Meteoritics & Planetary Science 38, Nr 4, 555–564 (2003)
Abstract available online at http://meteoritics.org

^{40}Ar-^{39}Ar chronology of lunar meteorites Northwest Africa 032 and 773

Vera A. FERNANDES,†* Ray BURGESS, and Grenville TURNER

Department of Earth Sciences, University of Manchester, Oxford Road, Manchester, M13 9PL, United Kingdom
†Present address: Instituto Geofísico da Universidade de Coimbra, Av. Dias da Silva, 3000–134 Coimbra, Portugal
*Corresponding author. E-mail: vfernandes@fs1.ge.man.ac.uk or veraafernandes@yahoo.com

(Received 18 November 2002; revision accepted 16 June 2003)

Abstract–The ^{40}Ar-^{39}Ar dating technique has been applied to the lunar meteorites Northwest Africa 032 (NWA 032), an unbrecciated mare basalt, and Northwest Africa 773 (NWA 773), (composed of cumulate and breccia lithologies), to determine the crystallization age and timing of shock events these meteorites may have experienced. Stepped heating analyses of several different samples of NWA 032 gave complex age spectra but indistinguishable total ages with a mean of 2.779 ± 0.014 Gyr. Possible causes of the complex age spectra obtained from NWA 032 include recoil of ^{39}Ar, or the presence of pre-shock ^{40}Ar incorporated into shock-melt veins. The effects of shock veins were investigated by laser fusion of 20 small samples expected to contain varying proportions of the shock veins. The laser ages show a narrow age distribution between 2.61–2.86 Gyr and a mean of 2.73 ± 0.03 Gyr, identical to the total age of ~2.80 Gyr obtained for the bulk sample. Diffusion calculations based on the stepped heating data indicate that Ar release can be reconciled by release from feldspar (and possibly shock veins) at low temperatures followed by pyroxene at higher temperatures. The exposure age of NWA 032 is 212 ± 11 Myr, and it contains low trapped solar Ar. Stepped heating of cumulate and breccia portions of NWA 773 also give a relatively young age of 2.91 Gyr. The presence of trapped Ar in the breccia makes the age determination of this component less precise, but release of Ar appears to be from the same mineral phase, assumed to be plagioclase, in both lithologies. A marked difference in exposure age between the 2 lithologies also exists, with the breccia having spent 81 Myr longer at the lunar surface; this finding is consistent with the higher trapped Ar content of this lithology. Assuming that 2.80 Gyr and 2.91 Gyr are the crystallization ages of NWA 032 and NWA 773 respectively, these two meteorites are the youngest lunar mare basalts available for study.

INTRODUCTION

Lunar samples returned by the Apollo and Luna missions are scarce and finite, and future manned or robotic sample return missions have not yet been scheduled. However, the recognition that some meteorites originate from the Moon has greatly increased lunar research possibilities. The polygon defined by the Apollo and Luna landing sites is <5% of the total lunar surface, and it has been suggested that most of the Apollo samples may pose bias in the understanding of the lunar history and evolution (Haskin 1998; Korotev 2000) because of their close proximity to the Procellarum-KREEP Terrain (PKT). In contrast, lunar meteorites may provide a more varied and less biased selection of lunar material, and some may derive from the lunar far side. Increasing numbers of lunar meteorites (some have been paired) are being discovered in both Antarctica and the Sahara Desert. The history of these materials, such as Northwest Africa 773 (NWA 773), is usually complex because they contain different lithological components (most are breccias) and have experienced multiple impact events. A few, however, are composed of a single lithology, as is the case of Northwest Africa 032 (NWA 032), which is a mare basalt, and in principle, ^{40}Ar-^{39}Ar age data from these samples should be more readily interpretable. K-Ar and ^{40}Ar-^{39}Ar measurements of bulk samples of highland-breccia lunar meteorites (compiled by Eugster et al. 1991) have produced ages with large errors, and whether these ages record crystallization or impact events within the history of each meteorite is uncertain. In addition to the problems of age interpretation posed by a complex geological history, lunar meteorites may also contain a mixture of different Ar components (trapped, cosmogenic, and radiogenic), which must be disentangled for a meaningful geological interpretation. In the present study, we present evidence from Ar-Ar studies for the young formation age of two recently discovered lunar meteorites from northwest Africa: NWA 032, an olivine mare basalt (Fagan et al. 2000); and NWA 773, which comprises two lithologies: an impact breccia and a cumulate (Fagan et al. 2001; and Korotev 2002). In a previous study, we obtained stepped heating Ar-Ar results indicating a young crystallization age of ~2.8 Gyr for NWA 032 (Fagan et al. 2002). In the present study, we provide a full discussion of the existing data for NWA 032 and present some new Ar-Ar data in an attempt to better constrain the age of this meteorite.

