Fig. 1; dotted line is trend for modern falls.

ment of this mixing line on the induced TL peak temperature-width diagram is largely fortuitous, given a fair degree of variation in the actual end-members. However, annealing data on the *H*5 chondrite Kernouve follow a trend very similar to the mixing line in Fig. 2b (Haq *et al.* 1988, Sears *et al.* 1991). Therefore, one way of accounting for the observed differences in the two Antarctic groups would be a greater proportion of high-temperature (disordered) feldspar in the >190 °C group than in the <190 °C group or the non-Antarctic *H* chondrites. This, in turn, would suggest significantly different thermal histories for the two Antarctic groups.

Induced TL and Cosmogenic Nuclides

We have also considered the relationship of the induced TL data to cosmic ray exposure ages for these meteorites (Sears *et al.* 1991). In principle, there is no reason to expect a direct relationship between the two parameters; induced TL properties are determined solely by petrologic criteria (e.g., feldspar chemistry/crystallography) whereas cosmogenic nuclide abundances are determined (with a few exceptions attributed to reheating) by the duration of cosmic ray exposure of the meteorite while it is part of a small (a few meters in diameter) meteoroid body in space. However, Fig. 3 shows that there is a very strong relationship between induced TL data and cosmic ray exposure age. All the Antarctic *H* chondrites of the >190 °C group have cosmic ray exposure ages of ~8 Myr. The meteorites of the <190 °C group, however, have cosmic ray exposure ages of >20 Myr. The only exception to this relationship, the *H*6 ALHA76008, has a cosmic ray exposure age of only 1.9 ± 0.1 Myr (Schultz *et al.* 1991). This meteorite also has a very low ^{26}Al activity (11 dpm/kg), which has been interpreted as reflecting both a long terrestrial age (~1.5 Myr) and a very short cosmic ray exposure age (Fireman *et al.* 1979). It has been suggested, however, that ALHA76008 has a relatively "normal" terrestrial age of 30,000–160,000 years and that it has experienced a two-stage exposure history, the first period of which was of >100 Myr duration and the second (and most recent) of only ~0.2 Myr (Nishiizumi *et al.* 1979a, b). If this is the case, ALHA76008 should be considered as a member of the >20 Myr cosmic ray exposure age group and there are no exceptions to the 8 Myr cluster in Fig. 3a.

Another application of cosmogenic nuclide data is in the determination of approximate meteoroid size during cosmic ray exposure (Graf *et al.* 1990). This can be shown graphically using the "Berne plot" of ^{3}He/^{21}Ne vs ^{22}Ne/^{21}Ne (Fig. 4a). This plot shows qualitatively the degree of "shielding" which, to a first approximation, is equivalent to the size of the meteoroid body in space. The two Antarctic *H*-chondrite TL groups show fairly good separation on this plot. The <190 °C group clusters at very low ^{3}He/^{21}Ne and ^{22}Ne/^{21}Ne ratios, indicating that

