POST-SHOCK ANNEALING OF MIL99301 (LL6) AND IMPLICATIONS FOR IMPACT HEATING OF ORDINARY CHONDRITES. Alan E. Rubin, Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90095-1567, USA (aerubin@ucla.edu).

One of the major unsolved problems of planetary science is the identification of the mechanism(s) responsible for heating chondritic asteroids. Most researchers favor heating by the decay of the short-lived radionuclide ^{26}Al [e.g., 1,2] and have rejected collisional heating models [3]. Nevertheless, Rubin [4] inferred support for such models from the positive correlation among ordinary chondrites (OC) between petrologic type and shock stage and from the invariably high petrologic types of unmelted chondritic clasts within OC impact-melt breccias. Rubin et al. [5] modeled the Portales Valley H chondrite as an impact-melt breccia that experienced significant melting, loss of metal from silicate clasts, and formation of thick metal veins. Most of the olivine grains in Portales Valley exhibit sharp optical extinction; this is indicative of shock stage S1 and signifies that the rock experienced post-shock annealing.

I report here observations of another ordinary chondrite, MIL99301, that provides unambiguous evidence of post-shock annealing. It seems likely that the annealing experienced by this rock was caused by impact heating.

MIL99301, LL6, is a 4037-g stone that has been significantly metamorphosed. It contains recrystallized chondrules and 50-100-µm-size polysynthetically twinned plagioclase grains. Grains of metallic Fe-Ni (140±150 µm, n=50) and sulfide (90±100 µm, n=130) are similar in size to those in type-6 OC (120±150 µm and 80±60 µm, respectively) [5].

MIL99301 also exhibits numerous shock features:

It possesses extensive silicate darkening caused by curvilinear trails of small blebs of metallic Fe-Ni and troilite within silicate grains; these trails formed during shock events [6] when localized temperatures exceeded that of the Fe-FeS eutectic (988°C). There are also thin melt veins of chromite within some silicate grains, indicating that in some regions temperatures reached ≥1635°C.

Rubin [7] showed that shocked OC tend to have a high occurrence abundance [100×{(number of occurrences)/mm^2}] of metallic Cu (i.e., values ≥2.5). The occurrence abundance of metallic Cu grains in MIL99301 is 3.1.

Chromite-plagioclase assemblages appear to be shock products; they occur in Portales Valley [5], the Ramsdorf and Smyer OC impact-melt breccias [8,9] and other shocked OC (e.g., L6 Kyushu, S5 [10]; L6 Paranaiba, S6 [11]). They also occur in MIL99301.

At shock pressures of 35-60 GPa, troilite becomes polycrystalline [12]. MIL99301 contains several grains of coarsely polycrystalline troilite.

Some metal-troilite assemblages in MIL99301 contain plessite consisting of a myrmekitic intergrowth of small, irregular, wormy kamacite grains surrounded by taenite.

MIL99301 contains several coarse (100×100 µm to 30×400µm) grains of low-Ca clinopyroxene exhibiting polysynthetic twinning and inclined extinction. Such grains form by rapid cooling from high temperatures. They are abundant within pyroxene chondrules in type-3 and -4 chondrites and are absent in unbrecciated type-5 and -6 chondrites. Because MIL99301 appears unbrecciated, the presence of low-Ca clinopyroxene indicates that this LL6 chondrite was shocked and rapidly cooled after it was metamorphosed. Any pre-existing low-Ca clinopyroxene would have transformed into orthopyroxene during thermal metamorphism.

Taken together these features seem consistent with a shock stage for MIL99301 of approximately S5. Olivine grains in an S5 OC should exhibit strong mosaic extinction, planar fractures and planar deformation features [13]. Plagioclase grains should have undergone at least partial maskelynitization.

Nevertheless, nearly every olivine grain in MIL99301 exhibits sharp optical extinction. This nominally indicates that the rock is shock stage S1, i.e., unshocked by the criteria of Stöffler et al. [13]. Furthermore, plagioclase grains in MIL99301 appear crystalline, not glassy. These seemingly contradictory observations can be reconciled by modeling MIL99301 as a rock that has experienced post-shock annealing.

The first important inference from these observations is that the rock was shocked after it was metamorphosed. Grain sizes of metallic Fe-Ni and sulfide increase from type-3 to type-6 chondrites [5]. The fact that some coarse troilite grains in MIL99301 are polycrystalline indicates that they had reached their present size before the shock event. An additional piece of evidence for post-metamorphic shock is the presence of low-Ca clinopyroxene. This phase cannot survive metamorphism to type-5 or -6 levels; its presence in MIL99301 indicates that shock-heating and quenching took place after most or all of the thermal metamorphism experienced by the rock had occurred.

During subsequent annealing to metamorphic levels approximating petologic type 4, the shock-induced damage of the olivine crystal lattice must have healed [14]. Because elemental diffusion in olivine is faster than in low-Ca pyroxene, olivine grains can be healed at lower temperatures and/or shorter heating durations than those necessary to transform low-Ca clinopyroxene into orthopyroxene. Also during annealing, any maskelynite that was present must have devitrified to form crystalline plagioclase. Shock experiments demonstrate recrystallization of maskelynite over the course of a few days at temperatures of 900°C [15]; recrystallization can occur over appreciably longer times at lower temperatures.

Because annealing took place after MIL99301 was shocked (and because the meteorite was shocked after it was metamorphosed), it is unlikely that ^{26}Al was responsible for the annealing; it would have largely decayed away by this time. The sole plausible heat source is by an impact. It is possible that the same impact event that shocked MIL99301 buried the rock beneath the crater floor in the vicinity of impact melts or deposited it within a thick ejecta blanket where annealing occurred.

A reasonable extrapolation of this inference that collisional events can cause annealing would be that such events are mainly responsible for the thermal metamorphism experienced by most OC. On high-porosity bodies kinetic energy is efficiently converted into heat. Impacts into asteroidal rubble piles might deposit thick insulating layers of finely crushed debris above strongly heated target rocks, allowing deeply buried rocks to cool slowly and anneal.

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