Samples

NWA 032 (300 g) was found in the Sahara Desert on the Morocco/Algeria border in October 1999. A comprehensive chemical and petrologic study of this meteorite has been reported by Fagan et al. (2002), and the following is a summary based on that work. NWA 032 is an unbrecciated mare basalt containing phenocrysts of olivine, pyroxene, and chromite in a matrix of radiating pyroxene and feldspar crystals (see Fig. 4 in Fagan et al. [2002]). The olivine phenocrysts make up 11.3 vol% of the meteorite and are up to 300 μm in size, while the pyroxene phenocrysts comprise 4.8 vol%. Coarse-grained and groundmass pyroxene, feldspar, and opaque phases (ilmenite, chromite, troilite, and trace iron metal) constitute 80.7 vol%. The remaining 3.2 vol% is in the form of high silica glass present in widely dispersed shock veins of <50 μm thickness (see Fig. 4 in Fagan et al. [2002]). Shock pressures greater than 25 GPa are indicated by the presence of the melt veins, maskelynized feldspar, and mosaicism in olivine crystals. Terrestrial weathering has caused only minor alteration, producing reddish to orange coloration due to the presence of ferric oxide or oxyhydroxide. The bulk composition of NWA 032 does not overlap that of any known mare basalts, including the mare basalt meteorites Asuka-881757 and Yamato-793169, which have lower abundances of FeO, TiO_2, and MgO. The bulk TiO_2 content of NWA 032 (3.08 wt%) places it in the low-Ti group of lunar basalts, similar to basalts from Apollo 12 and 15. However, NWA 032 contains lower MgO (8.5 wt%) than the Apollo 12 ilmenite basalt (11.5–16.5 wt%) and a higher proportion of olivine phenocrysts (12 vol%) than the Apollo 15 olivine-basalt (0.1–8.6 vol%). Petrogenetic modelling indicates that the olivine and pyroxene phenocrysts in NWA 032 formed slowly at a low pressure, producing steep zoning profiles and displaying decreasing Mg# from core to rim surrounded by an FeO-rich rim, followed by the rapid crystallization of the groundmass (Fagan et al. 2002). The most intriguing feature of this meteorite is that it has the highest Th/REE ratio of any mare basalt (including the two other basaltic lunar meteorites). Fagan et al. (2002) suggested that the source of NWA 032, in decreasing order of probability, is: Mare Humorum, Mare Fecunditatis, western Mare Serenitatis, Mare Crisium, and far western Oceanus Procellarum.

NWA 773 is an unusual lunar sample composed of 2 lithologies; an olivine-gabbro cumulate and a regolith breccia. It has a total mass of 633 g and was recovered in the desert near Dchira, Western Sahara in 2000 (Grossman and Zipfel 2001; Fagan et al. 2001). The cumulate lithology consists of olivine, pigeonite, augite, feldspar and opaques; the regolith breccia contains mineral and lithic fragments, including pieces of the cumulate portion, in a fine, granular matrix (Fagan et al. 2001) and is free of glass and impact melt components (Korotev et al. 2002). Korotev et al. (2002) describe the breccia as almost entirely consisting of very low titanium (VLT) basalt with some minor clasts of the cumulate and other basaltic lithologies. A lunar origin is supported by oxygen isotopes (Fagan et al. 2001) and the isotopic composition of trapped noble gases (Eugster and Lorenzetti 2001). NWA 773 appears to have experienced a more complex geological evolution than NWA 032, involving crystallization of the olivine-gabbro cumulate followed by brecciation of this and related basaltic lithologies (Fagan et al. 2001; Korotev et al. 2002).

