likely to be particularly useful; for example, in two-dimensional (COSY) spectra with the laser on in one time domain, we have verified that peaks are shifted in one dimension by the laser. Generalizations to multiple irradiation frequencies and other nuclear spins are also straightforward experimentally. However, much remains to be explored both theoretically and experimentally to determine the ultimate utility of this technique.

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The Breakup of a Meteorite Parent Body and the Delivery of Meteorites to Earth

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Whether many of the 10,000 meteorites collected in the Antarctic are unlike those falling elsewhere is contentious. The Antarctic H chondrites, one of the major classes of stony meteorites, include a number of individuals with higher induced thermoluminescence peak temperatures than observed among non–Antarctic H chondrites. The proportion of such individuals decreases with the mean terrestrial age of the meteorites at the various ice fields. These H chondrites have cosmic-ray exposure ages of about 8 million years, experienced little cosmic-ray shielding, and suffered rapid postmetamorphic cooling. Breakup of the H chondrite parent body, 8 million years ago, may have produced two types of material with different size distributions and thermal histories. The smaller objects reached Earth more rapidly through more rapid orbital evolution.

MORE THAN 10,000 ANTARCTIC meteorites have been collected (*1, 2*), some of them very rare and surprising types of meteorites, including meteorites from the moon (*3*). It has been suggested that there are differences, even in the most common ordinary chondrites, between Antarctic meteorites and those currently falling elsewhere in the world (*4*). These differences include elemental and isotopic composition (*5*) and the frequency of various classes and types of meteorites (*6, 7*). The interpretation of these differences is difficult, mainly because of the problems of pairing and the effects of weathering on the Antarctic meteorites, many of which have been on Earth for 300,000 years or more (*8, 9*). It has, however, been argued that differences between Antarctic and non-Antarctic meteorites should not be present, because the existence of such differences requires that the flux of meteorites impacting Earth changed, either in terms of average numbers or types, in the 10^5-year terrestrial age of the meteorites (*10*).

Another significant difference between the Antarctic and non-Antarctic collections is found in the H5 chondrites. H5 chondrites are among the most common ordinary chondrites in both collections; however, a significant proportion of the Antarctic H5 chondrites has distinctly different induced thermoluminescence (TL) properties. The induced TL properties of meteorites are determined by the amount of feldspar present and the degree of its crystallographic ordering, and hence these properties may be used as an indicator of metamorphism (feldspar growth) and extreme shock (feldspar destruction) (*11*). Figure 1 shows induced TL peak temperature versus peak width for Antarctic H5 chondrites. The Antarctic data form two distinct clusters, one at relatively high peak temperatures (hereafter referred to as the ">190°C group"). The other cluster, with lower peak temperatures (the "<190°C group"), is similar to modern non-Antarctic meteorites, which plot along the dashed line (*12*). The presence of the >190°C group among Antarctic H5 chondrites is independent of weathering and pairing (*12*). This unusual group is present only in the H5 chondrites; the other classes of ordinary chondrites (the L and LL chondrites) do not differ from their modern non-Antarctic equivalents in terms of induced TL data.

The >190°C group is not present at all the collection sites in the Antarctic. Rather, the group is best represented at sites with a significant number of meteorites with old terrestrial ages (generally >200,000 years), but the number is relatively small or absent at sites with meteorites with relatively young terrestrial ages (<100,000 years) (Fig. 2). The Allan Hills Main ice field has a large number of meteorites with old terrestrial ages [up to 300,000 years (*13*)], and natural TL data indicate that the upper ice tongue at Lewis Cliff likewise has a high proportion of meteorites with old terrestrial ages (*14*). The meteorites from the Allan Hills Farwestern ice field have not been examined in great detail, but natural TL data indicate that their average terrestrial age is similar to that of the meteorites from the Lewis Cliff upper ice tongue. The meteorites from the Yamato site have fairly young terrestrial ages [<140,000 years (*13*)]. Natural TL data indicate that meteorites from the lower ice tongue and meteorite moraine at Lewis Cliff have fairly young terrestrial ages; dating of ice bands at the former site gives ages of <30,000 years [see references in (*14*)]. These data show that the frequency of the >190°C group meteorites decreased with time and that the >190°C group is essentially absent in modern falls.

