SHOCK AND ANNEALING ON THE AUBRITE PARENT ASTEROID. Alan E. Rubin, Institute of Geophysics and Planetary Physics; Department of Earth, Planetary, and Space Sciences; University of California, Los Angeles, CA 90095-1567, USA. (aerubin@ucla.edu).

Introduction: Aubrites contain 75-98 vol.% orthopyroxene (opx) and 0.3-10 vol.% olivine (ol) [1]. Both phases could potentially be used to determine the shock stages of the whole rocks. If a different shock stage is indicated by olivine than by orthopyroxene, such a difference could provide important constraints on the geological history of the aubrite parent asteroid.

Shock Effects in Orthopyroxene: I examined 14 aubrites for this study. The majority of opx grains in most (8/14) of the aubrites are characteristic of shock-stage S4; they contain clinoenstatite lamellae on (100) and exhibit weak mosaic extinction. Although unbrecciated, LAP 02233 is more strongly shocked; its opx grains have strong mosaic extinction, characteristic of shock-stage S5. Shallowater, an unbrecciated aubrite that was probably derived from a different parent asteroid [1,2], exhibits only very weak shock effects (S2). Orthopyroxene grains in several of the aubrites exhibit a range of shock effects: ALH A78113 (S2-S5), Bustee (S3-S4), EET 90033 (S1-S4), Norton County (S1-S3).

Shock Effects in Olivine: I identified olivine grains in eight of the aubrites. In some cases, all or nearly all of the olivine grains in an individual aubrite exhibit similar optical properties to one another and are assigned to the same shock stage. These rocks include the monomict breccias ALH 83015 (S2) and Bishopville (S2) and the unbrecciated samples LAP 03719 (S1) and Shallowater (S2). In contrast, in the regolith breccias Bustee (S1-S2), Khor Temiki (S1-S2) and LAR 04316 (S2-S4), olivine grains exhibit a range of shock effects. An even larger range of inferred shock stages (S1-S4) is exhibited by olivine grains in Norton County.

In several cases, the shock-stage determined for olivine is significantly lower than that determined for orthopyroxene:

LAP 03719, an olivine-rich, unbrecciated, coarse-grained anomalous aubrite best illustrates these differences. The rock contains coarse opx grains ($Fs_{0.37\pm0.04}$ $Wo_{0.76\pm0.25}$; n=12), generally 2.5 mm – 2 cm in size, with polysynthetic twins and weak mosaic extinction (S4). Crystallographically oriented Ca-pyroxene (augite – diopside) exsolution blebs ($Fs_{0.14\pm0.03}$ $Wo_{44.4\pm0.85}$; n=12), generally 25×120 µm to 140×1200 µm in size constitute ~5 vol.% of the opx grains. In addition, the opx grains poikilitically enclose ~20 vol.% rounded olivine grains ($Fa_{0.30\pm0.03}$; n=17), typically 1 – 2 mm in diameter, with sharp optical extinction (S1). Also present in the rock are opaque inclusions up to a few hundred micrometers in size consisting of kamacite, taenite, troilite, daubréelite and ferroan alabandite [1].

Bishopville, a monomict fragmental breccia, contains 16 vol.% plagioclase ($Ab_{95}Or_{3.5}$; n=2); this is appreciably more plagioclase than in any other aubrite (~0.3-7 vol.%; [3]). Also present in Bishopville are minor diopside and troilite and accessory kamacite. The most abundant phase (75 vol.%) is orthopyroxene ($Fs_{0.03\pm0.02}$ $Wo_{1.2\pm0.29}$; n=8) containing clinoenstatite lamellae on (100) [4]; these grains exhibit weak mosaic extinction characteristic of shock-stage S4. Olivine grains (Fa 0.01 [3]), which range in size from 100 - 400 µm, constitute ~7 vol.% of the rock. Most of the olivine grains exhibit undulose extinction but lack planar fractures; this is characteristic of shock-stage S2.

Khor Temiki is a regolith breccia consisting of (in vol.%) 88% orthopyroxene, 6.6% sodic plagioclase, 1.5% diopside, 3.6% olivine, and accessory kamacite and troilite [3]. The opx grains (Fs 0.01 Wo 0.84; [3]) exhibit weak mosaic extinction characteristic of shock-stage S4; in contrast, the majority of olivine grains (Fa 0.01; [3]) have sharp optical extinction (S1). A few olivine grains show undulose extinction but no planar fractures (S2).

ALH 83015 is a poorly sorted monomict fragmental breccia that consists of large orthopyroxene grains (up to 2600 µm in maximum dimension) and smaller grains of olivine (typically 100 - 300 µm) and orthopyroxene. Also present are minor daubréelite, alabandite, metallic Fe-Ni and troilite. Most orthopyroxene grains exhibit weak mosaicism (S4); olivine grains typically exhibit undulose extinction and lack planar fractures (S2).

