SHOCK EFFECTS IN EH6 CHONDRITES AND AUBRITES: IMPLICATIONS FOR COLLISIONAL HEATING OF ASTEROIDS. Alan E. Rubin, Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90095-1567, USA (aerubin@ucla.edu).

EH6 Chondrites: The two principal groups of enstatite chondrites differ in their proportions of petrologic types. Among EL chondrites, ~20% are type 3 and ~60% are type 6, whereas among EH chondrites, ~75% are type 3 and ~3% are type 6. As of this writing, there are five EH6 chondrites listed in the Meteoritical Bulletin Database (MBD): A-882039, Y-793225 (EH6-an), Y-8404, Y-980211 and Y-980223.

Because many EL6 chondrites [1] and several EH chondrites have been described as impact-melt rocks or impact-melt breccias (e.g., Abee, Adhi Kot, ALH 82132, RKP A80259, LAP 02225, QUE 99473, Y-791790, Y-82189, Y-8414) [2-5], it is worthwhile to determine whether EH6 chondrites have also been impact melted. Most EH6 chondrites have not been extensively studied previously; I examined all of them except A-882039.

Lin and Kimura [4] classified EH6 Y-8404 as an impact-melt rock because it contains euhedral enstatite grains enclosed within globules of kamacite and troilite. This texture was produced by crystallization from a melt and is similar to that exhibited by the Abee EH impact-melt breccia [2,6].

The reaction principally responsible for Abee's unusual mineral chemistry [7] governs the sulfidation of enstatite and the production of keilite [(Fe,Mg)S], silica and metallic Fe at the expense of niningerite [(Mg,Fe)S] and troilite [FeS]: $MgSiO_3 + (Mg,Fe)S + 2FeS = 3(Fe,Mg)S + SiO_2 + Fe + ½O_2$. This reaction (coupled with element partitioning at low fO_2) accounts for several additional characteristics of EH impact-melt breccias: low MnO in enstatite (<0.04 wt.%), high Mn in troilite (>0.20 wt.%), the occurrence of keilite instead of niningerite, low Mn in keilite (≤4.3 wt.%), and abundant silica (>4 wt.%) [7,8]. Each of the four EH6 chondrites that I studied exhibits some of these features and thus appears to have been impact melted: Y-8404 and Y-980223 contain rare relict radial pyroxene chondrules and are impact-melt breccias; Y-793225 and Y-980211 are chondrule-free impact-melt rocks. All four meteorites contain euhedral enstatite grains surrounded by metal±sulfide, all four contain enstatite with <0.04 wt.% MnO, all but Y-793225 average ≥0.24 wt.% Mn in troilite, three (Y-8404, Y-980211 and Y-980223) contain keilite (with low Mn: 3.8, 3.8 and 4.1 wt.%, respectively) [8, this study], and Y-8404 (and its paired specimens) average ~12 wt.% silica [4] (whereas most EH3-5 chondrites contain ≤1 wt.% silica and many have <0.1 wt.% [7]).

These data allow one of two possibilities: (1) The EH6 chondrites have been properly classified, but EH6 chondrites are impact-melt rocks and impact-melt breccias. In this case, the mechanism mainly responsible for EH-chondrite metamorphism is impact heating. (2) The meteorites have been misclassified; they are impact-melted rocks and are not EH6 chondrites (which remain hypothetical).