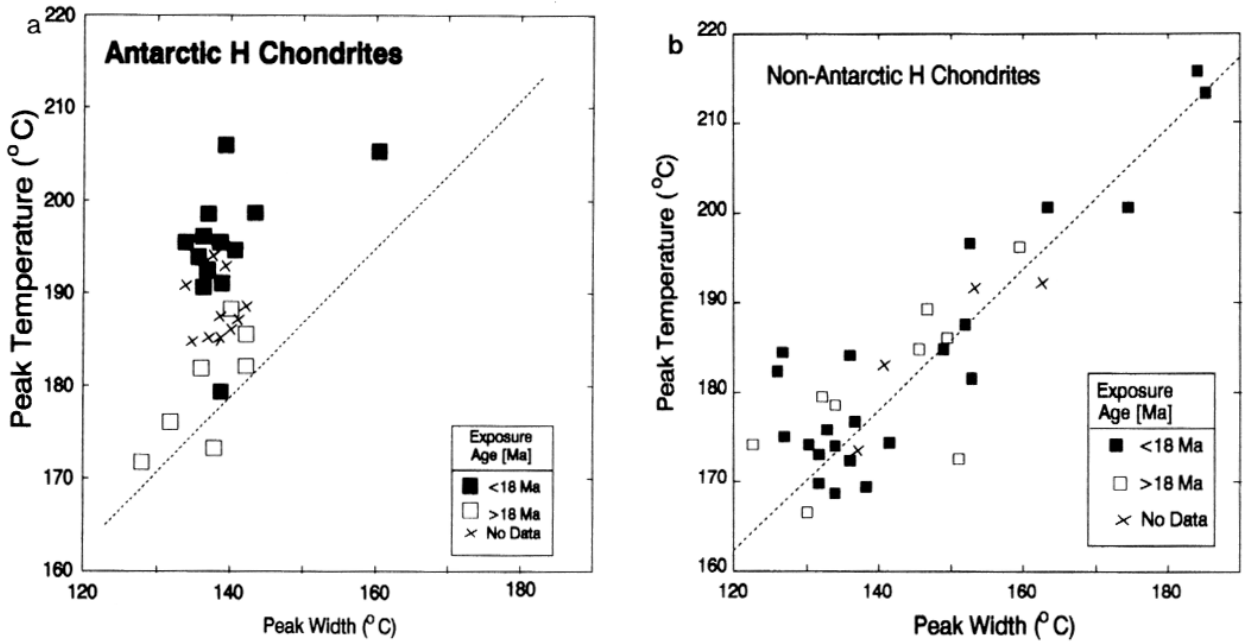

FIG. 3. Data from Fig. 1 coded according to cosmic ray exposure ages. Cosmogenic nuclide data for Antarctic meteorites from Schultz *et al.* (1991); equivalent data for non-Antarctic meteorites taken from Schultz and Kruse (1989) and reduced according to the procedures in Schultz *et al.* (1991). Note that the >190 °C group of Antarctic meteorites all have cosmic-ray exposure ages of ~8 Myr, whereas the <190 °C group are generally >20 Myr. The exception, ALHA76008, has a two-stage irradiation history.

these meteorites were relatively heavily shielded. The >190 °C group, however, has higher values of both ratios, indicating relatively small degrees of shielding. In comparison, there is no evidence for such clustering in the modern falls, which lack the >190 °C TL group (Fig. 4b). The shielding difference between the two TL groups

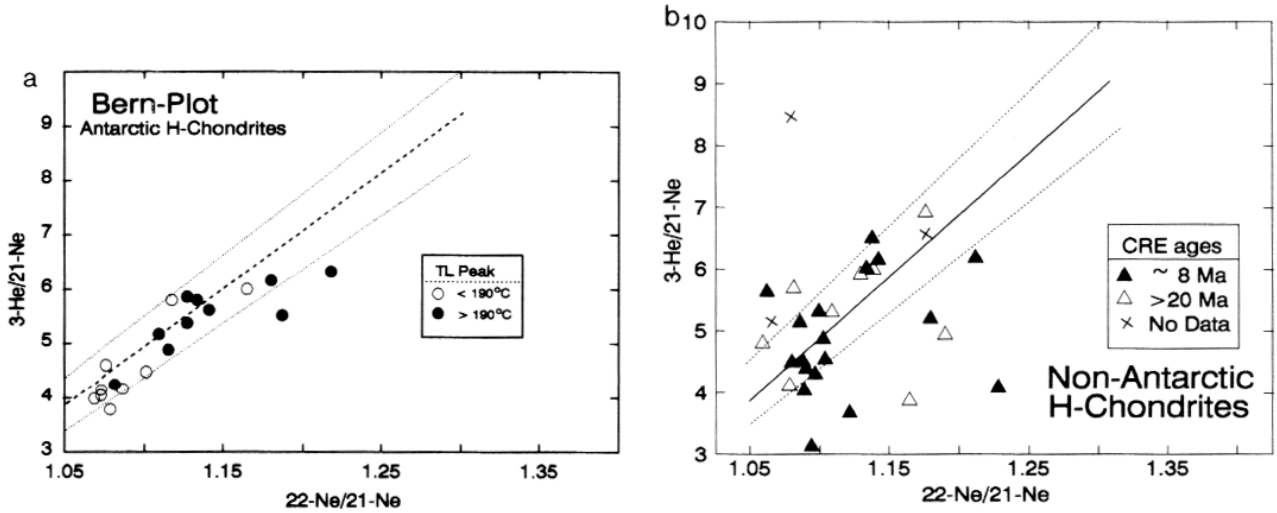

FIG. 4. $^{3}He/^{21}Ne$ versus $^{22}Ne/^{21}Ne$ ratios for (a) Antarctic meteorites and (b) modern falls for which TL data are given in Fig. 1. Shielding is greatest at lower left and least at upper right. The Antarctic data show strong clustering, with the >190 °C group, all with 8 Myr CRE ages, having the smallest amount of shielding. The modern falls, which have no >190 °C-group equivalent, show no apparent clustering. Trend and standard deviation lines for *H*-chondrites are from Nishiizumi *et al.* (1980). Antarctic cosmogenic nuclide data from Schultz *et al.* (1991); modern falls data from Schultz and Kruse (1989).