Experimental Methods

Ar-Ar stepped heating experiments were performed on two samples of NWA 032 (E and G) from different locations within the meteorite. Duplicate stepped heating Ar-Ar experiments were performed on sample G (G3 and G4) and a single sample of E. Laser probe Ar-Ar fusion analyses were obtained from 20 sub-samples of G. For NWA 773, Ar-Ar stepped heating experiments were performed on the cumulate and breccia lithologies of this meteorite.

NWA 032 samples were irradiated at the Sacavém reactor in Portugal (irradiation MN16) and NWA 773 in the SAFARI-1 reactor in Pelindaba, South Africa (MN18). Both meteorites received a similar fast neutron fluence of $\sim 2 \times 10^{18}$ neutrons cm^{-2}. Within each irradiation package, samples were positioned between Hb3gr monitors in a silica glass vial. The errors on Ar-Ar step ages include the 1% difference in J value obtained for the monitors and, for calculation of total ages, the additional 1.4% uncertainty introduced by the error on the age of the Hb3gr monitor (1072 ± 11 Myr, Turner et al. 1971). Ar-Ar ages are reported at the one standard error (1σ) level of uncertainty.

Argon gas was extracted from the samples using two heating techniques: resistance furnace stepped heating and laser probe fusion analysis. The laser probe consists of a Nd-YAG continuous wave laser (λ = 1064 nm) used in TEM00 mode. Argon was extracted by fusing the sample with a defocused beam of 3 mm diameter and 15 W laser output power (equivalent to an irradiance of $\sim 2 \times 10^6$ W m^{-2}) using a 1 min heating step. During stepped heating in a resistance furnace, Ar gas was released over the temperature interval 200–1600°C using steps of either 50 or 100°C of 30 min duration. The blank at low temperature (300–1000°C) is equivalent to 0.65 × 10^{-9} cm^3 STP ^{40}Ar and increases at high temperature (≥1200°C) to 4.0 × 10^{-9} cm^3 STP ^{40}Ar. All blanks have an approximately atmospheric isotopic composition. The data have been corrected for blanks, mass discrimination, and neutron-interference reactions. Further details of the experimental methods and data reduction procedures are given in Burgess and Turner (1998) and Fernandes et al. (2000).

RESULTS AND DISCUSSION

NWA 032

Ar-Ar Age Determination

The stepped heating results obtained from NWA 032 (samples G3 and G4) have been discussed previously (Fagan et al. 2002). The data for E2, from a different part of the meteorite, are presented mainly to confirm our previous findings and interpretations. The Ar-Ar age and K/Ca spectra are shown in Fig. 1, and the age and chemical information is summarized in Table 1. Both samples (G and E) contain negligible amounts of trapped solar Ar and retrapped ^{40}Ar as indicated by $^{38}Ar/^{36}Ar$ ratios that are, with the exception of the lowest and highest temperature steps, very close to that expected for cosmogenic argon (1.54). The age spectra of E and G samples show a similar complex pattern (Fig. 1a). There is evidence for a small amount of ^{40}Ar loss (3–5%) at low temperature (<400°C), followed by increasing apparent ages between 400–500°C, reaching a maximum of 3.2–3.5 Gyr over 20–30% of the ^{39}Ar release. Thereafter, apparent ages decrease to 2.4–2.8 Gyr for 70–80% of the ^{39}Ar release. The total Ar release ages obtained for G3, G4, and E2 are indistinguishable at 2.775 ± 0.092 Gyr, 2.800 ± 0.020 Gyr, and 2.741 ± 0.019 Gyr respectively (weighted mean = 2.779 ± 0.014 Gyr). Note that an age of 2.80 Gyr is within the range of the second lunar volcanism peak, e.g., young flows within the Mare Imbrium or Mare Serenitatis, as suggested by Hiesinger et al. (2000). The reasons underlying the complex spectra are not fully understood. Two possible interpretations, proposed by Fagan et al. (2002), are considered here:

