Data Repository Item

Analytical Procedures, Figure, and Constraints on the Variables and Diffusion Models.

ANALYTICAL PROCEDURES

Approximately 262 mg of LA meteorite was hand crushed, sieved and separated by standard heavy liquids procedures. Splits of the heavy-mineral fraction were mounted on double-sided carbon tape and individual phosphate grains were identified using a JEOL JXA-8600 electron microprobe (EPM), through qualitative energy dispersive spectrometry (EDS) and back-scattered electron (BSE) imaging. Merrillite and chlorapatite were distinguished by contrasting Cl and Fe concentrations. Approximately 20 phosphate grains without visible cracks were identified by this method and subsequently retrieved; several of them had small amounts of other mineral phases (mainly pyroxene and maskelynite) inside and outside of the grains. Retrieved grains were rinsed with alcohol and acetone, and individually wrapped in Pt tubes for (U-Th)/He dating. All other procedures are standard for Nd:YAG laser heating of single crystals in Pt tubes, analyses by Quadrupole mass spectrometer, in-packet HNO₃ dissolution and isotope dilution by sector ICP-MS as described in Mitchell and Reiners (2003). The small size, low U-Th, and young ages of these samples required careful monitoring of U, Th, and He blanks, which averaged 0.5 pg, 0.8 pg, and 0.05 fmol, respectively. Only samples with U and Th contents > 6 times higher than blank are included here. Most of these samples also yielded ⁴He contents > 6 times blank, although three merrillites and four chlorapatites contained 2-5 times the ⁴He blank (Table 1).

Corrections for cosmogenic ⁴He were made on the age calculations. Cosmogenic ⁴He contents were estimated as cosmogenic ⁴He = production rate × exposure age × sample mass. We assumed a ⁴He production rate of 8.05 × 10⁻⁸ cc/g-Ma (Eugster, 1988; Lorenzetti et al., 2003) and an exposure age of 3.1 Ma (Nyquist et al., 2001). Because of the small sample masses (< 5 μg), it was difficult to measure the masses with high precision and accuracy. Thus we weighed several relatively large grains of merrillite (LA111E35: 5 μg) and chlorapatite (LA111E51: 3 μg) using a microbalance, and calculated the masses of other grains by assuming identical Th and U concentrations. The inferred cosmogenic components in merrillites and chlorapatites are ca. 0.6-7.1 % and 2.9-14 %, respectively, of the total ⁴He measurements (Table 1). The uncertainties in the cosmogenic ⁴He estimates are probably ~50 %, but were not propagated into the age errors.

(insert Figure DR-I here)

CONSTRAINTS ON THE VARIABLES AND DIFFUSION MODELS

The two variables R (radius of the LA precursor) and d (distance from the surface of the LA precursor) were deduced from previous studies on cosmogenic isotopes and particle tracks. The minimum value for R was estimated as 26 cm based on Kr isotope compositions (Eugster et al., 2002). The ablation depth, or the thickness of the part removed during the meteorites’ journey from ejection to the present, was estimated for LA as ~10-20 cm in a 30-40 cm meteoroid (Nishiizumi et al., 2000) based on the
calibration with cosmic ray track densities (Bhattacharya et al., 1973). The calculated ablation depth may be slightly less for a larger parent body, but the estimates are well within the stated range even for a very large (1000 cm in radius) body. This estimated ablation depth is apparently greater than that of other shergottites (1-2 cm: Nishiizumi et al., 1986). The $d$ in the LA precursor body is (ablation depth + distance from the surface of the present LA). The average distance of the sample from the present LA surface is about 1 cm, thus $d$ is estimated as 1 cm + 15 cm (average ablation depth) = 16 cm. Based on this information, we used $R$ and $d$ values of 30–40 cm and 16 cm, respectively, for the calculation. The cooling paths are calculated for different $T_i$ and $R$ values (Fig. 1). The He concentrations at the grain boundaries and cracks on the phosphates are assumed to be 0 (complete sink of He). After the conductive cooling to -70ºC, the LA precursor body was assumed to have never been above 0ºC until it entered the Earth’s atmosphere. The heat generated by atmospheric friction and the Earth’s ambient temperature may have caused negligible He diffusion in the LA phosphates.

