RECRYSTALLIZATION OF CA-RICH PHASES IN EUCRITES AND CONSTRAINTS ON THE TIME OF THE CRUSTAL METAMORPHISM; Hiroshi Takeda[1,2], L. E. Nyquist[3], A. Yamaguchi[4], and M. Miyamoto[2]. [1] Chiba Inst. of Technology, 2-17-1 Tsudanuma, Narashino City, Chiba 275, [2] Mineralogical Inst., Faculty of Sci., Univ. of Tokyo, Hongo, Tokyo 113, Japan, [3] Code SN41, NASA Johnson Space Center, Houston, TX 77058, [4] Hawaii Inst. of Geophys. Planet., Univ. of Hawaii at Manoa, Honolulu, Hawaii 96822, U.S.A.

In order to correlate events of mineral formation to resetting of four isotopic systems in the Y792510 eucrite, the conditions of mineral formation in four eucrites have been studied by mineralogical techniques. We found formations of large augite grains in granoblastic areas of lithic clasts, and of clear augite grains and apatite with a silica phase in mesostasis. Because REE migrate together with Ca, our preferred interpretation is that these minerals formed within the period when live ^{146}Sm was present in Y792510. This conclusion implies that an episode of thermal metamorphism took place well before impact-related resetting of the Ar-Ar ages of Y792510 and many monomict eucrites. However, an alternative interpretation based on the Rb-Sr age is possible.

Introduction. Because the HED (howardite, eucrite, diogenite) parent body is now thought to be the asteroid 4 Vesta [1], we can understand basaltic volcanism, brecciation and metamorphism of the HED achondrites as processes taking place on a large differentiated body 520 km in diameter. Among the three classes of the HED achondrites, eucrites are abundant and many of them are brecciated and metamorphosed products of basaltic lavas [2,3]. Two major issues for understanding the homogenization of their pyroxenes in the context of the crustal evolution of the Vesta-like parent body are: (a) what was the heat source and (b) when did the metamorphism take place? The proposed models [2-5] are summarized as: (1) Impact heating at the floors of craters; (2) Metamorphism by successive lava flows [4]; and (3) Global crustal metamorphism by burial [5]. The last two models assume a partial melting model for eucrite formation. Hartman [7] pointed out that impacts may have punched through the rocky skin of a magma ocean, and mixed rock fragments with splashed magma.

Because chronologies based on five isotopic systems (^{147}Sm-^{143}Nd, ^{146}Sm-^{142}Nd, Rb-Sr, Ar-Ar, Mn-Cr) of Y792510 have been determined [8] and Ca is a carrier for Sr and the REE, we investigated Ca-rich phases (augite and apatite) in Y792510 by mineralogical techniques and compared them with similar phases in Juvinas, Sioux County and the Y75011,84 clast. We interpret their formation processes in the light of the chronology deduced from the isotopic systems, including short-lived ^{146}Sm and ^{53}Mn.

Samples and Analytical Techniques. We have studied five polished thin sections (PTS) by mineralogical techniques: Y792510,62F2, 62F3 and ,89-9 and also Juvinas 40E2-7 and Sioux County. The presence of augite grains in Y792510,62F3 and Juvinas has been detected in the BEI (back scattered electron image) of SEM. The chemical analyses of minerals were made using JEOL 733 electron probe microanalyser (EPMA) at the Ocean Research Inst., Univ. of Tokyo. The width and interval of pyroxene lammela were measured by line analyses of the EPMA for 1-3 μm intervals. The bulk compositions were also obtained by broad beam analysis.

Results. PTS Y792510,62F2 is rich in recrystallized mesostasis, which consists of fine grained transparent polygonal grains of augite (25 modal %) and apatite (5%) set in a matrix of silica mineral (50 %), spotted with minor troilite and ilmenite. A few large irregular shaped ilmenites up to 0.15 mm in diameter were grown in the mesostasis. Apatite is associated with silica. The bulk chemical composition obtained by line analyses is rich in SiO_2 (77 wt %), CaO (9%), FeO (7 %), and P_2O_5 (2%). PTS Y792510,62F3 and ,89-9 show a more moderately brecciated texture of subophitic basalt than other previously studied PTSs. Major pyroxenes in these PTSs are cloudy and the cores ($Ca_{8.6}Mg_{35.4}Fe_{56.0}$) include widely spaced (up to 50 μm) coarse exsolution lamellae of augite (up to 8 μm) and are mantled by rims of subcalcic augite ($Ca_{21.8}Mg_{33.5}Fe_{44.7}$) with fine exsolution (~1 μm). Such pyroxene is common in Sioux County and Stannern. Their overall textures are still ophitic or subophitic with large prismatic plagioclase crystals. The plagioclase crystals include fine dusty inclusions of K-, Na-rich feldspar (K_2O up to 0.31 wt %) and droplet-like inclusions of pyroxene composition in some regions in the interior.

At some areas in ,62F3 bounded by two plagioclase crystals meeting at an acute angle, pyroxene crystals are broken into small polygonal blocky grains of clear low-Ca pyroxenes and augite of different orientations. This texture is similar to that of the granoblastic pyroxene (GP) areas of Juvinas. The low-Ca pyroxene crystals ($Ca_{4.6}Mg_{35.9}Fe_{59.6}$) shows widely spaced exsolution lamellae. The augite crystals in ,62F3 is large (up to 0.20 × 0.15 mm) and blocky and include fine exsolution lamellae (Fig. 1). The bulk composions of two paired pyroxenes ($Wo_{8.8}En_{34.3}Fs_{57.0}$, $Wo_{42.1}En_{30.8}Fs_{27.1}$) give the last equilibrated temperature of 750 to 890°C [9]. In this area, two partly euhedral ilmenites (up to 0.13 × 0.09 mm) and a chromite (0.10 × 0.07 mm) are found with pyroxenes.

