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Geochimica et Cosmochimica Acta Vol. 55, pp. 1193–1197
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0016-7037/91/$3.00 + .00

LETTER

Evidence for differences in the thermal histories of Antarctic and non-Antarctic H chondrites with cosmic-ray exposure ages < 20 Ma

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(*Received October* 2, 1990; *accepted in revised form March* 5, 1991)

Abstract—Antarctic H chondrites show a different range of induced thermoluminescence properties compared with those of H chondrites that have fallen elsewhere in the world. Recent noble gas data of SCHULTZ et al. (1991) show that this difference is displayed most dramatically by meteorites with cosmic-ray exposure ages < 20 Ma, and they confirm that the differences cannot be attributed to weathering or to the presence of a great many fragments of an unusual Antarctic meteorite. Annealing experiments on an H5 chondrite, and other measurements on a variety of ordinary chondrites, have shown that induced TL properties are sensitive to the thermal histories of the meteorites. We conclude that the event(s) that released the <20 Ma samples, which are predominantly those with exposure ages of 8 ± 2 Ma, produced two groups with different thermal histories, one that came to Earth several 10^5 years ago and that are currently only found in Antarctica, and one that is currently falling on the Earth.

A RECENT WORKSHOP dealt with possible differences between Antarctic meteorites and those from the rest of the world (KOEBERL and CASSIDY, 1990). Differences in elemental and isotopic composition (DENNISON et al., 1986; DENNISON and LIPSCHUTZ, 1987; JAROSEWICH, 1990; GRADY et al., 1990; CLAYTON and MAYEDA, 1990) and in size and class distributions (HARVEY and CASSIDY, 1989; TAKEDA, 1990; WASSON et al., 1989) are undisputed, but the interpretations of these differences are sensitive to assumptions about weathering (CLAYTON and MAYEDA, 1990; GRADY et al., 1990; JAROSEWICH, 1990) and pairing (TAKEDA, 1990). However, some authors maintained that the differences were pre-terrestrial and the result of different populations of meteorites reaching the Earth in the past and now (CASSIDY, 1990; LIPSCHUTZ, 1990; SEARS, 1990), an idea that has met with considerable resistance.

One of the major arguments commonly used against the idea that Antarctic and non-Antarctic meteorites are sampling different cosmic populations concerns orbital evolution theories. The evolution of orbits occurs on a much slower timescale than the <1 Ma terrestrial ages of the Antarctic meteorites, which means that the meteorites would have to be coming to Earth in streams. There are theoretical arguments against meteorite streams, mainly that they are short-lived (<2 Ma, maybe as little as 0.2 Ma) compared to cosmic-ray exposure ages (WETHERILL, 1989; see also WETHERILL, 1986). However, contrary to this conclusion, there is evidence for such streams in the data for ordinary chondrites (OLSSON-STEELE, 1988; HALLIDAY et al., 1990), including H chondrites (WOOD, 1982; DODD, 1989), and lunar impacts (OBERST and NAKAMURA, 1987). Another more recent argument is that the cosmic-ray exposure (CRE) age histograms for Antarctic and non-Antarctic H chondrites are identical, including the major peak at around 8 Ma (SCHULTZ et al., 1991). This suggests that the two groups came from a single parent body that fragmented 8 Ma ago. SCHULTZ et al. (1991) also found that the Antarctic and non-Antarctic H chondrites had different distributions in ^{40}Ar data, an effect which they attributed to inferior data for the latter group of meteorites. It is also possible that the ^{40}Ar data (and possibly also the ^{4}He data; see Fig. 4 in SCHULTZ et al., 1991) may be reflecting differences in thermal history.

Our group recently published data for the induced thermoluminescence of meteorites in which we pointed out that (1) 33 Antarctic H chondrites were skewed to lower values of TL sensitivity (by about a factor of 3) relative to 41 non-Antarctic H chondrites, and (2) that the two groups of H chondrites plotted in different fields on a plot of TL peak-width against TL peak-temperature (HAQ et al., 1988). We suggested that the TL sensitivity differences reflected weathering, since acid-washing three weathered Antarctic meteorites (i.e., weathering category "C," GOODING, 1986) increased their TL sensitivity by a factor of about 3 (SEARS et al., 1982). However, this is not true for the TL peak shape parameters which acid washing shows to be unaffected by weathering. We suggested that the difference in peak-width and peak-temperature data could be of considerable significance with regard to the thermal history.