Because there are no published estimates of He diffusion characteristics in merrillite, and $^4$He contents in these samples are too low for $^4$He diffusion experiments, here we assumed He diffusion properties for merrillite are the same as those for terrestrial apatite ($E_a = 33$ kcal/mol and log $D_0 = 1.5$ cm$^2$/sec: Farley, 2000). The similarity of He diffusion properties in these two phases is indirectly supported by the systematic relationships between He diffusion and fission track annealing kinetics in several minerals. For typical crystal sizes and a cooling rate of ~10ºC/Ma, He closure temperatures are ~70ºC in apatite (Farley, 2000), and ~180-200 ºC titanite and zircon (Reiners and Farley, 1999; Reiners et al., 2004). Temperatures of fission-track partial annealing show a similar trend in these phases: apatite (60-120 ºC: Green et al., 1989; Corrigan, 1993) $<$ titanite (200-280 ºC: Harrison et al., 1979) $\approx$ zircon (230-310 ºC: Tagami & Dumitru, 1996; Hasebe et al., 2003). The retention temperatures (temperatures at which 50% of fission tracks are retained) in extraterrestrial apatites are estimated as 81 ± 20 ºC (Mold et al., 1984; recalculated in Pellás et al., 1997) or 97 ± 20 ºC (Pellás & Perron, 1984) for a cooling rate of ~1-2 ºC/Ma. Merrillite’s retention temperature is estimated to be 115 ± 25 ºC (Mold et al., 1984; recalculated in Pellás et al., 1997), slightly higher than that of apatite. If the He diffusion and fission track annealing in merrillites also follow the general trend found in the terrestrial apatite, titanite and zircon, the He closure temperature of merrillite is expected to be similar to but slightly higher than that of apatite. Therefore, the initial metamorphic temperatures ($T_i$) based on apatite’s diffusion properties need to be considered as minima.

We estimated a diffusion domain radius $a$, of 50 µm, based on the ~100 µm size of most merrillite grains we analyzed, as well as from the BSE images of in-situ grains in LA (Fig. DR-1). Although in thin-section, merrillites and chlorapatites are typically larger than this, in most cases they contain abundant cracks, possibly impact-induced, thus diffusion domains are likely to be smaller than the originally continuous crystal sizes. BSE images suggest that the typical distance between detectable textural discontinuities is ~100 µm for reasonably large grains, which are more likely to be selected for analysis (grains significantly smaller than this or with obvious cracks in EPM images were not selected for analysis).

Apatites were not used for the thermal modeling mainly because (1) the apatites’ diffusion domains are smaller than those of the merrillites, and (2) He diffusion in
apatites is expected to be faster than in merrillites, thus the calculated minimum metamorphic temperatures would be even lower than those obtained from merrillites.

REFERENCES CITED IN REPOSITORY


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Pellas, P., Fiéni, C., Trieloff, M., and Jessberger, E.K., 1997, The cooling history of the Acapulco meteorite as recorded by the $^{244}$Pu and $^{40}$Ar-$^{39}$Ar chronometers: Geochimica et Cosmochimica Acta, v. 61, p. 3477-3501.

**DR FIGURE CAPTION**

Figure DR-1. Back-scattered electron (BSE) photomicrographs of Los Angeles (LA) Martian meteorite showing textural relationship of various mineral phases. (a) Large merrillite grain at the center is fractured into several pieces and the fracture-free area is generally up to ~200 µm in length. The smaller two grains at the top are more intensively cracked producing much smaller fracture-free domains. Grains selected for (U-Th)/He analyses were about 100 µm in diameter. (b) Few grains of merrillite, SiO$_2$, K-feldspar, sulfide and symplectite are included in large crystals of clinopyroxene. Radial cracks are well developed in clinopyroxene suggesting high pressure metamorphism followed by large volume increase. The fracture-free domain size in merrillite is ~100 µm (in diameter), approximate mean value for reasonably large grains. Abbreviations: Px, pyroxene; Kfs, K-feldspar; Mas, nakelynite; Mer, merrillite; Sul, sulfide; Sym, symplectite (pyroxferroite: Rubin et al., 2000).
Figure DR-1. Min et al., 2004