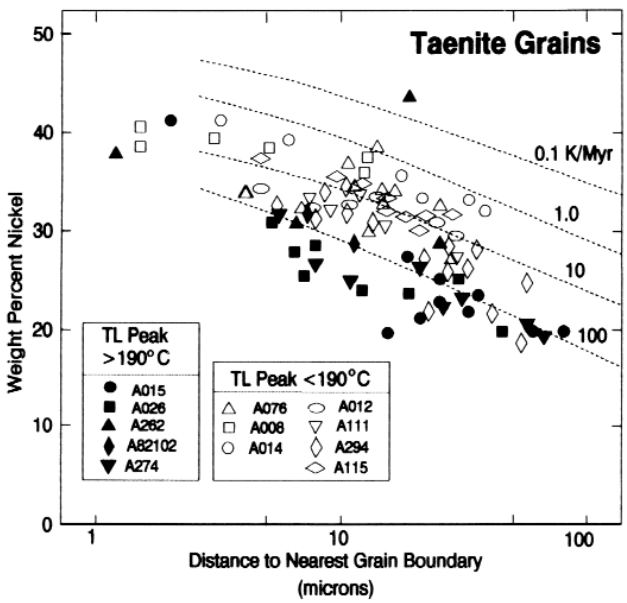

FIG. 5. Central nickel content data for taenite grains for 12 Antarctic H5 meteorites. No discrete taenite grains were found in the ALHA77182 section. Meteorites of the >190 °C group have distinctly higher cooling rates than the <190 °C group. Cooling rate lines are from Willis and Goldstein (1981). Sample names are abbreviated from listings in Haq *et al.* (1988) and Table I.

in the Antarctic database cannot be quantified with the existing data, given the insensitivity of the $^{22}Ne/^{21}Ne$ ratio at large degrees of shielding (Garrison *et al.* 1991), but could be examined by additional cosmogenic nuclide determinations [e.g., Graf *et al.* (1990)].

Metallographic Cooling Rates

In order to examine the thermal history of the unusual >190 °C group in greater detail, we have determined metallographic cooling rates for six Antarctic meteorites from the >190 °C and seven from the "normal" <190 °C group. The results are summarized in Table II and shown in Fig. 5. It is immediately apparent that the >190 °C meteorites have significantly higher cooling rates than the <190 °C group meteorites. Furthermore, the rates for the >190 °C group are significantly higher than virtually all modern *H*-chondrite falls, which have an average cooling rate of approximately 10–20 °C/Myr (Taylor and Heymann 1971, Wood 1979, Holland-Duffield *et al.* 1991, Sears and Batchlor 1991). One of the few exceptions is the *H*4 chondrite Bath, which has a metallographic cooling rate of ~100 °C/Myr (Willis and Goldstein 1981); Forest Vale [*H*4], Ste. Marguerite [*H*4] and perhaps Nadiabondi [*H*5] (Lipschutz *et al.* 1989) are also exceptions. Leighton [*H*5] (Wood 1967) is also thought to have a cooling rate of <~100 °C/Myr but it is a multicomponent breccia similar to Fayetteville and its high apparent cooling rate is at least partly the result of shock reheating. However, unlike the metallographic data for Leighton, the data for the present Antarctic meteorites form coherent trends parallel to the theoretical cooling rate/grain size lines, which is not expected if shock reheating had affected the taenite composition in these meteorites. There is no apparent relationship between shock classification and metallographic cooling rate for the meteorites in this study and, considered as a whole, these meteorites do not differ significantly in observed petrographic shock features from non-Antarctic meteorites (Stoffler *et al.* 1991).

While the two groups of Antarctic meteorites are very similar in general petrographic and bulk chemical senses, the unusual >190 °C group consistently has a much lower abundance of discrete taenite grains that the <190 °C group. Such grains *are* usually present (though rare) in the >190 °C group and have well-developed "*M*"-shaped Ni profiles but there is a strong tendency for nickel to be concentrated in tetrataenite rims on kamacite grains in these meteorites. No discrete taenite grains were found in the section of one meteorite of the >190 °C group, ALHA77182. We suggest that the lower abundance of discrete taenite grains in the >190 °C group is consistent with their extremely rapid cooling rates; cooling was sufficiently rapid to favor Ni concentration near existing metal grains rather than the formation of discrete taenite grains.