Figure 1 reproduces the HAQ et al. (1988) plots of TL peak-temperature against peak-width for H chondrites. The data for non-Antarctic chondrites (Fig. 1a) are coded according to the levels of shock experienced using the classification scheme of DODD and JAROSEWICH (1979). Non-Antarctic H chondrites plot along a statistically significant correlation line with chondrites of shock facies a–c spread along the length of the line. Ten out of eleven chondrites of shock facies c, c–d, and d plot near the main cluster of data, at the bottom of the trend. It is possible that shock has affected

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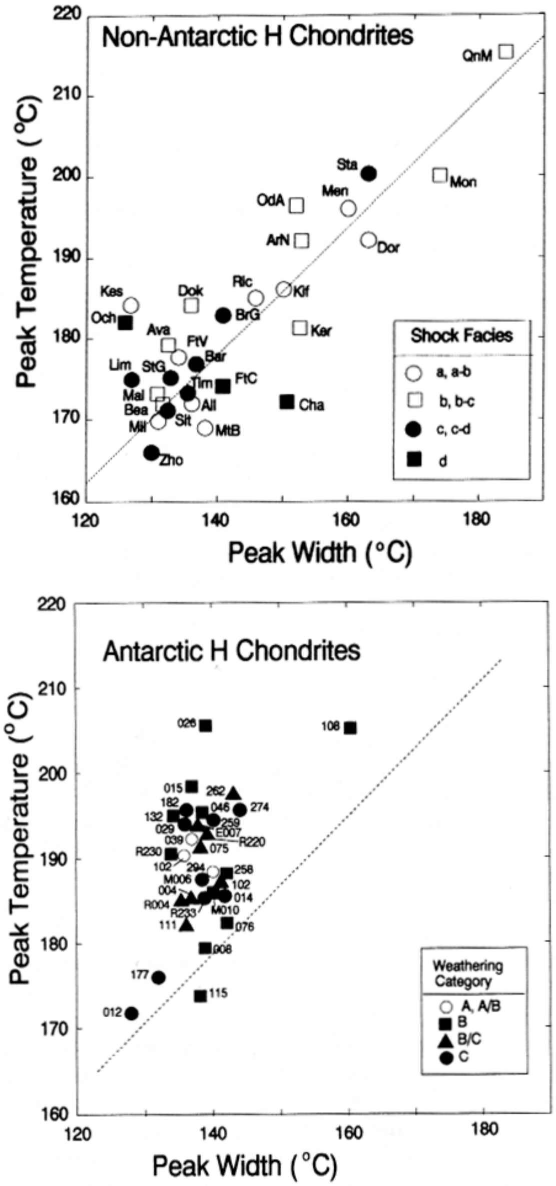

FIG. 1. Plots of thermoluminescence peak-temperature against peak-width for (a) 37 H chondrites which have been observed to fall world-wide and (b) 31 H chondrites which have been recovered in the Antarctic. Meteorites are identified by the first three letters or last three digits of the meteorite name (see Tables 2 and 3 in HAQ et al., 1986). The non-Antarctic meteorites are coded to indicate the shock facies as determined from petrographic criteria (DODD and JAROSEWICH, 1979). The diagonal line is a regression line which is also shown in Fig. 1b (data from HAQ et al., 1986). The Antarctic and non-Antarctic H chondrites show very different distributions on these plots, and the factors controlling position do not appear to be weathering or shock level.

peak shape, but there is not a simple correlation between shock and TL peak shape. Data for Antarctic meteorites (Fig. 1b) are coded according to weathering category. Category B and C samples are spread fairly uniformly, while the three category A or A/B samples are located near the center of the field. There is no indication that weathering is driving peak temperatures to higher values. We stress, however, that the weathering categories are, at best, only a rough and subjective evaluation of hand specimen appearance, and recent data (e.g., VELBEL and GOODING, 1990) shed much doubt on their value in determining degree of terrestrial alteration. We therefore return to this point below.