One way to choose between these alternatives is to examine the EH4, EH4/5, EH5 and EH7 chondrites. If many of them appear to have been impact melted, then impact heating is probably the major mechanism responsible for EH-chondrite metamorphism. The MBD lists 15 EH4 and EH4/5 chondrites (after pairing is taken into account). At least four of these (Abee, Adhi Kot, ALH 82132, Y-791811) are impact-melt breccias [2,3,6,8]. Keilite has been reported in all of these rocks except ALH 82132 [8], and the latter contains euhedral enstatite grains enclosed within kamacite globules [2]. The MBD lists six EH5 chondrites: A-881475, LEW 88180, QUE 93372, RKP A80259, St. Mark's, Saint-Sauveur. At least three of these are impact-melt breccias: LEW 88180 contains keilite [8], RKP A80259 displays igneous textures and contains impact-melted feldspar [5] and keilite [8], and Saint-Sauveur contains keilite, low-MnO enstatite, and euhedral enstatite grains surrounded by metallic Fe-Ni [7-9]. One meteorite, QUE 94204, is classified as EH7. This is a chondrule-free rock that contains euhedral enstatite grains with <0.03 wt.% MnO and exhibits an igneous texture [10]. Its paired specimen, QUE 99059, contains abundant silica [11] and is likely to be an impact-melt rock.

In summary, a large fraction (≥0.67) of EH5-7 chondrites and a significant fraction (≥0.27) of the set of EH4 and EH4/5 chondrites appear to have been impact melted. It thus seems likely that collisional heating is the principal mechanism responsible for EH-chondrite metamorphism. The less-metamorphosed rocks tend to show less evidence of impact processes.

Aubrites: I examined shock effects in 11 aubrites and determined whole-rock shock stages using established criteria [12,13]: ALH A78113 (S4), ALH 83015 (S3), ALH 84007 (S4), Bishopville (S4), Cumberland Falls (S4), EET 90033 (S3), LAP 03719 (S3), LAP 03780 (S4), Mayo Belwa (S4), Peña Blanca Spring (S4) and Shallowater (S2). Rocks of shock-stage S3 and S4 have coarse polysynthetically twinned clinoenstatite, exhibiting undulose extinction and weak mosaic extinction, respectively. EET 90033 (S3) also contains a few pyroxene grains with sharp optical extinction. Some of the olivine grains in Bishopville (S4) and Mayo Belwa (S4) exhibit weak mosaic extinction and contain curvilinear trails of troilite blebs, consistent with the shock stage determined from enstatite.

I studied five chondritic clasts in Cumberland Falls (S4) (UCLA sections 512, 567, 575, 589, 602). The clasts have been shocked to approximately the same extent as their aubritic host. Olivine grains in the clasts contain planar fractures and have undulose to weak mosaic extinction. Both olivine and pyroxene exhibit silicate darkening [14] caused by the dispersion within grain interiors of small sulfide blebs. The chondritic clasts contain fine-grained metal-sulfide intergrowths, metal-troilite veins, and polycrystalline troilite.

Shallowater (S2) is an unbrecciated aubrite with ~9 wt.% metallic Fe-Ni that may have been derived from a separate aubritic asteroid [15-17]. The vast majority of enstatite grains are ordered orthorhombic crystals [18] that show well-developed {210} cleavage and exhibit undulose extinction, but do not have polysynthetic twins. Twinned clinoenstatite grains are rare and occur mainly in xenocrysts [16]. Many orthoenstatite grains poikilitically enclose olivine that exhibits sharp optical extinction (a shock-stage S1 feature). Shallowater was not significantly shocked after it crystallized from a melt, but appears to have been mildly annealed.

Two aubrites appear to have experienced post-shock annealing: (1) Peña Blanca Spring (S4) contains a coarse enstatite grain that exhibits undulose extinction and encloses a 220×500-μm-size olivine grain with sharp optical extinction (characteristic of shock-stage S1). The olivine grain contains several 150-200-μm-long curvilinear trails composed of 0.1-1-μm-size troilite blebs. (2) The anomalous aubrite LAP 03719 (S3) contains coarse polysynthetically twinned clinoenstatite crystals that poikilitically enclose rounded 180-1900-μm-size olivine grains with sharp optical extinction. A 1720×1900 μm olivine grain is traversed by a 2-7-μm-thick discontinuous troilite-rich vein that extends into the surrounding pyroxene.