^{39}Ar Recoil Artefact: The fine-grained texture of the K-bearing phases in NWA 032 (See Fig. 4 in Fagan et al. [2002]) means that ^{39}Ar recoil is likely to influence the Ar release. During nuclear irradiation, recoil of ^{39}Ar from fine-grained K-rich plagioclase and shock-melt veins to K-poor pyroxene may lead to artificially high apparent ages at low temperatures and low apparent ages during high temperature release from pyroxene (Turner and Cadogan 1974). This change in release from plagioclase and shock veins to pyroxene with increasing temperature is supported by results from G2 and G3, which show a decrease in K/Ca from 0.25 to 0.04 with increasing temperature (Fig. 1b). Sample E2 shows a similar trend of a decreasing K/Ca ratio but has a significantly lower value of ~0.07 at low temperature. This may be explained most easily by the lower plagioclase content of this sample inferred from its low K content (Table 1). The decrease in K/Ca (Fig. 1b) from ~0.25 to ~0.001 (G3 and G4) with increasing release temperature indicates that the low temperature Ar release is dominated by plagioclase and shock-melt veins, while the high temperature Ar release is dominated by pyroxene (the most abundant phase in NWA 032). If this is the explanation for the complex age spectrum, then the total Ar-Ar age of 2.80 Gyr can be interpreted as having geological significance, possibly indicating the time of the original crystallization.

Retention of Pre-Shock ^{40}Ar in Melt Veins: Ar-Ar laser probe measurements of melt glass in the Peace River meteorite (McConville et al. 1988) have shown that radiogenic ^{40}Ar can be retained preferentially in shock-produced melt glass that is rapidly quenched. If this occurred during the formation of the shock-melt veins in NWA 032, it is possible that the highest apparent ages represent partial retention of pre-shock radiogenic ^{40}Ar by the melt glass. In this case, the intermediate release ages of 2.4–2.8 Gyr may record the time of thermal annealing following the impact. However, it is considered unlikely that this represents the timing of a major impact responsible for the formation of the melt veins. Fagan et al. (2002) have argued that the melt veins are more likely to be formed by the impact that ejected NWA 032 from the lunar surface, an event that did not affect the K-Ar systematics significantly.

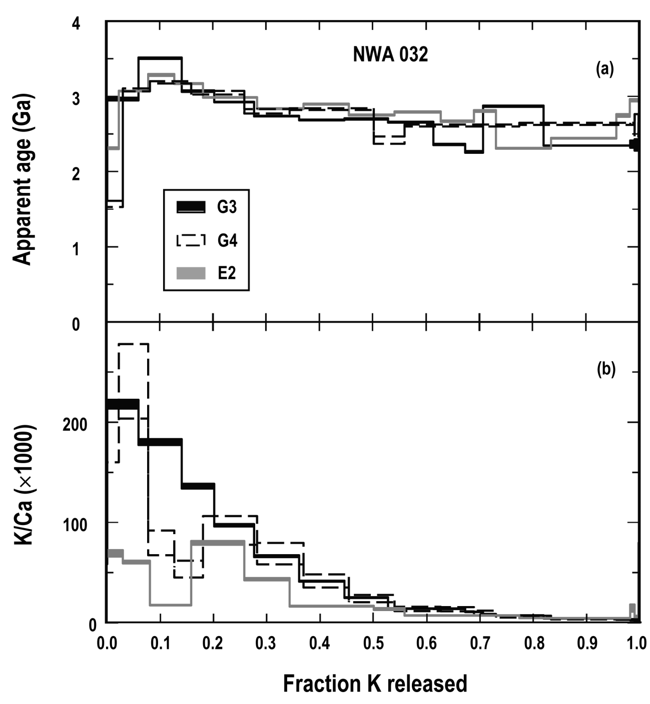

Fig. 1. Step-heating results for NWA 032 fragments G3, G4, and E2: a) apparent age versus fraction of ^{39}Ar released; b) K/Ca versus fraction of ^{39}Ar released.

Table 1. Summary of ^{40}Ar-^{39}Ar age data for Northwest Africa 032 lunar meteorite obtained by stepped heating and Ar laser fusion.

Sample	Weight (mg)	K[a] (ppm)	Ca[a] (%)	Age (Ga)	CRE age (Myr)
Ta-Furnace step-heating					
G3	14.073	1206 ± 16	9.89 ± 0.10	2.78 ± 0.09	213 ± 2
G4	11.730	1061 ± 12	9.22 ± 0.02	2.80 ± 0.02	212 ± 33
E2	8.803	210 ± 3	1.73 ± 0.03	2.74 ± 0.02	209 ± 2
Laser single-shot					
G2 subfragments	0.04–0.1	nd[b]	nd	2.73 ± 0.03 (2.61–2.86)	232 ± 8 (217–256)

[a]K and Ca content reported were calculated based on the ^{39}Ar and ^{37}Ar released during laser heating.
[b]nd = not determinable.