HAQ et al. (1988) also showed that a sample of the H5 chondrite Kernouve plotted in the main cluster of data at the bottom of the trend in Fig. 1a, and that samples annealed in the laboratory at temperatures of 500–900°C for ≤10 h, or at 1000°C for 1 or 2 h, plotted along the trend line towards higher temperature and width values (Fig. 2a). Samples annealed at 1000°C for 10, 20, and 100 h plotted off the trend line, changing little in peak-width but moving to higher peak temperatures. The data for the annealed Kernouve samples can be modelled rather well using various mixtures of two curves, one to represent the low-temperature form of the phosphor, and one to represent the high-temperature form (Fig. 2c; see GUIMON et al., 1985). The resultant curve (Fig. 2c) at first displays a correlation between TL peak-temperatures and width, and then turns up so that peaks become more narrow but continue to increase in temperature. In fact, the pattern is almost identical to the data in Fig. 2a. To some extent this agreement is fortuitous, because the curve is strongly dependent on the assumed endmembers, which are subject to considerable variations. The exact placement of the curve on the plot is therefore highly uncertain, but these calculations serve to show that peak shape differences of the sort observed could plausibly be produced by differences in thermal history. Other studies on a wide variety of meteoritic and terrestrial materials, in which feldspar is the dominant source of TL, have also shown that thermal history is the most important factor in determining induced TL peak shape (see SEARS, 1988, for a recent review). Either many of the Antarctic chondrites have experienced a different thermal history from that of non-Antarctic chondrites or these samples were pieces of a single unusual meteorite that underwent considerable fragmentation after entering the atmosphere.

There is considerable overlap between our sample data base and that of SCHULTZ et al. (1991), so that it is now possible to compare cosmic-ray exposure ages with position on our TL temperature-width plots. In Fig. 3, both plots are coded according to cosmic-ray exposure age, the cosmogenic data being taken from SCHULTZ et al. (1991) and SCHULTZ and KRUSE (1989). For the non-Antarctic H chondrites there appears to be no relationship between TL peak shape and cosmic-ray exposure age; however, this is not the case for the Antarctic H chondrites. The distribution of TL data for the Antarctic specimens might be considered as two clusters, both with peak widths of 128–144°C, but one with peak temperatures of 170–188°C and another with peak temperatures of 190–210°C. Of the 21 meteorites on this plot for which cosmic-ray exposure ages are available, all of those with ages > 20 Ma (7 samples) plot in the lower cluster, and all but one with ages < 20 Ma (13 samples) plot in the upper cluster. Weathering cannot be responsible for low cosmic-ray ages, because the cosmic-ray exposure age histograms for Antarctic and non-Antarctic H chondrites are identical and both include the 8 Ma peak. Also, NISHIIZUMI (1990) investigated the effect of weathering on cosmogenic isotopes and con-

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cluded that there was little or none. The relationship between induced TL peak shape and cosmic-ray exposure age confirms our earlier conclusion that unlike TL sensitivity the unique distribution of peak shapes for Antarctic H chondrites is not a weathering artifact.

Furthermore, these data demonstrate that neither cluster in Fig. 3b is dominated by a single meteorite which has undergone multiple fragmentation. SCHULTZ et al. (1991) considered pairing among these samples in some depth. Taking into consideration both cosmic-ray exposure age, where available, and TL peak temperature and width data within a given petrologic type, the following meteorites are almost certainly paired: ALH A78075 with ALH A81039, ALH A79046 with ALH A81015, ALH A79029 with ALH A82102, and RKP A80220 with RKP A80230 in the upper cluster and ALH A77012 with ALH A77177 and RKP A80233 with RKP A79004 in the lower cluster. We suspect that ALH A77294 and ALH A78111 might also be paired. (They have ages of 28.82 ± 1.60 and 29.33 ± 1.80 Ma, respectively, but because of the relative values of $^{3}He/^{22}Ne$ and $^{21}Ne/^{22}Ne$, Schultz and his coworkers thought pairing unlikely.) As argued by SCHULTZ et al. (1991), and confirmed here although we differ over a few details, even those samples with 8 Ma ages constitute at least six discrete falls. There are apparently around twelve discrete falls in each of the upper and lower clusters.