The presence of the >190°C group of meteorites in the Antarctic collection, and the reason for its unexpected temporal decay, should provide new insights into the origins of meteorites. Members of the >190°C group have cosmic-ray exposure ages of <20

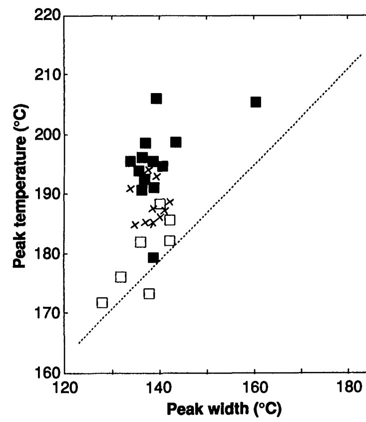

Fig. 1. Induced TL peak temperature versus peak width for Antarctic H chondrites (*12*). Exposure age: filled squares, <18 Ma; open squares, >18 Ma; ×, no data. The dashed line is the trend for non-Antarctic H chondrites (see Fig. 2). These properties are determined by the structural state of feldspar and therefore by the cooling rate after metamorphism. Two distinct groups, which have experienced different thermal histories, are apparent. Cosmic-ray exposure ages (*16*) are also different for the two groups.

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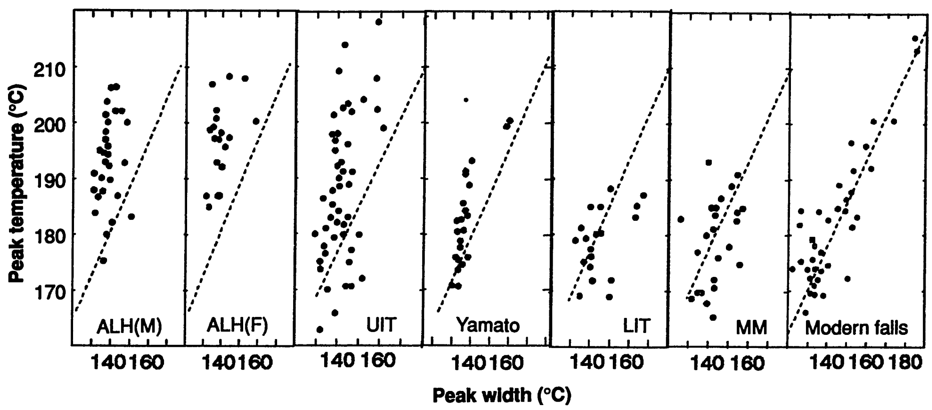

Fig. 2. Induced TL peak temperature versus peak width for Antarctic H chondrites, separated by collection site. ALH(M) and ALH(F), Allan Hills Main and Farwestern ice fields, respectively; UIT and LIT, upper and lower ice tongue at Lewis Cliff, respectively; MM, meteorite moraine at Lewis Cliff. The dashed line is the trend for non-Antarctic H chondrite falls, shown at the 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.

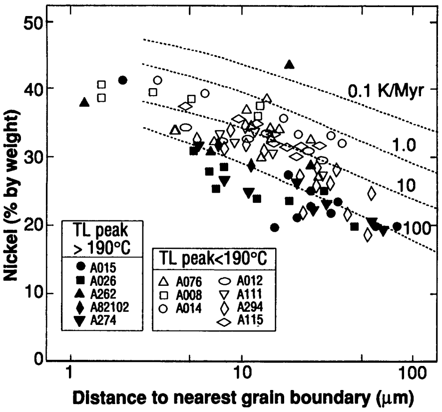

Fig. 4. Central Ni content data for taenite grains in Antarctic H5 chondrites. Cooling rate lines are from (*19*). Sample names are abbreviated from the full listing in (*12*). The two TL groups clearly have different cooling rates, and the unusual >190°C group cooled relatively rapidly.

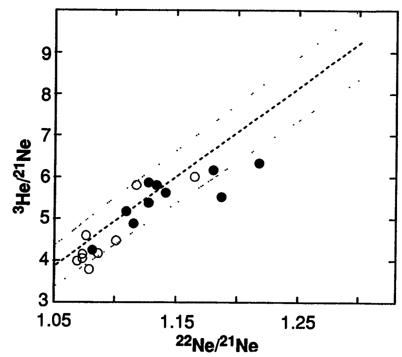

Fig. 3. The $^3He/^{21}Ne$ ratio versus the $^{22}Ne/^{21}Ne$ ratio for Antarctic H5 chondrites from Fig. 1. The dashed line is the trend line (approximate standard deviation, dotted lines) for all chondrites (*18*). These ratios are used to infer the degree of shielding during cosmic-ray exposure in space. Least-shielded samples plot in the upper right. TL peak: open circles, <190°C; filled circles, >190°C.