In an attempt to minimize the effects of melt veins, and to better study the effects of any trapped ^{40}Ar within the sample, the apparent ages of 20 small sub-fragments of G2, weighing between 0.04 and 0.10 mg, were determined using laser fusion (results summarized in Table 2). Shock-melt veins comprise only 3.2 vol% of the bulk meteorite and are present as linear features (Fagan et al. 2002), so it is reasonable to expect that each sample will contain a different proportion of vein material. Furthermore, using the mass of each sample and assuming each is a sphere with a density of 2.95 g/cm^2 (using the method of Wieczorek et al. 2001), a size range of 300–400 μm is estimated. The samples are, therefore, of similar size to the phenocrysts and significantly smaller than the distance between shock veins, which are typically ~1 mm apart. Thus, it is unlikely that all the randomly selected samples contain the same proportions of shock vein material. If the shock veins contain preshock ^{40}Ar, according to the second hypothesis above, the apparent ages obtained by laser fusion would be expected to show a continuous distribution between 2.8–3.5 Gyr, with the apparent age of each subfragment being dependent on the amount of shock vein present. If, on the other hand, the high ages of 3.2–3.5 Gyr in the age spectrum result from ^{39}Ar recoil effects between feldspar and pyroxene as in the first hypothesis, a much narrower age distribution centered at the whole-rock age of ~2.8 Gyr is expected. The results obtained by laser fusion of 20 subsamples of G2 are shown as a histogram in Fig. 2. With the exception of 1 low age of 2.4 Gyr, a narrow range of apparent ages is obtained between 2.61–2.86 Gyr with a mean of 2.73 ± 0.03 Gyr (Fig. 2, Table 2). Moreover, in 2 samples, Ar was extracted in 2 steps, with 1 step being below the fusion temperature of the basalt. Only 1 of these samples showed a higher apparent age from that of the low temperature step, for the other, the 2 steps gave ages that were indistinguishable within error. The lack of any laser probe ages >3 Gyr seems to indicate that shock-melt veins do not contain pre-shock ^{40}Ar and that recoil is the most likely explanation for the complex shape of the age spectra. The mean age obtained from the laser probe results is in good agreement with the total ages obtained by stepped heating of G3, G4, and E2, again indicating that the basalt crystallized 2.8 Gyr ago. Further insight into the origin of the low temperature release is provided by argon diffusion studies discussed in the next section.

Argon Diffusion in NWA 032

In an attempt to better understand the Ar release pattern of the NWA 032, we have carried out a series of diffusion calculations. The aim of these calculations is to determine the source of the high apparent ages observed during the low temperature steps as well as the sites (phases) releasing ^{37}Ar and ^{39}Ar. Release profiles of ^{37}Ar and ^{39}Ar as a function of temperature are shown in Figs. 3a and 3b. The ^{39}Ar release pattern (Fig. 3a) shows a bimodal distribution with a small intermediate-temperature release at 650–800°C (34–45% of the total ^{39}Ar) and a high temperature peak at 1000–1050°C (12–21% of the total ^{39}Ar). The bimodal release of ^{39}Ar indicates release from 2 different minerals that differ by several orders of magnitude in the ease at which argon diffuses at a given temperature (Bogard and Hirsch 1980). The increase in ^{37}Ar release above 900°C (Fig. 3b), combined with a low K/Ca ratio (~0.002), indicates the presence of a high temperature (K-poor) phase with a major release at 1000–1100°C accounting for between 64–75% of the total ^{37}Ar release. The most likely phase is pyroxene, which is abundant in the groundmass of NWA 032 and is present as phenocrysts.