The H6 chondrite, ALH A76008, is an interesting special case. It is the only sample with a cosmic-ray exposure age of <20 Ma which plots in the lower cluster; according to SCHULTZ et al. (1991) it has a cosmic-ray exposure age of 1.94 ± .14 Ma. FIREMAN et al. (1979) found that this meteorite had an extremely low ^{26}Al activity (11 dpm/kg) and also thought that this reflected a large terrestrial age (1.5 Ma) and short cosmic-ray exposure age (1.5 ± 0.2 Ma). However, NISHIIZUMI et al. (1979a,b) argue that the terrestrial age of this meteorite is only 30,000–160,000 years and that the meteorite suffered a two-stage irradiation in space, the first of >100 Ma duration and the second of 0.24 ± .4 Ma.

We have, of course, considered the possibility that the trends we have observed are the result of systematic errors in the TL data, but have ruled this out with a high degree of confidence. (1) HAQ et al. (1988) used the Kernouve H5 chondrite as a day-to-day standard for TL peak temperature and width; in fact, the standard was run at the beginning and end of each day's work. (2) A spot check of these trends was made by an independent worker (Clarke Chickering) prior

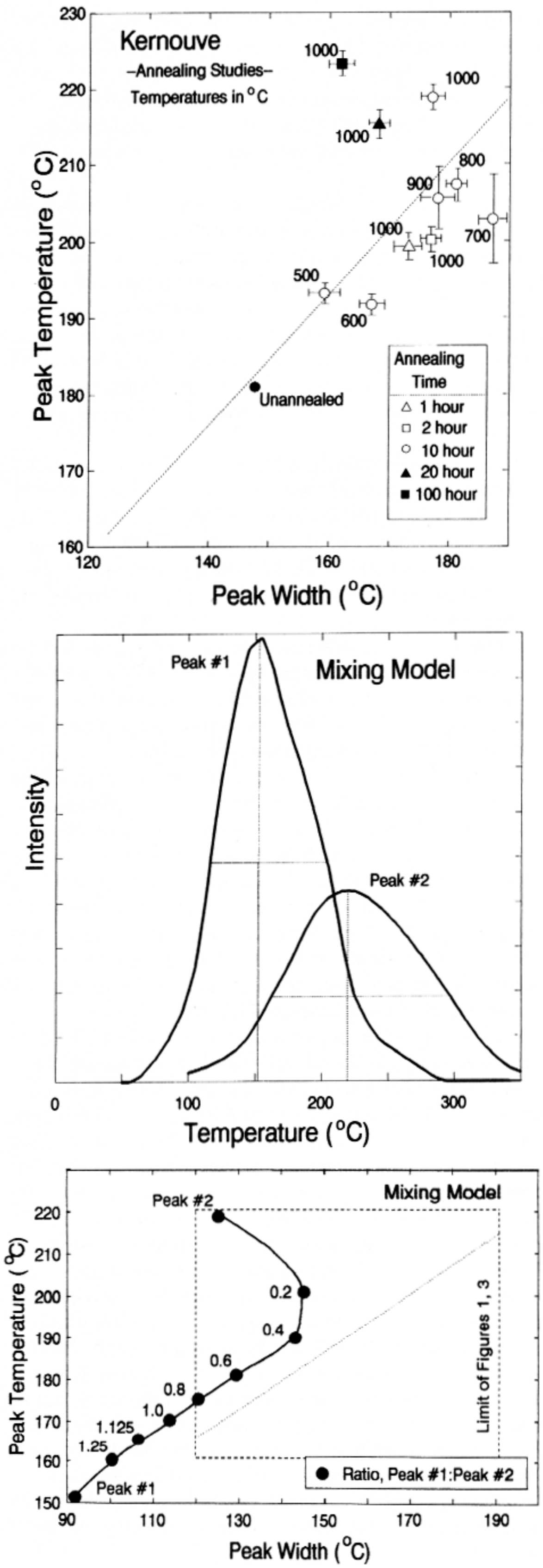

FIG. 2. (a) Data for samples of the Kernouve meteorite annealed for the times and at the temperatures indicated. The diagonal line is the regression line in Fig. 1a (these data and the experimental details were described by HAQ et al., 1986). (b) Glow curves used for the mixing model. These curves are based on those of GUIMON et al. (1985), with minor corrections to the temperature axis, for samples of