Aubrites with a Range of Shock Stages Exhibited by Individual Minerals: There is a range of shock effects exhibited by orthopyroxene grains in ALH A78113 (S2-S5) and EET 90033 (S1-S4) (both of which contain little or no olivine) and by both orthopyroxene and olivine grains in Bustee (opx: S3-S4 and ol: S1-S2) and Norton County (opx: S1-S3 and ol: S1-S4). ALH A78113 is a polymict breccia [5]; EET 90033 and Bustee are regolith breccias [1]; and Norton County is a fragmental breccia containing a diverse population of igneous clasts [6]. It is clear that these four rocks (a) acquired material that had been shocked to different extents from a range of sources in the regolith or mega-regolith of the aubrite parent body and (b) were not significantly annealed and equilibrated after final assembly.

Although nearly all of the opx grains in two other regolith breccias, Khor Temiki and LAR 04316, are of shock-stage S4, the olivine grains in these two meteorites exhibit a larger range of shock stages (S1-S2 and S2-S4, respectively). It seems possible that moderate annealing affected some of the olivine grains in these rocks, lowering their apparent shock stages from S4. Such moderate annealing could have left the orthopyroxene grains unaffected because of the more-sluggish diffusion rates in orthopyroxene relative to olivine [7].

Diffusion Rates and Post-shock Annealing: Olivine grains in aubrites tend to be significantly smaller than orthopyroxene grains, e.g., ~1 mm vs. ~5 mm in mean radius in LAP 03719. Diffusion times can be approximated by the equation $t = x^2 \cdot D^{-1}$ where t is the time (in seconds), x is the diffusion distance (in m s^{-1}) and D is the diffusion coefficient (in $m^2\ s^{-1}$). If, for purposes of discussion, all other parameters are considered equal, then on the basis of size alone, olivine would equilibrate about 25 times faster than orthopyroxene in LAP 03719.

A more-significant factor is the difference in diffusion rates between olivine and orthopyroxene: Fe-Mg diffusion is at least two orders-of-magnitude slower in orthopyroxene than in olivine [7]. Therefore, longer annealing times and/or higher temperatures would be necessary to heal orthopyroxene crystal lattices than those required to heal olivine lattices.

Thus, if some aubrites experienced moderate annealing, then the crystal lattices of their shock-damaged olivine grains would heal much faster than those of their shock-damaged orthopyroxene grains. This is consistent with experimental results [8,9] showing that shock-damaged olivine crystal lattices can be repaired during annealing at subsolidus temperatures.

History of the Aubrite Parent Asteroid: The presence in some aubrites of olivine grains exhibiting significantly lower shock stages than associated orthopyroxene grains suggests that aubrites have experienced post-shock, impact-induced annealing. After the aubrite parent asteroid melted, differentiated and cooled [2], major collisions caused extensive brecciation of near-surface materials and damaged orthopyroxene and olivine crystal lattices. As a result of these impact events, some aubritic material was shocked and buried within warm ejecta blankets where S4 olivine crystal lattices healed to S1, but S4 orthopyroxene lattices were little affected and retained their shock-damaged features. This process resulted in the formation of rocks such as LAP 03719 with rounded S1 olivine grains enclosed within large S4 orthopyroxene grains.

Some regolith breccias may have formed at shallower depths in the ejecta blanket so that olivine grains were only partly annealed. This could account for the S1-S2 olivine in Khor Temiki, the S2-S4 olivine in LAR 04316, and the S4 orthopyroxene in both of these rocks.

As pointed out previously [10], it seems unlikely that a rock could be annealed so precisely that its S4 olivine grains would heal their planar fractures, recrystallize and lose their mosaicism, but still manage to retain undulose extinction (characteristic of shock-stage S2). It seems more probable that shock-damaged S4 olivine grains would be completely healed as were those in LAP 03719. Unshocked (S1) olivine grains would result. In that case, aubrites such as ALH 83015 with S4 orthopyroxene and S2 olivine may have been shocked, buried, partly annealed, exhumed and (very weakly) shocked again.

Conclusions: Many asteroidal meteorite groups (e.g., ordinary chondrites [10-12], CK chondrites [13], EL chondrites [14], ureilites [15], and aubrites [this study]) contain some members that experienced post-shock annealing and, in many instances, post-annealing shock. It seems likely that asteroids commonly experienced major collisions that caused material to be buried within warm ejecta blankets. This allowed diffusion to heal some shock features, notably olivine crystal lattices, but preserve a myriad of other shock features that were more resistant to erasure by annealing. In the case of aubrites, these resistant features included shock-damaged orthopyroxene grains.

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