The diffusion coefficient (D) is related to temperature (T) by an Arrhenius equation:

$$\frac{D}{a^2} = \left(\frac{D_0}{a^2}\right)e^{\left(-\frac{E}{RT}\right)}$$

Where E is the activation energy, R is the gas constant, and a is the grain radius. A plot of ln D/a^2 versus 1/T for volume diffusion in a mineral should give a linear relationship from which the activation energy and the pre-exponential factor (D_0/a^2) can be derived. However, in whole rock samples comprising polymineralic systems, the Arrhenius plots become complex, mainly as a result of the transition from the degassing of a low temperature phase to a higher temperature phase, but also from possible recoil of ^{39}Ar and ^{37}Ar between

Table 2. Chemical composition, ^{40}Ar-^{39}Ar age, and CRE-age data for subfragments G2 of Northwest Africa 032 lunar meteorite obtained by Ar laser-fusion.

Subfragments	Weight (mg)	K[a] (ppm)	Ca[a] (%)	Age (Ga)	CRE age (Myr)
1 (Fusion)	0.06	414 ± 2	3.17 ± 0.02	2.78 ± 0.01	235 ± 2
2 (Fusion)	0.07	3473 ± 6	2.95 ± 0.02	2.73 ± 0.03	234 ± 2
3 (Fusion)	0.10	283 ± 1	2.46 ± 0.01	2.77 ± 0.01	235 ± 1
4 (Fusion)	0.07	61 ± 1	1.29 ± 0.01	2.70 ± 0.01	239 ± 2
5 (Fusion)	0.05	331 ± 3	3.30 ± 0.01	2.82 ± 0.03	232 ± 3
6 (Fusion)	0.06	282 ± 2	2.40 ± 0.01	2.61 ± 0.01	218 ± 2
7 (Fusion)	0.05	192 ± 2	1.56 ± 0.01	2.71 ± 0.01	227 ± 2
8 (Fusion)	0.07	335 ± 3	2.73 ± 0.02	2.71 ± 0.01	226 ± 2
9 (Fusion)	0.04	701 ± 5	6.27 ± 0.03	2.68 ± 0.01	229 ± 1
10 (Fusion)	0.09	249 ± 2	2.11 ± 0.01	2.45 ± 0.01	217 ± 1
11 (Fusion)	0.08	313 ± 2	2.51 ± 0.01	2.83 ± 0.01	234 ± 2
12 (11.5 A)	0.10	54 ± 1	0.17 ± 0.00	2.74 ± 0.02	256 ± 10
12 (Fusion)	0.10	125 ± 1	1.29 ± 0.01	2.79 ± 0.02	232 ± 2
13 (Fusion)	0.05	212 ± 2	1.61 ± 0.01	2.76 ± 0.02	231 ± 2
14 (Fusion)	0.07	372 ± 3	2.68 ± 0.02	2.8 ± 0.01	237 ± 2
15 (Fusion)	0.07	259 ± 138	17.84 ± 1.11	2.75 ± 0.01	223 ± 1
16 (Fusion)	0.06	259 ± 3	2.36 ± 0.01	2.70 ± 0.02	234 ± 2
17 (Fusion)	0.08	279 ± 1	2.67 ± 0.01	2.74 ± 0.01	229 ± 1
18 (Fusion)	0.05	195 ± 1	1.90 ± 0.01	2.70 ± 0.01	226 ± 2
19 (Fusion)	0.08	245 ± 1	2.10 ± 0.01	2.74 ± 0.01	233 ± 2
20 (11.2 A)	0.10	96 ± 1	0.35 ± 0.00	2.86 ± 0.02	239 ± 4
20 (Fusion)	0.10	188 ± 2	2.05 ± 0.01	2.68 ± 0.01	231 ± 2

[a]K and Ca content reported were calculated based on the ^{39}Ar and ^{37}Ar released during laser heating.

different mineral phases. In NWA 032, the transition between low and high temperature phases during Ar release can be identified by using the decrease in K/Ca values. ^{37}Ar and ^{39}Ar data from each sample were partitioned into a "low temperature" release (low T; ≤1000°C), having K/Ca range of 0.24–0.014, and a "high temperature" release (high T; ≥1000°C), defined by having K/Ca between 0.017–0.002. Values of D/a^2 for each temperature step were calculated using the equations of Fechtig and Kalbitzer (1966) assuming volume diffusion of Ar from spherical grains.

