PARTICLE TRACK AND MICROCRATER RECORDS IN LUNAR SAMPLES AND METEORITES, J. N. Goswami, Univ. of Calif. Berkeley, I. D. Hutcheon, Univ. of Chicago, and J. D. Macdougall, Scripps Inst. of Oceanography.

Pre-compaction features (implanted solar wind ions, solar flare tracks, microcraters) in lunar and meteoritic breccias reflect the radiation and particle environment at different times and places in solar system history. Emphasized here are features produced $>4.2$ b.y. ago (1) in carbonaceous chondrites, and comparison with the present day lunar environment. Studies of lunar breccias, of uncertain compaction age, are in progress and should provide further evidence of possible solar flare and/or micrometeorite flux variations.

Particle track data: Olivine crystals from two Cl chondrites (Alais and Orgueil) and six C2's (Cold Bokkeveld, Haripura, Mighei, Murchison, Murray and Nogoya) have been examined. Major results are: 1) The fraction of track-rich crystals ranges from $<1\%$ to $\sim20\%$, with both Cl's showing high values relative to the C2's. 2) Roughly $25\%$ of these crystals have track gradients attributable to surface (unshielded) exposure; the steepest measured gradients are similar to those produced by present day solar flares. 3) Absolute track densities vary greatly. Fig. 1 shows some of our data. Filled circles with arrows represent maximum optically measurable densities for crystals with gradients; open circles are grains without gradients. 4) The fraction of track rich grains and absolute densities, especially in the C2's, are lower than for lunar gas-rich breccias and most other types of gas-rich meteorites.

Microcrater data: Of five track-rich grains with gradients examined from Murchison, three exhibit microcraters with diameters of 0.07-1.8$\mu$m. This is a much higher fraction than observed in lunar soil (2). Submicron craters have also been observed on a track-rich olivine from Murray. Important points of the microcrater investigations are: 1) Based on 60 craters on one Murchison crystal, the size-frequency distribution is similar to that in lunar samples (3,4), with possible depletion of craters $<0.3\mu$m. 2) Depth/diameter ($d/D$) ratios are lower than lunar values. Four well defined Murchison craters give $d/D = 0.18$ to 0.35; lunar values are mostly $>0.5$ with a peak at $\sim 0.7$ (5). 3) The crater to track density ratio [N(diam. > 0.5$\mu$m) / (at 10$\mu$m)] for Murchison is $\sim 100$ times greater than in a recently exposed lunar vug crystal (4). Measurements were made in an identical fashion by the same observer, and track gradient shapes are similar for the two crystals.

Discussion (A): Parent body regoliths. The features described above, as well as petrographic evidence, are consistent with a regolithic history for these meteorites. If Ne exposure ages are taken as upper limits for the possible regolith residence time, the track density data from Fig. 1 can be used to estimate maximum regolith thickness. In fact, since Al$^{26}$ ages are generally comparable to Ne$^{21}$ ages for meteorites unsaturated in Al$^{26}$, this is probably a large overestimate. Therefore we perform the calculation only for Nogoya and Cold Bokkeveld with low (0.15 and 0.25 m.y.) Ne$^{21}$ ages. Using the present day galactic track production rate (5) we calculate depths of $\sim 1$ cm for the crystals with lowest track densities. The existing data for Orgueil give a similar value in spite of the long (4.5 m.y.) Ne$^{21}$ exposure age.
Micrometeorite flux and impact velocity: The smooth morphology of microcraters in Murchison grains suggests that they were produced by single particle impacts. Using microcrater data in lunar pyroxene (4) and laboratory simulation data (7) as a guide, we conclude that the microcraters observed in Murchison were produced by low velocity (< 5 km/sec) impact of projectiles with density between 2.5-3gms/cc. This low impact velocity is compatible with irradiation and brecciation of C2 meteorites in the outer asteroid belt (∼ 4AU) where the expected relative velocities of asteroidal bodies is < 5 km/sec. It has previously been proposed (8,9) that the irradiation of C1 and C2 chondrites took place further away from the Sun than the gas-rich ordinary chondrites and achondrites.

Since the solar flare track density acts as an exposure-meter one can calculate the flux of micrometeorites at ∼ 4.2 b.y. ago compared to the contemporary lunar value by using the observed crater to track ratios in Murchison and lunar samples. However, the effect of low velocity impact and the radial gradient of solar flare intensity must be considered. Assuming an r^{-3} dependence of solar flare intensity (10) and using the enhancement factor of 100 for the crater/track ratio observed in Murchison, we estimate that the micrometeorite flux in the mass range > 2 × 10^{-13} gm was higher by a factor of ∼ 8-20 at 3-4 A.U. ∼ 4.2 b.y. ago, compared to the contemporary value at the moon. This estimate takes into account the differing projectile mass/crater diameter relationship for the differing impact velocities in lunar and meteoritic cases, based on laboratory data (11), and assumes constancy of solar flare activity (however, see below).

Regolith turnover rates and ancient solar flare activity: The low concentration of solar wind ions in gas rich meteorite has been attributed to fast regolith stirring or turnover (8). This implies a higher meteoritic flux. In addition, Chapman and Davis point out (12) that the flux of large bodies (< 100 km) in the asteroid belt at > 4.2 b.y. ago was probably higher by a factor of 200 than the present day value. However, as mentioned earlier, our data do not show a comparable enhancement for small (micron) size particles. The calculated flux values would be higher if the solar flare activity at > 4.2 b.y. was much higher than at present.

Another important consideration is loss of surficial material from parent body regolith. Even for a primary impact velocity of 5 km/sec a significant amount of secondary material will have a velocity greater than the escape velocity (∼ 0.1 km/sec) for a body of 150 km radius. Loss of surficial material could explain the small fraction of irradiated grains and generally lower track densities in carbonaceous chondrites compared to lunar samples.

The similarity in observed track density gradients in Murchison and Surveyor glass implies approximately the same solar flare energy spectrum at ∼ 4.2 b.y. and today. However, the similarity need not apply to intensity. In fact, our data suggest higher solar flare activity. For Cold Bookeveld (Ne^{21} age = 0.25 m.y.) track densities and gradients for some grains require irradiation between 100-400 μm from the surface during the entire exposure age, assuming a present day solar flare track production rate (4) and
a radial gradient of solar flare intensity. As explained earlier, the Ne$^{21}$ age almost certainly overestimates the regolith residence, and rapid stirring would imply even shorter surface residence times for individual grains. This requires higher solar flare intensity. Our treatment assumes a similar exposure for bulk meteorite and irradiated grains.