$^{39}\text{Ar}$-$^{40}\text{Ar}$ AGE OF IBITIRA: DATING THE TIME OF CHEMICAL EQUILIBRATION OF EUCRITIC PYROXENES? D.H. Garrison$^1$ and D.D. Bogard, NASA Johnson Space Center, Houston, TX 77058 ($^1$ Also LESC-JSC, Houston, TX).

Abstract: We determined a $^{39}\text{Ar}$-$^{40}\text{Ar}$ age of 4.49 Ga for the Ibitira eucrite, which may be the time of HED metamorphism that also produced chemical equilibration in eucritic pyroxenes.

Introduction: Eucritic achondrites display two characteristics produced by thermal metamorphism, which may or may not have been caused by the same heating events. These two characteristics are (a) textures and varying degrees of chemical equilibration in pyroxenes produced in response to prolonged thermal annealing (1), and (b) strong resetting of $^{39}\text{Ar}$-$^{40}\text{Ar}$ ages for essentially all eucrites, mostly in the time interval of 3.5-4.1 Ga and presumably in response to impact heating (2). Whether the chemical equilibration in pyroxenes was caused by the same impact events that reset Ar-Ar ages, or was produced earlier in parent body history as a result of endogenic heat sources was addressed in prior studies, but was not resolved (3, 4, 5). A precise and old $^{39}\text{Ar}$-$^{40}\text{Ar}$ age just determined for the Ibitira eucrite, combined with previous results for the Y-75011 eucrite (5), now permit us to better relate these two characteristics.

$^{39}\text{Ar}$-$^{40}\text{Ar}$ Age of Ibitira: Fig. 1 plots the $^{39}\text{Ar}$-$^{40}\text{Ar}$ age, the K/Ca ratio, and the relative concentration of $^{39}\text{Ar}$ (in arbitrary units) as a function of the cumulative release of $^{39}\text{Ar}$ for stepwise temperature extractions of a 66 mg whole rock sample of Ibitira. Uncertainties in each age are given by the width of the data "boxes" and were derived from uncertainties in ratio measurements, in corrections for system blanks and reactor interferences, and in the neutron flux monitor (J-value = 0.09803 ± 0.00011). The hornblende flux monitor has an age uncertainty of ±0.5%. The K and Ca concentrations for the sample were 173 ppm and 7.67%, respectively. The first ~10% of the $^{39}\text{Ar}$ release shows slightly younger ages indicative of recent Ar diffusion loss. However, nine extractions releasing 16-100% of the $^{39}\text{Ar}$ show a very constant $^{39}\text{Ar}$-$^{40}\text{Ar}$ age of 4.490 ± 0.008 Ma (where the error is the weighted two-sigma variation from the mean). The total $^{39}\text{Ar}$-$^{40}\text{Ar}$ age of the whole spectrum is 4.43 Ga. Although the K/Ca ratio changes by an order of magnitude throughout the extraction, the $^{39}\text{Ar}$ release profile (Fig. 1) and the relatively linear Arrhenius plot for $^{39}\text{Ar}$ diffusivity suggest that most Ar is released from a common phase. The very constant K/Ca ratio over 16-88% of the $^{39}\text{Ar}$ release indicates a single, homogeneous mineral phase, which also defines an $^{39}\text{Ar}$-$^{40}\text{Ar}$ age of 4.490 ± 0.008 Ma. The apparent recent Ar loss at low extraction temperatures is associated with higher K/Ca ratios. The last ~12% of the $^{39}\text{Ar}$ release has a considerably lower K/Ca, suggesting a different phase, but its age of 4.50 ± 0.02 Ga is the same. An isochron plot of $^{40}\text{Ar}$/^{36}\text{Ar}$ vs. $^{39}\text{Ar}$/^{36}\text{Ar}$ passes through the origin indicating the absence of any excess $^{40}\text{Ar}$ not associated with K. We conclude that Ibitira was totally degassed of its radiogenic Ar 4.49 Ga ago and has not been significantly heated since that time.