^{37}Ar and ^{39}Ar Arrhenius plots for the NWA 032 samples are shown in Figs. 3c and 3d. The results for samples G3 and G4 overlap for both the low and high temperature groups, indicating that both samples have a similar mineralogical composition. However, the data obtained for fragment E2 do not show the same overlap at low temperature, and this is considered to reflect differences in mineralogical composition for this fragment compared with the other 2 fragments analyzed. For ^{39}Ar calculations, the activation energy (E) obtained for the low temperature steps is in the range of 15.9–19.6 kcal mol^{-1}. The low temperature activation energy obtained here is much lower than the typical value for feldspar in unshocked chondrites of 45 ± 7 kcal mol^{-1} (Turner et al. 1978), but is characteristic of heavily shocked chondrites (Turner et al. 1978; McConville et al. 1988) and may be characteristic of maskelynite. The activation energy for high temperature ^{39}Ar release is 55.9–71.8 kcal mol^{-1}, similar to values previously obtained by McConville et al.

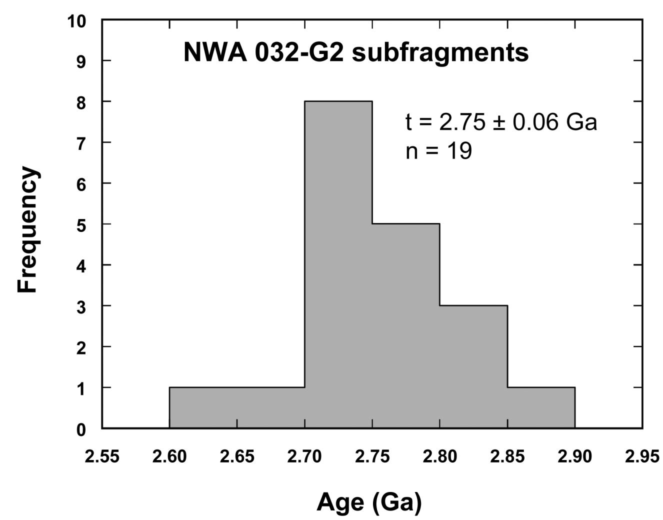

Fig. 2. Histogram of laser fusion ages for subfragment G2 of NWA 032 representing the frequency of ages obtained.

(1988) for pyroxene of ≥50 kcal mol^{-1}. Activation energies obtained for ^{37}Ar (Fig. 3d) at low temperature are in the range of 17.4–26 kcal/mol. The activation energy (E), associated with the release of ^{37}Ar during high temperature steps, is in the range of 64–98 kcal/mol, overlapping but extending to higher energies than obtained from ^{39}Ar release. The high activation energy and the high ^{37}Ar release temperature (Fig. 3a) imply release from pyroxene.

To determine whether NWA 032 resided for any time on the lunar surface or spent most of its history buried at depth, laboratory results are inferred to mimic the natural outgassing (effective outgassing) on the lunar surface (Turner 1979; 1981; McConville et al. 1988). The "effective outgassing temperature" (T_e) is defined as the temperature required to produce, during a nominal half-hour heating period (t_0) in the laboratory, a fractional loss of ^{39}Ar equivalent to the fractional loss of radiogenic ^{40}Ar that occurred in nature. The "effective outgassing" temperature is related to the annealing time (t) during which the meteorite was heated to a temperature (T) by the equation:

$$\frac{1}{T_e} = \frac{1}{T} - \frac{R}{E}\ln\left(\frac{t}{t_0}\right)$$

An "effective outgassing" temperature of 1000°C was chosen for the calculation because most of the argon in feldspathic phases is released at this temperature. Using the results obtained for Ar diffusion calculations, the activation energy (E) obtained for a half-hour heating step at 300°C was determined to be equivalent to the heating at 27°C for 2.80 Gyr. Thus, following formation at 2.80 Gyr, NWA 032 has not experienced a significant heating event. In a study of the bulk thermal properties of the surrounding regolith material of the Apollo 15 and 17, Langseth et al. (1976) showed that the heat-flow gradient in the upper regolith layer is small to negligible. For NWA 032 to lose 3–5% ^{40}Ar means that it had to be deposited deep for temperatures to be >300°C and be shielded from the lunar diurnal surface heating.