Induced TL Variations with Terrestrial Age

The Antarctic meteorite collection is important not only in the large numbers and unusual types of meteorites collected, but also in the opportunity it presents to study the meteorite flux over a time span of approximately 1 million years. We have collected induced TL data for over 800 Antarctic meteorites, largely as part of a routine survey of natural TL levels (e.g., Score and Lindstrom 1990). We will next discuss data for Antarctic *H* chondrites in light of the TL groupings identified above.

Figure 6 shows induced peak temperature–peak width data for Antarctic meteorites and modern falls, with the Antarctic data sorted by collection site. It is immediately apparent that the >190 °C group is not equally abundant at all collection sites and is, in fact, absent at two Antarctic sites, namely Meteorite Moraine and the lower ice tongue at Lewis Cliff. The >190 °C group is most abundant at the Lewis Cliff upper ice tongue and at the Farwestern field and the Main icefield at Allan Hills. Thus, the detection of the group in a suite of samples (Haq *et al.* 1988) was largely fortuitous due to the fact

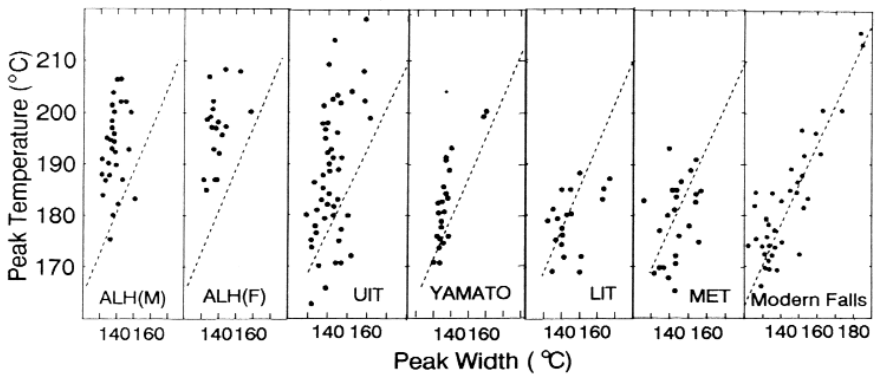

FIG. 6. Induced TL peak temperature verses peak width for Antarctic *H* chondrites for different collection sites. ALH(M) and ALH(F), Allan Hills Main and Farwestern icefields, respectively; UIT and LIT, upper and lower ice tongues at Lewis Cliff, respectively; and MM, meteorite moraine at Lewis Cliff. Dashed line is trend for non-Antarctic *H*-chondrite falls, shown at far right. Sites are arranged in approximate order of decreasing mean terrestrial age of meteorites, left to right. The >190 °C group becomes less prominent with decreasing terrestrial age.

that most of the samples shown in Fig. 1a came from the Main icefield at the Allan Hills.

There are a number of plausible explanations to explain the variable abundance of the >190 °C group between icefields. The least likely of these is that the group is solely the result of extensive pairing (i.e., the group represents only a few, nonrepresentative actual meteorites). While extensive pairing does exist at several icefields (Huss 1991), the widespread geographic distribution, the inclusion of the full range of equilibrated petrologic types, and TL pairing studies (Benoit *et al.* 1992a,b) argue against pairing as the major cause of the group's abundance. Another explanation may lie in the terrestrial age of the meteorites. The meteorites of the Allan Hills Main icefield show the greatest range of terrestrial ages of all Antarctic sites, ranging from 10,000 to 950,000 years as determined by ^{36}Cl analyses, and a significant fraction of meteorites from this field have terrestrial ages greater than 300,000 years (Nishiizumi *et al.* 1989). Similar measurements on Yamato samples yield terrestrial ages generally <100,000 years and many Yamato meteorites appear to have been on Earth for <20,000 years. While direct measurements of terrestrial ages have not yet been obtained for significant numbers of Lewis Cliff meteorites, dating of tephra bands within the ice at the lower ice tongue gives ages of approximately 20,000 years (Fireman 1990). Natural TL measurements confirm the large number of meteorites with large terrestrial ages at the Allan Hills Main icefield and suggest that the average terrestrial age of meteorites from the Allan Hills Farwestern field is also fairly large (Benoit *et al.* 1992a). While terrestrial ages for three meteorites from the Farwestern ice field range from only 9,500–21,000 years (Jull *et al.* 1989), and hence would seem to disagree with the natural TL data, it should be noted that all three are achondrites chosen for their unusual character and thus are not necessarily representative of the general meteorite population at the site. Natural TL measurements also suggest that the meteorites of the Lewis Cliff upper tongue have fairly large terrestrial ages but those from the lower tongue and Meteorite Moraine have generally small terrestrial ages (Benoit *et al.* 1992a).

