
Introduction: The generally young K/Ar and 40Ar/39Ar ages [1-3; cf. 4] of CM chondrites made us wonder whether carbonaceous xenoliths (CMX) en-tombed in HED meteorites might retain more radiogenic 40Ar than do ‘free-range’ CM-chondrites. To find out, we selected two HED breccias with carbonaceous inclusions in order to compare the 40Ar/39Ar release patterns and ages of the inclusions with those of nearby HED material.

Experimental methods: NWA6475 is a polymict achenondite breccia dominated by mafic/eucritic lithic clasts and mineral fragments with no recognized diogenetic component and has been classified as a polymict eucrite [5]. NW6695, also a polymict breccia, has a significant diogenite component, and therefore is classified as a howardite. Clasts in both samples consist of matrix-supported assemblages of chondrules with fine-grained rims and lithic clasts. Matrix consists mainly of phyllosilicates, tochilinite and Fe-Ni sulfides. We conclude that these clasts are mainly CM2 material. One CM2 clast contains a fine-grained lithic clast that is C1 rather than CM1 as it apparently lacks chondrules. NWA 6474 and 6695 are part of the spectrum of HED polymict achenondrites; their populations of achondritic materials (clasts and minerals) and carbonaceous clasts overlap with respect to textures and mineral chemistry [5].

The samples were irradiated for 78 hours at the USGS TRIGA nuclear reactor (no Cd shielding). The irradiated samples were heated stepwise with a CO2 laser and the Ar isotopes released analyzed with a MAP215-50 mass spectrometer [6]. Typical blanks (1018 mol) were: 40Ar, 4680; 39Ar, 7; 38Ar, 4; 37Ar, 48; 36Ar, 18.

Results: Mafic clast in NWA 6475; matrix in NWA 6695. The integrated, plateau, and isochron ages of these two silicate samples agree within the uncertainties at ~3.7 Ga comparable to a peak comprising eight HED meteorites with ages between 3.7 Ga and 3.8 Ga noted by [7].

The measured 36,38,40Ar concentrations are typical of howardites and eucrites [8]. The concentrations of cosmogenic 38Ar were calculated from the relation $38Ar = 5.35 \times 38Ar - 35Ar / (5.35 - 0.65)$, where 5.35 and 0.65 are the trapped and cosmogenic 36Ar/38Ar ratios, respectively. 38Ar is produced primarily from Ca, for which the measured quantity $37Ar/36Ar$ (reactor-produced, calcium-derived 37Ar) serves as a proxy. The measured ratios of $38Ar/39Ar_{Ca}$ are roughly proportional to exposure age. Ignoring shielding and using the production rates of [9], we obtain cosmic-ray exposure ages of 17 Ma for NWA 6475 mafic clast and 18 Ma for NWA 6695 matrix.

Carbonaceous xenoliths (CMX) in NWA 6475 and NWA 6695—The integrated ages (Ma±1σ) of 2821±28 and 2894±17 are noticeably lower than those of their silicate counterparts, 3709±27 and 3730±23. No step age for either CMX exceeds those of the silicates.

Only ~35% of the 39Ar was released from CMX NWA 6475 at the lowest temperatures. This limited, low-temperature release and a generally rising release pattern (~2.7 Ga to 3.6 Ga), are unusual for CM material [2,10,11]. The apparent ages of CMX in NWA 6695 also mostly increase with increasing temperature, from 2.1 to 3.3 Ga with minor exceptions for steps E and F.

Relative to HED meteorites, CM chondrites typically contain higher concentrations of trapped 36,38Ar and lower concentrations of 40Ar. The measured 38Ar and 40Ar concentrations of our samples conform to these generalizations.

By assuming the CMXs contain no trapped 36,38Ar, we set an upper limit on the concentration of cosmogenic 38Ar. The results are larger than for adjacent silicates, despite higher concentrations of Ca-derived 37Ar and hence of Ca in those silicates. We infer that much of the measured 38Ar in the CMXs derived from the irradiation of CI in the nuclear reactor.

Discussion: Pairing - NWA 6475 and NWA 6695 may be paired. The 40Ar/39Ar ages, release patterns, and cosmic-ray exposure ages agree. Although their official types shock classifications differ [5], the two meteorites appear to have sampled effectively identical Vestan lithologies in different proportions. Confirmation of pairing requires further comparisons of the petrographic and isotopic properties of lithic clasts and the determination of the terrestrial ages.

40Ar losses: CMXs vs. silicates - Bogard [7] argued that an intense early bombardment of the Solar System re-set the 40Ar/39Ar ages of many HED meteorites. In this picture, a large impact on Vesta indirectly heated near-surface material enough to de-gas Ar. Such heating likely degassed the Ar in carbonaceous xenoliths as well, if we discount the remote possibility that they were captured later. Judging from their flat release patterns, the silicate samples retained all the Ar that accumulated...
thereafter. In contrast, the \(^{40}\text{Ar}/^{39}\text{Ar}\) ratios of the CMXs suggest the loss by diffusion of about 40% of the radiogenic \(^{40}\text{Ar}\) during the same period. Larger losses for the CMXs are expected qualitatively based on a consideration of relative diffusion parameters, but the full extent of those losses may have been reduced by the lower porosity of the surrounding achondrite matrix.

\(^{40}\text{Ar}\) losses: CMXs vs. Murchison and other CMs –

We assess the magnitudes of \(^{40}\text{Ar}\) losses from CMs based on formation ages of ~4.57 Ga [12]. So calculated, the \(^{40}\text{Ar}/^{39}\text{Ar}\) loss is 58% for a CM chondrite with an age of 3.2 Ga and 82% for an age of 2.0 Ga. These values exceed the 40% losses inferred for the CMXs. Furthermore, the patterns of \(^{40}\text{Ar}\) release in most Murchison samples and the CMXs differ. The former tend to decrease and the latter to increase with increasing heating temperature. Primary factors influencing the integrated losses in space include the value of, and the time spent at, the peak temperature. The cosmic ray exposure ages of NWA 6475 and NWA 6695 are 10 to 20 times larger than those of Murchison [13] and, typically, of other CMs [14]. We infer that either 1) the orbits of the two HED meteorites studied had larger perihelia than the orbits of CMs; and/or 2) as noted above, the matrix surrounding the CMXs impeded the loss of radiogenic \(^{40}\text{Ar}\). Observations of the \(^{40}\text{Ar}/^{39}\text{Ar}\) systematics of heavily altered CMs extend these trends [11].

Conclusions: Carbonaceous inclusions (CMXs) in two HED meteorites lost a greater fraction of radiogenic \(^{40}\text{Ar}\) than did surrounding host material, but a smaller fraction of it than did free-range CM-chondrites such as Murchison or more heavily altered ones. Importantly, however, the sitting of the CMXs in HED matrix did not prevent the \(^{40}\text{Ar}\) loss of about 40% of the radiogenic \(^{40}\text{Ar}\), even from phases that degas at high laboratory temperatures. We infer that carbonaceous asteroids with perihelia of 1 AU probably experience losses of at least this size. The usefulness of \(^{40}\text{Ar}/^{39}\text{Ar}\) dating for samples returned from C-type asteroids may hinge, therefore, on identifying and analyzing separately small quantities of the most retentive phases of carbonaceous chondrites.