Relation of Ar Ages and Pyroxene Equilibration: A pristine clast from Y-75011 shows almost no evidence of chemical equilibration of pyroxene, the lowest amount yet measured for an eucrite, and gave Sm-Nd and Rb-Sr isochron ages of 4.55 ± 0.14 Ga and 4.60 ± 0.05 Ga (6). Yet this clast showed substantial Ar degassing by an impact event 4.0 Ga ago (5). These results indicate that impact brecciation on the early HED parent body could produce enough heating in cratering ejecta to substantially reset $^{39}\text{Ar}$-$^{40}\text{Ar}$ ages without producing significant chemical equilibration of pyroxene. Ibitira, on the other hand, has a relatively high degree of pyroxene equilibration (level 5 out of a scale of 1-6; 1). However, Ibitira is practically unique among eucrites in that it is vesicular and shows no evidence of brecciation (7). Thus, Ibitira presents just the opposite case to that for Y-75011, i.e., an eucrite which experienced enough heating to cause pyroxene equilibration, but which apparently escaped the heating produced by impact brecciation that reset K-Ar ages of almost all other eucrites. The fact that Ibitira gives a well-defined $^{39}\text{Ar}$-$^{40}\text{Ar}$ age of 4.49 Ga argues that, not only did the meteorite escape chronometer resetting during the cataclysmic bombardment (2), but also that the pyroxene equilibration occurred much earlier than this bombardment, at least as early as 4.49 Ga. One issue remains unresolved, however. What was the nature of the 4.49 Ga Ar degassing event for Ibitira, and does the Ar-Ar age date the time of pyroxene equilibration, or did the equilibration occur earlier still? This issue is addressed in the next section.

Formation Age of Ibitira: Prior chronological studies of Ibitira have yielded Pb-Pb model ages of 4.556 ± 0.006 Ga (8) and 4.560 ± 0.003 Ga (9) and a Rb-Sr isochron age of 4.52 ± 0.25 Ga (11). The Pu-(fission)Xe age of Ibitira was reported as 5 Ma earlier than that for Angra dos Reis (12), for which Sm-Nd and Pb-Pb ages of 4.55-4.56 Ga have been reported (e.g., 13). In addition early decay of short-lived $^{146}\text{Sm}$ within Ibitira also

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suggested formation ~5 Ma prior to ADOR (10, 14). In contrast to these ages, which indicate that Ibitira formed 4.55-4.56 Ga ago, a considerably younger Sm-Nd isochron age of 4.46 ± 0.02 Ga has also been reported (10). There exists evidence that a few cumulate eucrites may be ~0.05-0.1 Ga younger than the expected ~4.55 Ga formation age of monomict eucrites, but it is not clear whether these younger ages reflect crystallization processes or parent body metamorphism (15, 10, 12). Although Ibitira is not a cumulate eucrite, its younger Sm-Nd age has been interpreted as representing later disturbance (10).

Few accurately measured 39Ar-40Ar ages of meteorites are as old as 4.55 Ga, the approximate formation time for several types of chondrites and achondrites. The 39Ar-40Ar age of 4.49 Ga for Ibitira is slightly younger than the oldest Ar-Ar ages of ~4.50-4.53 Ga for unshocked ordinary chondrites (16) and some primitive achondrites (17). We do not believe that this tendency toward younger Ar-Ar ages in meteorites is caused by a bias in the technique. The total uncertainty in the 40K decay constant produces an uncertainty in Ar-Ar age of ~13 Ma in a 4.55 Ga sample, which is less than the age uncertainty associated with the 87Rb and 147Sm decay constants. Several neutron fluence monitors used by different laboratories for Ar-Ar dating have been intercalibrated to an absolute age precision of <±0.5%. Furthermore, the significant spread of Pb-Pb ages (~60 Ma; 18) and K-Ar ages (~200 Ma) in ordinary chondrites, along with ample evidence for extended metamorphism and slow cooling, indicates that these parent bodies experienced metamorphism over ~0.1 Ga. But, can metamorphism, either endogenic to the parent body or impact-produced, explain the younger K-Ar and Sm-Nd ages for Ibitira? Modest metamorphism ~4.49 Ga ago could conceivably reset the K-Ar age for Ibitira without significantly disturbing other chronometers; impact resetting of K-Ar without appreciable resetting of other chronometers did occur 3.5-4.1 Ga ago for many other eucrites (2). However, it is more difficult to explain how such metamorphism could reset the 147Sm-143Nd chronometer without resetting the 146Sm-142Nd, Pb-Pb, or Pu-Xe chronometers (e.g., 10). A related question is whether the prolonged heating that caused chemical equilibration of pyroxene in Ibitira is the same metamorphism that is dated by the K-Ar age, or did the equilibration occur earlier and nearer to the time of formation of Ibitira ~4.55 Ga ago? When did pyroxene equilibration occur in those few additional eucrites that suggest ages as young as ~4.46 Ga? One reasonable assumption is that the same post-formational metamorphism, whether endogenic or impact-produced, reset the K-Ar age of Ibitira and caused the equilibration of pyroxenes in Ibitira and some cumulate eucrites. On the other hand, it has been suggested that after prolonged annealing, Ibitira was strongly shocked, followed by recrystallization of plagioclase (7). Thus, the K-Ar age may reflect a lesser heating event subsequent to the prolonged annealing that equilibrated pyroxene. The Sm-Nd age may have a similar explanation, as (10) suggested that REE in plagioclase were much more affected than in pyroxene. We do not have answers to these questions, but Ibitira may be a key meteorite to understanding the early history of the HED parent body.