Using all these data, we have arranged the various collection sites in Fig. 6 in approximate order of the mean terrestrial ages of the meteorites. We stress that this ordering is only a first approximation pending further isotopic measurements but, based on the present database, it seems highly unlikely that new data will radically alter the ranking given here.

It is apparent from Fig. 6 that the unusual >190 °C *H* chondrites decrease in abundance with decreasing terrestrial age. The group is best represented at the "oldest" sites (Allan Hills Main and Farwestern icefields and Lewis Cliff upper tongue), far less abundant at the "youngish" Yamato site, and absent at the very young sites (Lewis Cliff lower tongue and Meteorite Moraine) as well as in the modern falls. Differences in trace element concentrations between meteorites from two different regions of Antarctica seem to support this general idea, although sufficient data are not yet available to do a site by site comparison as has been done here for TL data (Wolf and Lipschutz 1992). The implications for such a dependence on terrestrial age, which is not, as mentioned above, a function of weathering, are discussed below.

DISCUSSION

We divide our discussion of these data into two separate topics, namely, the implications of these data on the structure of an H chondrite parent body and on the na-

ture of the H chondrite meteorite flux over the last million years.

H-Chondrite Parent Body Structure

It has been suggested that the *H*-chondrite parent body was not stratified during metamorphism (Scott and Rajan 1981, Taylor *et al.* 1987). This idea is supported by the lack of a correlation between metamorphic type and metallographic cooling rate in *H*-chondrite modern falls. It is clear from our present work, however, that the 8 Myr event which released many *H*-chondrite meteoroid bodies includes two types of material, at least among *H*5 chondrites. One group (represented by the modern falls and the <190 °C group of Antarctic meteorites) has "normal" metallographic cooling rates and came to Earth as predominantly large bodies. The other group (the >190 °C group) has very rapid cooling rates (~100 °C/Myr) and came to Earth as relatively small bodies. One possible interpretation of these data is that the *H*-chondrite parent body was stratified, with the >190 °C group composed of material from smaller depths than the modern falls. Using the metallographic data (Table II) and the thermal model of Wood (1967) it is possible to calculate a formation depth of ~30–40 km for *H*5 chondrites among the modern falls but a depth of only a few kilometers for the >190 °C *H*5 chondrites. While these depths are subject to assumptions concerning heat sources and heat conductivity (see Scott *et al.* 1989), they do suggest that the >190 °C group represents a near-surface layer of the parent body. In this case, it is possible that the >190 °C group was more extensively fractured by the 8 Myr impact event, thus forming smaller meteoroid bodies.

The idea of a stratified, or "onion-skin," parent body has been a recurrent one in meteorite research (see Lipschutz *et al.* 1989 for review). Evidence of such a parent body for the *H* chondrites has, however, been rather scanty. Ar–Ar ages, which are expected to be depth dependent due to their dependence on closure temperatures, are indistinguishable for *H* chondrites of all petrologic types (Pellas and Fieni 1988). The lack of a relationship with petrologic type has been attributed to the small size of the tentative parent body, which would have to be less than ~100 km in diameter to cool rapidly enough. U–Pb dating of phosphates in *H* chondrites, on the other hand, make a stronger case for a stratified parent body or bodies, with differences observed in the ages of *H*6 and *H*4–5 chondrites (Gopel *et al.* 1991). Lipschutz *et al.* (1989) have noted an apparent trend in which metallographic cooling rates for *H* chondrites are inversely related to petrologic type, which is, as noted below, the trend expected in a stratified parent body. These data, however, seem to disagree with those of Taylor *et al.* (1987). Trace element concentration correlations with petrologic type have also been noted (Lingner *et al.* 1987), but these trends are not strong and may have been obscured by secondary processing. The picture is further complicated by mixed models, in which a stratified parent body is disrupted prior to cooling below ~500 °C (i.e., before setting metallographic cooling rates) and then reassembled into a "rubble pile" (Taylor *et al.* 1987). There is thus uncertainty as to (a) whether there ever was a stratified *H*-chondrite parent body or bodies, and (b) whether this stratified body, if it did exist, disaggregated shortly after formation or only relatively recently.

