THREE UNBRECCIATED EQUILIBRATED EUCRITES: GLOBAL METAMORPHISM ON THE EUCRITE PARENT BODY
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We compare the petrology of two unbrecciated eucrites, EET 90020 and A-881388, with Ibitira. Unlike most eucrites, these three rocks were not significantly shocked (<1-5 Ga) after thermal metamorphism. These rocks have different textures. EET 90020 preserves a well-defined primary subophitic texture with lath-shaped plagioclase overprinted by thermal metamorphism. A-881388 shows medium-grained equigranular texture; we classified it as an eucritic granulite. Ibitira is intermediate between them; it is recrystallized but still shows the ghost of an igneous texture [1]. The pyroxene in EET 90020 is pigeonite with a uniform distribution of fine exsolution lamellae of augite, which may have formed at high temperature (>1000°C) to erase the original Ca-zoning. Ibitira and A-881388, on the other hand, contain large augite grains showing relatively high equilibration temperatures (up to 1115°C). Coarse aggregates of tridymite, plagioclase and pyroxene in EET 90020 and large, elongated lathes of tridymite in EET 90020 and Ibitira might have formed by eutectic melting during metamorphism. These eucrites appear to have experienced metamorphism at high peak temperatures (presumably, just below the melting point) and prolonged slow cooling. Considering the time scale of metamorphism, these eucrites could be metamorphosed basaltic formed at the time of crust formation [e.g., 2-4]. The very low post-metamorphic shock makes these samples ideal for age determinations.

INTRODUCTION. Eucrites are pristine crustal rocks from a large asteroid, probably 4 Vesta [5]. Most of the eucrites have features indicative of prolonged thermal histories during or shortly after volcanism [e.g., 2-4]. They were brecciated to fragment size of less than centimeters, and therefore original textures are generally strongly disturbed. However, there are several unbrecciated, non-cumulate eucrites which preserve primary metamorphic and/or igneous features. We have studied the petrology of two unbrecciated non-cumulate eucrites, EET 90020 [6] and A-881388 [7] and compared them with a well-studied unbrecciated eucrite, Ibitira [1] to gain a better understanding of the earliest thermal and shock history on the eucrite parent body. (Equilibration temperatures of pyroxenes were calculated using the Kretz Ca-thermometer [8].)

RESULTS. EET 90020 is an unbrecciated metamorphic eucrite [6,9]. This rock (PTS, 18) has a subophitic texture consisting of lath shaped plagioclase with curved edges (900x400 μm) and anhedral pigeonite (Fig. 1). A few large elongated lathes of tridymite (<780x90 μm) are present. In mesostasis regions (<1.2x3 mm in size), granular to rectangular plagioclases (~60x100 μm) are set in a tridymite matrix. The pyroxene is composed of homogeneously distributed fine (<3 μm), closely spaced (~5-10 μm) (001) augite lamellae in a pigeonite host. No clouding is observed in the pyroxenes. Exsolved augite (Wo41.0En30.2) in pigeonite (Wo34En35.6) indicates an equilibration temperature of ~874°C. Plagioclase is slightly zoned from core to rim (Or0.4-0.5Ab8.8-11.3) and is clear in appearance, although it contains tiny inclusions of pyroxene (<8 μm) near the center of the crystal. Tridymite contains a significant amount of K2O (~0.19-0.26 wt%).

A-881388 is an unbrecciated recrystallized rock [7] that consists of granules of pigeonite, augite, and plagioclase (all ~100 μm in diameter), and minor minerals. In contrast to EET 90020 and Ibitira [1], there is no unambiguous remnant igneous texture; some plagioclases show irregularly elongated shape (~300x60 μm), which might be the vestige of the original igneous texture. Small opaque minerals (~80 μm in size), such as ilmenite and chromite, are scattered evenly throughout the PTS. The pigeonites contain very fine-grained, closely spaced augite lamellae (~1-2 μm), but the separated augite grains appear to be free of inclusions or exsolved phases. No clouding was observed in either pyroxene or plagioclase. Chemical compositions of plagioclases vary slightly (An88-91) [6]. Ilmenite is often associated with chromite. The final equilibration temperature of the two-pyroxenes pair is 912 °C.