Ma (million years ago); most ages cluster near 8 Ma (*15, 16*). In contrast, the meteorites of the <190°C group have cosmic-ray exposure ages of >20 Ma, with the exception of one meteorite, ALHA76008, which is known to have an unusual history of radiation exposure (*15*). In addition, meteorites in the >190°C group have high $^3He/^{21}Ne$ and $^{22}Ne/^{21}Ne$ ratios (Fig. 3). These isotopic ratios provide an indication of the shielding of the meteorite during cosmic-ray exposure; values as high as those observed are usually interpreted as indicating that the original meteoroid bodies were relatively small (*16*). It therefore appears that the >190°C meteorite group was liberated, at approximately 8 Ma, as a pulse of relatively small bodies (compared to modern meteoroid bodies) that eventually struck Earth in a fairly concentrated orbital "stream."

Further constraints on the history of the >190°C group would be possible if the origin of their high TL peak temperatures could be better understood. It seems clear on the basis of annealing experiments (*12*) and numerical modeling of the shape of the glow curve (*15*) that thermal history was the major factor, involving either low-grade shock or metamorphism. To clarify the origin, we examined the Ni profiles of taenite (Ni-rich metal) grains in meteorites. Wood (*17*) showed that it is possible to determine absolute cooling rates, between approximately 200° and 500°C, by determining the Ni content of the cores of taenite grains as a function of grain size. We obtained taenite Ni profiles for six meteorites from the >190°C group and seven from the <190°C group (Fig. 4). There is a strong relation between induced TL group and metallographic cooling rates. The >190°C group clearly has a higher cooling rate, by approximately an order of magnitude, than the <190°C group. Also, taenite grains are less abundant in the >190°C group than in the <190°C group. In meteorites of the >190°C group Ni tends to be concentrated in tetrataenite rims on kamacite (Ni-poor metal) rather than as discrete taenite grains. One meteorite, ALHA77182, had no taenite grains suitable for Ni profiling; its Ni is concentrated in tetrataenite rims on both kamacite and troilite (iron sulfide). This observation is also indicative of a relatively fast cooling rate. Cooling was rapid enough to prevent or reduce Ni diffusion through the meteorites to form discrete taenite grains.

One interpretation of the differences in cooling rates between the two groups is that the >190°C group formed at shallower depths in their parent bodies than the <190°C group. For the thermal model of Wood (*17*), the cooling rates indicate that the <190°C group formed at depths of >40 km on a body (or bodies) >100 km in diameter, whereas the >190°C group formed at much shallower depths, perhaps as little as a few kilometers below the surface. These estimates are obviously dependent on assumed thermal diffusivities and the nature of the heating process and are only suggestive.

We suggest that, if the >190°C group formed at shallow depths in the source body, then it could have been extensively fractured and ejected at high velocities during the breakup event, which occurred at 8 Ma. These pieces, relatively small and numerous compared with those of the more protected interior fragments, might then have evolved to Earth-crossing orbits and dominated the meteorite flux up to approximately 200,000 years ago. However, these small bodies would have been prone to destruction by the usual mechanisms for bodies in unstable orbits [collisions in the asteroid belt, ejection from the solar system by interaction with the outer planets, as well as impact with the inner planets (*10*)], and thus their numbers might be rapidly depleted. The meteoroids of the <190°C group produced by this event, which would also have 8-Ma cosmic-ray exposure ages, also evolved to Earth-crossing orbits, perhaps more slowly than the >190°C group but were less depleted in numbers by the various mechanisms by virtue of their larger size. The <190°C group would then gradually come to dominate the terrestrial H5 meteorite flux starting about 200,000 years ago, until it represented virtually all of the meteorites among the modern falls derived from this parent body. This idea is a slight variant on the orbital dynamic model suggested by Wasson (7) to account for the high number of unusual iron meteorites in the Antarctic collection. Our data show, however, that there is also a "background" source of <190°C group H5 chondrites (for example, Fig. 1), with cosmic-ray exposure ages of >20 Ma, which might represent earlier breakup events or even fragments of a completely different parent body.

In summary, we suggest that we can now account for the origin and destruction of a large group of H5 chondrites found only in the Antarctic meteorite collection. Our data show that the terrestrial meteorite flux is not a constant. Numbers, sizes, and relative proportions of different meteorite types can change over relatively short periods of time, at least in some cases. In this light, we suggest that a more critical examination of the large Antarctic meteorite collection may well turn up more cases of temporal changes in the meteorite flux.