The apparently unshocked olivine grains in Peña Blanca Spring and LAP 03719 must once have been shocked to the same degree as the surrounding enstatite. These aubrites may have been buried within an insulating ejecta blanket produced by the same impact event that caused the shock effects. The rocks were annealed by heat generated by the impact to a degree sufficient to repair shock-induced damage to the olivine crystal lattices, but insufficient to affect pyroxene significantly. This is consistent with the higher rates of elemental diffusion in olivine than in pyroxene [19,20] and with experiments showing that microfractures in olivine can heal at sub-solidus temperatures [21,22].

Aubrites join a list of meteorite groups in which some members have been inferred to have experienced post-shock annealing: ordinary chondrites [23-25], CK chondrites [14], EL chondrites [1,13], ureilites [26], acapulcoites and lodranites [27]. The parent asteroids of these groups may have been high-porosity rubble piles [28-30], in which collisional energy was distributed through relatively small volumes of material [31] and efficiently converted into heat [32-34].

It is to be expected that different asteroids of similar size and structure would behave similarly when struck by large meteoroids. Shock and post-shock annealing are natural processes that probably occur on all rocky bodies subject to hypervelocity impact events.

References: [1] Rubin A. E. (2006) *MPS, 41,* A154. [2] Rubin A. E. and Scott E. R. D. (1997) *GCA, 61,* 425-435. [3] Rubin A. E. (1983) *EPSL, 64,* 201-212. [4] Lin Y. and Kimura M. (1998) *MPS, 33,* 501-511. [5] Fagan T. G. et al. (2000) *MPS, 35,* 319-330. [6] Rubin A. E. and Keil K. (1983) *EPSL, 62,* 118-131. [7] Rubin A. E. (2008) *MPS, 43,* 1481-1486. [8] Keil K. (2007) *Chem. Erde, 67,* 37-54. [9] Keil K. (1968) *JGR, 73,* 6945-6976. [10] Weisberg M. K. et al. (1997) *LPS, 28,* abstract#1358. [11] McCoy T. and Welzenbach L. (2001) *Ant. Met. Newslet., 24,* no. 1. [12] Stöffler D. et al. (1991) *GCA, 55,* 3845-3867. [13] Rubin A. E. et al. (1997) *GCA, 61,* 847-858. [14] Rubin A. E. (1992) *GCA, 56,* 1705-1714. [15] Keil K. (1989) *Meteoritics, 24,* 195-208. [16] Keil K. et al. (1989) *GCA, 53,* 3291-3307. [17] Foshag W. F. (1940) *Am. Mineral., 25,* 279-286. [18] Reid A. M. and Cohen A. J. (1967) *GCA, 31,* 661-672. [19] Buening D. K. and Buseck P. R. (1973) *JGR, 78,* 6852-6862. [20] Freer R. (1981) *Contrib. Mineral. Petrol., 76,* 440-454. [21] Bauer J. F. (1979) *PLPSC, 10th,* 2573-2596. [22] Ashworth J. R. and Mallinson L. G. (1985) *EPSL, 73,* 33-40. [23] Rubin A. E. (2002) *GCA, 66,* 3327-3337. [24] Dixon E. T. et al. (2004) *GCA, 68,* 3779-3790. [25] Rubin A. E. (2004) *GCA, 68,* 673-689. [26] Rubin A. E. (2006) *MPS, 41,* 125-133. [27] Rubin A. E. (2007) *GCA, 71,* 2383-2401. [28] Bottke W. F. et al. (1999) *Astron. J., 117,* 1921-1928. [29] Cheng A. F. and Barnouin-Jha O. S. (1999) *Icarus, 140,* 34-48. [30] Veverka J. et al. (1999) *Icarus, 140,* 3-16. [31] Stewart S. T. and Ahrens T. J. (1999) *LPS, 30,* abstract#2020. [32] Melosh J. (1989) *Impact Cratering: A Geologic Process*. Oxford Univ. Press, New York. [33] Housen K. R. and Holsapple K. A. (1999) *LPS, 30,* abstract#1228. [34] Britt D. T. et al. (2002) In *Asteroids III*, Univ. Arizona Press, Tucson.