Ibitira is a strongly recrystallized, unbrecciated eucrite, but it shows a ghost-like igneous texture [1]. In this study, we observed rare irregular augite grains (~300x200 μm in size), which contain fine exsolution lamellae of pigeonite. Bulk compositions of the augite grains (Wo31.7En32.5) and bulk pigeonite (Wo41.4En37.0) indicate an equilibration temperature at ~1115°C. On the other hand, the final equilibration temperature estimated from the exsolution lamellae of augite is <913°C.

Shock features. Shock stages were estimated by [10]. No shock effects in EET 90020 are observed; plagioclase and pyroxene have no minor fractures but have very sharp extinction (≤2°), indicating that EET 90020 did not experience shock metamorphism more than 1-5 GPa [10]. Ibitira and A-881388 show weak mottled extinction in the plagioclase.

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DISCUSSION. We suggest that the difference in the metamorphic textures of the three rocks may reflect the degree of brecciation before or during metamorphism. The subophitic textures in EET 90020 are probably igneous. The preservation of this igneous texture, combined with the highly metamorphosed features (see below) in EET 90020, is unique among eucrites [2]. This eucrite was probably not shocked significantly (i.e., <1-5 GPa) [10] before metamorphism. A-881388, on the other hand, is totally recrystallized; the precursor of this rock could be a fragmental breccia. We classified the rock as an eucritic granulite. Ibitira has a texture intermediate between EET 90020 and A-881388. This rock was shocked [1], but the shock metamorphism may not have been so intense that it completely destroyed the igneous texture.

On a basis of plagioclase sizes [11], initial cooling rates from the melt of EET 90020 are \(-1^\circ C/h\). Although the original igneous textures of A-881388 and Ibitira are almost completely obliterated by recrystallization, if some lath-like plagioclase represent the remnant igneous texture, the initial cooling rates are also \(-1^\circ C/h\). Thus, these rocks could have cooled rapidly, which is typical for many non-cumulate eucrites. However, the pyroxenes in the three rocks have been equilibrated and do not have remnant Ca-zoning (type 5) [12]. This implies high temperature metamorphism; peak temperatures could have exceeded \(-1000^\circ C\) to erase the possible original Ca-zoning [2]. The large elongate laths of K-bearing tridymites found in EET 90020 and Ibitira [1], and coarse-grained silica-rich areas in EET 90020 might have been formed by eutectic melting during such high temperature annealing \((-1100^\circ C\) ), rather than by solid state recrystallization [13]. The large augite grains found in Ibitira and in A-881388 could have been grown during the metamorphism [2,4]. Because there is no hint of igneous relationships of the large augite grains to pigeonites or plagioclase (e.g., augite does not rim of pigeonite), we suspect that the augite grains may have been grown during the annealing. These data suggest peak temperatures of the annealing of about \(1100^\circ C\) and prolonged slow cooling.

Considering the scale of the thermal history, these eucrites could be metamorphosed during the short period of crust formation [e.g., 2-4], probably in several million years [14]. Although much effort has been made to date the early metamorphism, the radiometric studies do not always support the idea that the metamorphism took place at the early stage because later shock events have disturbed the isotopic systems [15]. If shock metamorphism of the eucrites affects the radiometric ages, the \(^{39}\text{Ar}^{40}\text{Ar}\) age (4.47 Ga) of the unbrecciated Ibitira [16] strongly supports the idea of early metamorphism. Further studies are required to determine the radiometric ages of these very weakly shocked eucrites and to understand the relationship between the degree of shock metamorphism and the extent of radiometric disturbance.

Figure 1. Photomicrograph (partially polarized) of EET 90020, 18, showing a well-defined primary subophitic texture with lath-shaped plagioclase overprinted by thermal metamorphism. No shock effects are observed. Width is 8.5 mm.