If the stratified parent body model were valid, one might assume that the *H*4 chondrites would all have very high cooling rates similar to the near-surface >190 °C group of *H*5 chondrites. While TL data suggest that this is true for some Antarctic meteorites (Haq *et al.* 1988) this is clearly not the case for *H*4 modern falls, many of which appear to have "normal" cooling rates of ~10–20 °C/Myr (Lipschutz *et al.* 1989). Although Haq *et al.* (1988) only measured a few *H*6 chondrites, none of which appeared to belong to the >190 °C group, our current data (Fig. 7) show that there are a significant number of *H*6 chondrites in this group (Table III lists a few of these meteorites). If all the *H* chondrites formed in a single stratified body, this would require the unlikely situation of a rapidly cooling layer under a much more slowly cooling layer. The Antarctic *H*5 chondrites show a greater range of induced TL peak temperatures than *H*6 chondrites (Fig. 7), which *might* be interpreted as indicating that a portion of the >190 °C *H*5 group cooled at even faster rates. This would indicate that there is a continuum between the *H*5 and *H*6, with the thermal break between the >190 °C and <190 °C groups falling within the *H*6 layer. Since there is clearly a large number of *H*5 chondrites (including all the modern falls) in the <190 °C group and since there is no apparent continuum of very high induced TL peak temperatures among the *H*4 chondrites (although the database is limited by the scarcity of these meteorites), a single, layered parent body does not

TABLE III
Induced Thermoluminescence Data for Selected Antarctic H6 Chondrites Belonging to the >190 °C TL group

Name	TL sensitivity (Dhajala = 1)	Peak temp. (C)	Peak width (C)
ALH85020	1.5 ± 0.2	201 ± 4	137 ± 2
ALH85028	1.1 ± 0.1	198 ± 5	140 ± 2
ALH85030	3.7 ± 0.4	193 ± 1	137 ± 1
ALH85031	2.3 ± 0.3	197 ± 4	136 ± 2
ALH85108	1.5 ± 0.3	197 ± 7	137 ± 6
ALH85127	0.37 ± 0.04	198 ± 5	143 ± 6
ALH88047	1.9 ± 0.2	191 ± 3	137 ± 2
LEW85402	0.71 ± 0.09	214 ± 9	143 ± 1

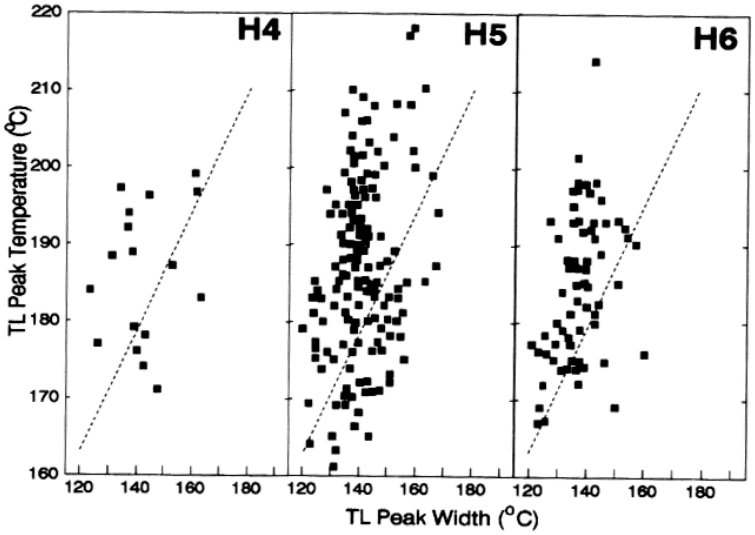

FIG. 7. Data from Fig. 6 plotted without differentiation by find site, separated according to metamorphic type. While the >190 °C group is predominantly composed of *H5*, it is apparent that types 4 and 6 are also represented.

seem likely for the *H* chondrites. It is important to remember, however, that this model is vastly oversimplified; it is quite possible that even a stratified body could have been heavily modified (by impact, for instance) during metamorphism, thus giving a range of cooling rates. The nature of the heat source (induction, internal radiation, etc.) would obviously be of major importance as well.