the type 3 ordinary chondrite ALH A77214 before and after annealing at 900°C for 200 h. The two curves are associated with feldspar in the low and high temperature forms. (c) The TL peak-temperature vs. peak-width plot resulting from mixtures of these two annealing curves shown in (b). The inset box has the same axes as Figs. 1 and 3. The exact placing of the curve is dependent on the curves chosen for the mixing model, for which there is some uncertainty, and the slight displacement of the model curve to the left of the regression line is not significant.

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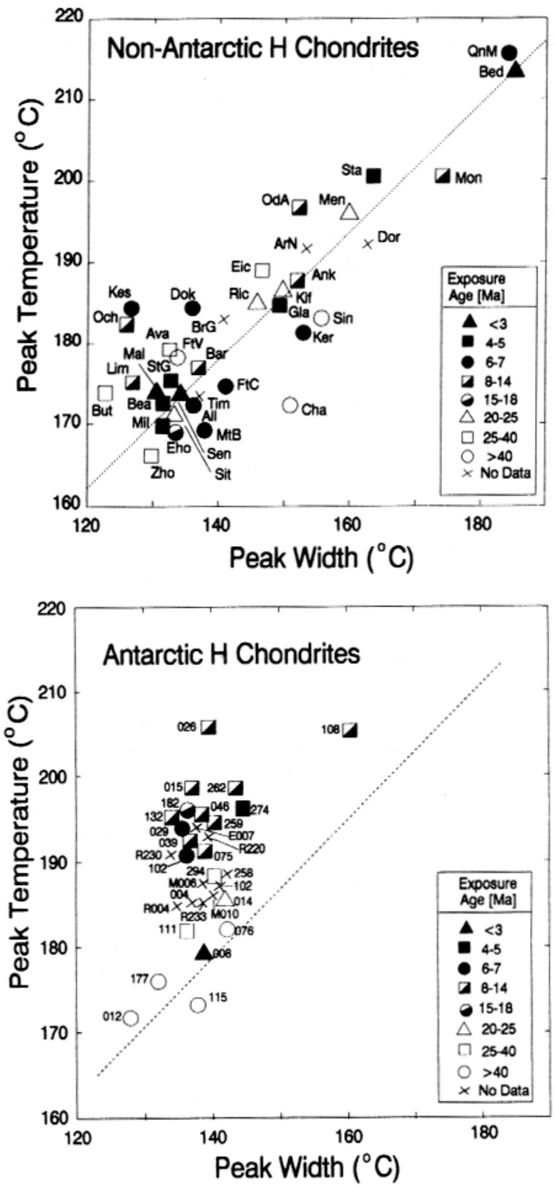

FIG. 3. Plots of thermoluminescence peak-temperature against peak-width for (a) non-Antarctic H chondrites and (b) Antarctic H chondrites. Labelling of the meteorites is described in the caption to Fig. 1. The data are coded to indicate cosmic-ray exposure age; ages for Antarctic meteorites are from SCHULTZ et al. (1991); and ages for non-Antarctic meteorites were calculated from the data of SCHULTZ and KRUSE (1989) using the methods described in SCHULTZ et al. (1991). For non-Antarctic H chondrites, there is no relationship between position on these plots and cosmic-ray exposure age, but for Antarctic H chondrites, those with cosmic-ray exposure ages < 20 Ma have higher TL peak temperatures than those with ages > 20 Ma. An exception is ALH A76008, which has a 2 Ma cosmic-ray exposure age when calculated in the normal way, but which has experienced a multi-stage irradiation involving a >100 Ma exposure age interval according to NISHIIZUMI et al. (1979a,b).