Augite in the GP area of Juvinas ($Ca_{40.2}Mg_{32.5}Fe_{27.3}$) is in similar configuration to that of Y792510, but is finer grained than Y792510 and fills interstices of polygonal crystals of low-Ca pyroxene ($Ca_{4.9}Mg_{39.6}Fe_{29.9}$) with fine exsolution lamellae of augite on (001). The dusty appearance of the Juvinas pyroxene has disappeared, and coarser opaque minerals (chromite and troilite) were grown in the GP area. Sioux County includes a variety of clasts and pyroxenes outside the definition of monomict eucrites. Pigeonite with coarse exsolution lamellae similar to that in Y792510 is not rare. The cooling rate of a leucocratic clast was estimated in a companion paper [10]. Sioux County is characterized by the presence of veins of Fe-rich olivine and primary orthopyroxene.

Discussion. When we discuss the degree of homogenization of pigeonite, we assume that the original materials were quickly cooled basalts with ophitic or subophitic textures. In such lava-like basalts, primary augite is rare. It is also to be noted that these eucritic basalts are always brecciated except for Ibitira etc.[11], which itself could have been a large clast in a breccia. Keeping these basaltic features in mind, we point out that the presence of large dust-free augite crystals in granoblastic areas produced within normal basalts seems to be unusual and their origin is difficult to understand. We interpret their presence in local configurations but with well defined crystallization texture, to formation of augite after the clouding was produced in pyroxene by shock disturbances at grain boundaries at high temperature, and subsequent annealing. Well developed crystals suggest that the augite was formed just below the melting temperature.

Yamaguchi *et al.* [5] studied 17 equilibrated eucrites and found 12 which contained recrystallized pairs of augite and pigeonite, although their grain sizes were not as coarse as those in Y792510. Equilibration temperatures were mostly in the range from 800 to 900°C, which are the same as those for Y792510. By comparing the mesostasis of Y792510,62F2 with similar mesostasis in the Y75011,84 clast [12], we conclude that the augite in it may also be the product of recrystallization.

Because the ^{146}Sm-^{142}Nd and ^{53}Mn-^{53}Cr chronologies [8] suggest that these short-lived radioactivities were still live in Y792510 and because REE should migrate with Ca, one possibility is that the recrystallization occured ~4.45 Ga ago, as indicated by the ^{146}Sm-^{142}Nd age. In this case, the recrystallization of augite and apatite took place at approximately the same time of the ^{39}Ar-^{40}Ar resetting of Ibitira [11]. The time of homogenization of pyroxene would have been earlier, because the clouding in pyroxene was erased by the formation of the granoblastic areas. In a companion paper, Miyamoto *et al.* [10] proposed that the cooling of Sioux County took place in a hot breccia of ~40 m thick for ~10^4 years. This model assumes that hot materials were mixed during brecciation, and is similar to Hartman's model [7], in which hot materials were heated by magma mixed with impact breccia and by magma beneath the crust. These processes would represent another heating episode in addition to that required to produce granoblastic augite. Furthermore, Hartman's results show that intense brecciation and pulverization of rock materials must have occured to a depth of at least tens of kilometers in the eariest lunar history. Similar phenomena but on a smaller scale will take place on Vesta. The resetting of the Rb-Sr isotopic system of Y792510 may be related to the presence of K-, Na-rich phases in cloudy pyroxne and plagioclase, which will be influenced by shock [13], but an alternative interpretation is possible [8].

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References: [1] Binzel R. P. and Xu S. (1992) *Science* 260, 186-191. [2] Yamaguchi A. *et al.* (1994) *Meteoritics* 29, 237-245. [3] Takeda H. and Graham A. L. (1991) *Meteoritics* 26, 129-134. [4] Scott E. *et al.* (1989) *Asteroid II*, 729. [5] Yamaguchi A. *et al.* (1996) *Icarus*, submitted. [6] Nyquist L. E. *et al.* (1986) *J. Geophys. Res.* 91, 8137-8150. p. 155-171. [7] Hartman W. K. (1980) *Proc. Conf. Lunar Highland Crust*, [8] Nyquist *et al.* (1996) *Lunar Planet. Sci.* XXVII, this volume. [9] Lindsley D. H. (1983) *Amer. Miner.* 68, 477-493. [10] Miyamoto M. *et al.* (1996) *Lunar Planet. Sci.* XXVII, this volume. [11] Bogard D. D. and Garrison D. H. (1995) *Geochim. Cosmochim. Acta* 59, 4317-4322. [12] Takeda H. *et al.* (1994) *Earth Planet. Sci. Lett.* 122, 183-194. [13] Hervig R. et al. (1986) *Meteoritics* 21, 395.

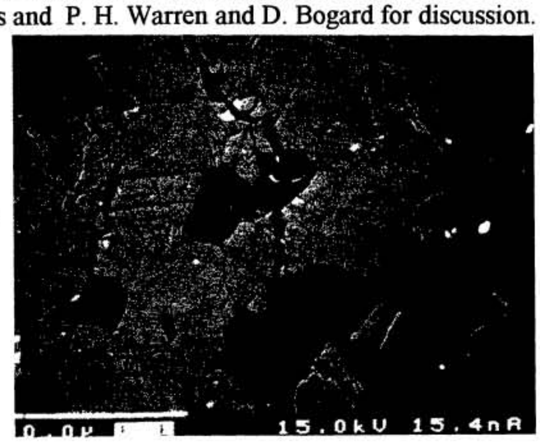

Fig. 1. BEI of augite (dark) and low-Ca pyroxene (light) of granoblastic area of a pigeonite in Y792510. Width is 0.5 mm.