Another plausible model would be that there were multiple *H*-chondrite parent bodies, one of which possessed a significant amount of >190 °C material (including types 4 and 6). The other body, which might have been larger (and hence cooled slower), is the source of modern falls and a subset of the <190 °C Antarctic meteorites. One major problem with this model is the abundance of 8 Myr material from both sources; one would have to postulate that two bodies of the same class collided ~8 Myr ago, which would seem fortuitous. While no definitive chondritic asteroid bodies have yet been identified in the asteroid belt, a few having been tentatively identified among the near-Earth asteroids (Gaffey 1984, Lipschutz *et al.* 1989), it seems logical that, if there are multiple bodies, they might be located in the same region of the belt. The rarity of clasts of different classes within ordinary chondritic breccias suggests that the ordinary chondrite classes were fairly well separated in space, at least during the period of their formation (Wasson and Wetherill 1979, Scott *et al.* 1989). Thus there might be many *H*-chondrite parent bodies located in one zone of the asteroid belt; the fragments generated in a collision between two of these might then dominate the *H*-chondrite flux.

Still another plausible model would require that the 8 Myr event excavated both unusual >190 °C and normal *H* chondritic meteoroid-sized bodies from a mixed, reassembled parent like that suggested by Scott and Rajan (1981). The difficulty with this model is that the event would have to fortuitously break the >190 °C material into smaller fragments than the "normal" material and there is still the problem of a source (or sources) for the two types of *H6* and *H4* chondrites. Could the >190 °C have been *formed* during the 8 Myr event, perhaps by extensive heating (beyond the zone of detectable shock features) during a large collision? Considering that changing the feldspar ordered/disordered ratio (Fig. 2) would probably require very high temperatures (>~800 °C) which probably would have left petrographic evidence for shock-heating, this seems highly unlikely.

The present data cannot differentiate among the above models (and others not mentioned). However, they do indicate that the *H*-chondrite parent body (or bodies) was a complex entity. Any model will have to explain the presence of two very different types of material in the 8 Myr event, as well as an additional "normal" group of meteoroid bodies (a subset of the <190 °C group and some modern falls) which was produced by an impact event at least 20 Myr ago. Graf and Marti (1991), on the basis of cosmic ray exposure ages and time-of-fall data, have suggested that there are distinct differences between non-Antarctic *H5* and *H3,4,6* meteorites. They suggest that the *H5* and the *H3,4,6* meteorites with cosmic ray exposure ages of ~8 Myr were either generated in two independent collisions or produced by the colli-

sion of two *H* parents, one of which was predominantly composed of *H*5 material. While it is tempting to ascribe these differences to one of the models given above, we stress that our present database shows that most of the equilibrated non-Antarctic *H* chondrites have very similar induced TL parameters (i.e., the >190 °C group is essentially absent in this collection) and thus the present *H*-chondrite flux appears to be dominated by a single parent or at least by a single type of parent. We would also suggest that more time-of-fall data (i.e., more observed falls) are needed to better define the trends suggested by Graf and Marti (1991).

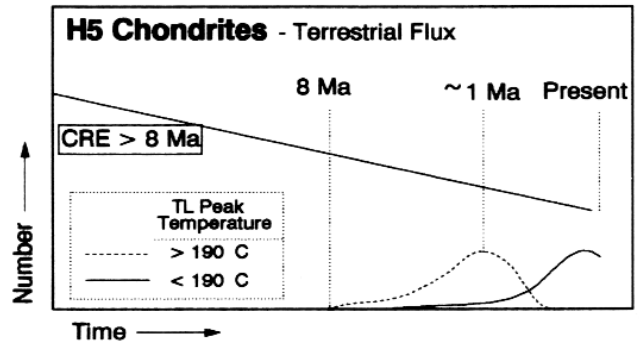

FIG. 8. Schematic diagram of the evolution of the terrestrial flux of *H*5 chondrite groups over the last ~8 million years. The 8-Myr event generated meteoroid (meter in diameter) bodies of both the >190 and <190 °C groups. The former, as smaller bodies, evolved more rapidly to Earth-crossing orbits and dominated the flux at ~1 Myr. These bodies were also more rapidly destroyed, however, and the larger bodies of the <190 °C group became the increasing dominant source of meteorites until, in modern times, they represent ~100% of all *H*-chondrite falls. A "background" level of <190 °C-group *H*-chondrites from bodies generated in earlier events (CRE ages of >20 Myr) are also present throughout this time span.