to their presentation in Vienna (SEARS, 1990). (3) The difference between Antarctic H and L chondrites also observed by HAQ et al. (1988) has appeared in other independent data sets. HASAN et al. (1987) found the same trend in their study and this was mentioned in an unpublished report (HASAN and SEARS, 1986). (4) Most importantly, we received the noble gas data of SCHULTZ et al. (1991) over three years after the TL data were gathered and about two years after the TL data were published. We do not see how we could, even unwittingly, have anticipated the cosmic-ray data when the TL data were obtained.

We are forced to conclude that Antarctic H chondrites with short cosmic-ray exposure ages (<20 Ma) have a different thermal history from non-Antarctic H chondrites or from Antarctic H chondrites with long cosmic-ray exposure ages (>20 Ma). In fact, ten of the twelve meteorites in or near the upper cluster, and for which we have exposure age data, have cosmic-ray exposure ages of 8 ± 2 Ma. It may be that all were produced by the break-up of a single object around 8 Ma ago, along with the non-Antarctic H chondrites with 8 Ma CRE.

We also conclude that meteorite streams of H chondrites have been encountered by the Earth, a conclusion shared by WOOD (1982) and DODD (1989). In fact, Wood showed that the orbital properties of H chondrites with small exposure ages differed from those with large cosmic-ray exposure ages. From the present data we infer that meteorite streams are stable for 8 Ma, maybe <20 Ma, but not >20 Ma.

The source of the differences in thermal history for the two types of material released by a single 8 Ma event is a matter of speculation. Maybe different strata of the parent body were ejected into different orbits. GREENBERG and CHAPMAN (1983) have suggested that it is primarily the nature of a few collisional events that determines the nature of the material reaching Earth. Maybe the force of ejection was responsible for the thermal history of the samples and also for the type of orbit. Step-wise heating shows that under laboratory conditions most Ar is lost at about 800°C (HAQ et al., 1988), a similar temperature to that at which major TL changes occur. Perhaps this is because both are associated with feldspar. It should be stressed, though, that in the meteorite case it is the time-temperature history that determines Ar loss and changes in induced TL properties.

It is also a plausible interpretation of the induced TL data that the Antarctic H chondrites with CRE ages around 8 Ma cooled faster after parent body metamorphism than non-Antarctic H chondrites with similar CRE ages, in other words, that the parent body was stratified with respect to thermal history. In this connection it is interesting to note that meteorites in the lower cluster have lower values of $^{3}He/^{21}Ne$ and $^{22}Ne/^{21}Ne$ than those in the upper cluster. This suggests that the samples in the upper cluster suffered less cosmic-ray shielding than the others, and that there is a relationship between thermal history and details of the break-up of the parent object. It will take many kinds of data for correct interpretation of these trends. A detailed petrographic study, looking particularly for shock and metamorphic differences, would be a reasonable start. However, our TL data and the SCHULTZ et al. (1991) data for cosmogenic isotopes show fairly clearly that there is a relationship between thermal history and cosmic-ray exposure age for the H chondrites found in the Antarctic which is not shared by the H chondrites which have fallen during the last few hundred years over the rest of the world.

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Acknowledgments—We are most grateful to Ludolf Schultz and his coworkers for sending us their most stimulating paper on cosmogenic isotope studies of Antarctic meteorites, Christian Koeberl and William Cassidy for organizing the Vienna workshop, and Michael Lipschutz for coordinating our work with that of the Mainz group. Helpful reviews were provided by Michael Lipschutz, Harry Y. McSween, and Stephen Sutton. Our work was funded by NASA grant NAG9-81.

Editorial handling: G. Faure

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