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Response of Regional Seismicity to the Static Stress Change Produced by the Loma Prieta Earthquake

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The 1989 Loma Prieta, California, earthquake perturbed the static stress field over a large area of central California. The pattern of stress changes on major faults in the region predicted by models of the earthquake's dislocation agrees closely with changes in the regional seismicity rate after the earthquake. The agreement is best for models with low values of the coefficient of friction ($0.1 \leq \mu \leq 0.3$) on Bay Area faults. Both the stress models and measurements suggest that stresses were increased on the San Andreas fault north of the Loma Prieta rupture, but decreased slightly on the Hayward fault. This relaxation does not warrant lower probability estimates for large earthquakes on the Hayward fault in the next 30 years, however.

THE MAGNITUDE (*M*) 7.1 LOMA PRIETA earthquake was the largest earthquake to strike the San Francisco Bay region since 1906 (*1*). In addition to radiating seismic waves, the earthquake introduced a static stress perturbation to the region as a result of its displacement, which averaged about 2 m between depths of 6 and 18 km. An immediate concern after the earthquake was the possible effect this stress perturbation might have had on other major faults in the Bay Area. On two occasions in the 1800s a large earthquake on one side of the Bay had been followed within 3 years by a second large earthquake on the opposite side (*2*). Because the Hayward fault probably ruptured on both of these occasions, the stress changes on the Hayward fault were of particular interest (*3*). To evaluate the possibility of such interactions we determined the static stress changes produced within an elastic half space by model dislocation surfaces, and compared the results to regionally observed changes in the rates of seismicity (*4, 5*).

For our stress calculations we simulated the Loma Prieta displacement at depth by a rectangular dislocation surface inferred from geodetic measurements made before and after the earthquake (*6*). Although complexities in the seismic waveforms observed during the earthquake suggest that the rupture was complex (*7*), we chose to use a simple model for initial calculations; our calculated results are least accurate in the near field (within about 40 km of the rupture surface) where the details of the slip distribution are important. In the far field, the details of the slip distribution become less important than the total moment of the earthquake and the average orientation of the rupture plane.

The major faults in the Bay Area were represented by alignments of vertical 10-km-long rectangular patches extending from the surface to a depth of 13 km (*8*). Stress changes were calculated at the centers of the patches (*9*). Both shear stress and normal stress changed on the fault surfaces as a result of the Loma Prieta earthquake. Because the major vertical Bay Area faults are probably loaded predominantly by right-lateral shear, the shear stress changes imposed by the Loma Prieta rupture can either increase (if the change is right-lateral) or decrease (if the change is left-lateral) the shear load. Laboratory studies of rock friction and failure suggest that normal forces are important in determining resistance to sliding (*10*). We defined a Coulomb failure function (*CFF*) for comparison with changes in rates of seismicity:

$$CFF \equiv |\tau| - \mu(\sigma - p) - S$$

This function is based on the Coulomb criterion for shear failure of rocks

$$|\tau| \geq \mu(\sigma - p) + S$$

where $|\tau|$ is the magnitude of shear traction acting on the plane, σ is the normal traction (positive for compression), p is the pore fluid pressure, μ is the coefficient of internal friction, and S is the cohesion (*11*). Thus changes in the *CFF* are given by

$$\Delta CFF = |\tau| - |\tau_0| - \mu(\Delta\sigma - \Delta p) - \Delta S$$

This expression is nonlinear in the changes in shear stress (*12*). It can be simplified by assuming that for vertical strike-slip faults the horizontal shear stresses are most important and that changes are superposed on a preexisting background level of right-lateral shear for most faults in the Bay Area. This leads to

$$\Delta CFF \approx \Delta\tau_{hrl} - \mu\Delta\sigma$$

where $\Delta\tau_{hrl}$ is the change in horizontal component of right-lateral shear stress (positive for more right-lateral) and $\Delta\sigma$ is the change in normal stress (positive for more compression) (*13*). We also assume here that changes in p and S are negligible.

As discussed below, a choice of $\mu = 0.2$ yielded the best agreement with observed seismicity rate changes (Fig. 1). Changes in *CFF* ranged from a few bars to less than 0.01 bar (Fig. 1). San Andreas fault segments at either end of the Loma Prieta

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