Delivery of Meteorites to Earth

Orbital calculations suggest, to a first approximation, that the meteorite flux to Earth should be fairly constant on the 10^6 year time frame (Wetherill 1986, 1989). While a meteorite "stream" (Dodd 1989; Halliday *et al.* 1990) might dominate the flux for a short period of time (~10^4 years), such a stream should not be able to survive as a distinct entity on the 10^5 year time scale after evolving to an Earth-crossing orbit. Figure 6, however, seems to show that the meteorite flux can vary over a time span of ~300,000 years. One scenario which would explain the trends in Fig. 6 is summarized in Fig. 8. Regardless of how (or where) the >190 °C group was formed, it is apparent that the 8 Myr event generated two distinctly different types of *H*5 chondrite. The >190 °C group is abundant in the older portion of the Antarctic collection (with terrestrial ages of ~300,000 Myr) but is very rare at the Yamato site (~30,000 years) and absent in modern falls. Likewise, the "normal" <190 °C group with cosmic ray exposure ages of ~8 Myr is essentially absent in the older Antarctic collection (Fig. 3) but very common in modern falls. We suggest that these data indicate that the >190 °C group dominated the *H*-chondrite flux ~300,000 years ago but decreased in abundance fairly rapidly as the <190 °C group rose in abundance (Fig. 6). Throughout this evolution there was a fairly constant input of "normal" <190 °C group meteorites with cosmic ray exposure ages >20 Myr. This scenario may also assist in explaining the results of Dennison and Lipschutz (1987), in which differences in trace element concentrations were noted between meteorites from the Allan Hills main ice field and modern falls and similarities were found between Yamato meteorites and modern falls.

It is possible that the difference in evolution between the two 8 Myr groups is related to the difference in meteoroid size in space (Fig. 4). One plausible explanation using this variable would suggest that the >190 °C group evolved to Earth-crossing orbits faster than the "normal" <190 °C group because their small size made them more susceptable to gravitationally induced orbit changes. However, the smaller size of these bodies would also make them more susceptable to destruction by the various hazards associated with inner-Solar System orbits (collisions during asteroid belt transits, planetary impact, and ejection from the Solar System). As the >190 °C group was rapidly depleted, the larger, more hardy <190 °C meteoroid bodies came to dominate the meteorite flux to Earth. It has been previously suggested that the small size of Antarctic meteorites might be the result of atmospheric passage at higher velocities than are typical for modern falls, perhaps as a result of the Antarctic meteorites being in higher inclination orbits (Dennison and Lipschutz 1989). This is not supported by the present data, which shows that the >190 °C group meteoroid bodies were smaller than those of most members of the <190 °C group (including modern falls) *prior* to Earth impact. Wasson (1990) also considered size effects in iron meteorites over time, but he attributes trends in his data as being due to a broader range of source region space being sampled by the smaller Antarctic meteorites, which might have had higher initial velocities. We suggest that size alone, perhaps linked with initial velocity differences, may be the major source of the evolutionary difference in the *H* chondrites.

CONCLUSIONS

(1) We have identified two distinct groups of *H* chondrites which have induced TL peak temperatures of >190 °C and <190 °C. Metallographic cooling rate determina-

tions confirm our suggestion (Sears *et al.* 1991) that these groups differ in cooling rates. The meteorites of the >190 °C group have cooled at very high rates (~100 K/Myr) relative to the <190 °C group. There is no evidence that the >190 °C group was produced solely by shock.

(2) The >190 °C group have cosmic ray exposure ages of ~8 Myr. Antarctic meteorites of the <190 °C group have cosmic ray exposure ages of >20 Myr. Modern *H*-chondrite falls, which are all of the <190 °C group, have cosmic ray exposure ages of 8 and >20 Myr. Cosmogenic noble gas data show that, in general, the >190 °C group meteorites were smaller (less shielded) than the <190 °C group during cosmic ray exposure in space.

(3) While the >190 °C group is not represented among modern falls, our database shows that the group's abundance is directly related to terrestrial age. The >190 °C group dominates the *H*-chondrite collection from Antarctic sites with meteorites of high terrestrial ages (e.g., ~300,000 years at Alan Hills) but is rare at sites with smaller average ages (e.g., ~30,000 years at Yamato).

(4) We suggest that the both the >190 °C group and part of the <190 °C group were produced by an impact event at ~8 Myr and that the meteorites of the >190 °C group, by virtue of their generally smaller size, evolved more rapidly to Earth-crossing orbits. Their small size made them prone to destruction and the <190 °C group came to dominate the modern *H*-chondrite flux. A subset of the <190 °C group with cosmic ray exposure ages of >20 Myr were generated in an earlier event.

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