NWA 773

A summary of the age and chemical information for NWA 773 is presented in Table 3. Ar-Ar results of the cumulate and breccia portions of NWA 773 are shown in Fig. 4. Initial inspection of the age spectra (Fig. 4a) would seem to suggest that the two lithologies have different Ar age spectra despite yielding similar total ages of 2.67 ± 0.01 Gyr and 2.94 ± 0.01 Gyr for the cumulate and breccia respectively. However, when the apparent ages are plotted against the fraction of ^{37}Ar (Fig. 4b), the pattern of the age spectra are more similar, indicating that Ar is being released from the same mineral phases in both samples but that the proportion of these phases is different in each lithology. The lower K content of the cumulate (400 ppm) and lower K/Ca for the low temperature steps (Fig. 4c), when compared to the breccia K content (1200 ppm), suggests it has a lower feldspar content. Zeigler and Korotev (personal communication 2002) have observed the existence of a K-rich phase within the breccia portion of NWA 773.

The breccia contains a significant amount of trapped ^{40}Ar with a $^{40}Ar/^{36}Ar$ = 1.27, as determined from a plot of $^{36}Ar/^{40}Ar$ versus $^{39}Ar/^{40}Ar$ (not shown). The presence of solar noble gases has previously been reported for the regolith breccia with $^{4}He/^{20}Ne$ of ~9 (Eugster and Lorenzetti 2001; Fagan et al. 2001), similar to gas-rich lunar meteorites. In contrast, the cumulate fraction does not contain trapped Ar. Therefore, the data are in no case compromised by trapped Ar. Correction of the breccia Ar data for trapped ^{40}Ar results in an age spectrum similar to that of the cumulate (Fig. 4b). The relatively high trapped Ar content of the breccia means that the apparent ages obtained from most steps are sensitive to the choice of $^{40}Ar/^{36}Ar$ used for the trapped component such that it is not possible to determine whether the 2 lithologies have different ages. Rather, the similarity in the age spectra between the 2 samples seems to argue in favor of both of them having an age of ~2.7 Gyr with the slightly older apparent age of the breccia due to an under correction for, or variation in, the trapped $^{40}Ar/^{36}Ar$ ratio. Note that this value would only have to be lowered slightly to 1.53 to obtain a total age of ~2.7 Gyr for the breccia. For the cumulate, the age obtained for Ar released above 1100°C, corresponding to 54% of the ^{39}Ar release, is 2.91 ± 0.01 Gyr (Fig. 4a). That our sample of cumulate does not contain any breccia material is indicated by the lack of any trapped ^{40}Ar and differences in exposure age between breccia and cumulate lithologies (discussed below). The cumulate and breccia appear to have very similar Ar-Ar ages but differ in their amounts of trapped and cosmogenic Ar contents. If a major shock event affected the Ar system at 2.9 Gyr, assembling the 2 lithologies in their present close proximity, then trapped and cosmogenic Ar should also have been outgassed from the basalt. However, this is not observed. If the 2 lithologies were intermixed, therefore, explaining how the breccia, but not the cumulate, could have experienced surface exposure is difficult. An explanation more consistent with the data would be that the VLT basalt and the genetically related, deeper-formed cumulate both crystallized at 2.9 Gyr. The upper basalt layers were then subsequently brecciated, but not melted, in the upper levels of the lunar regolith, causing no substantial resetting of the K-Ar system. Mixing with cumulate material could then have occurred during the impact that removed the meteorite from the lunar surface.

Exposure Ages

The cosmic ray exposure (CRE) ages of NWA 032 and NWA 773 were determined for each temperature step using the $^{38}Ar_c$/Ca (where $^{38}Ar_c$ is the measured ^{38}Ar corrected for trapped ^{38}Ar) value. Cosmic-ray production rates of ^{38}Ar are based on the method of Eugster and Michel (1995), which takes into account the contribution from Ca, Fe, Ti, Cr, Mn, K, and Ni. For these calculations, we used the bulk chemical compositions of NWA 032 and NWA 773 published by Fagan et al. (2002) and Jolliff et al. (2003) respectively. Using this approach, Ca is estimated to account for 82% of the $^{38}Ar_c$ in NWA 032. The corresponding figures for NWA 773 are 87% and 79% of Ca-derived $^{38}Ar_c$ in the breccia and cumulate, respectively. The calculated 2π production rates, in units of $\times 10^{-8}$ cm^3 STP/g Ca/Myr, are as follows: 1.111 for NWA

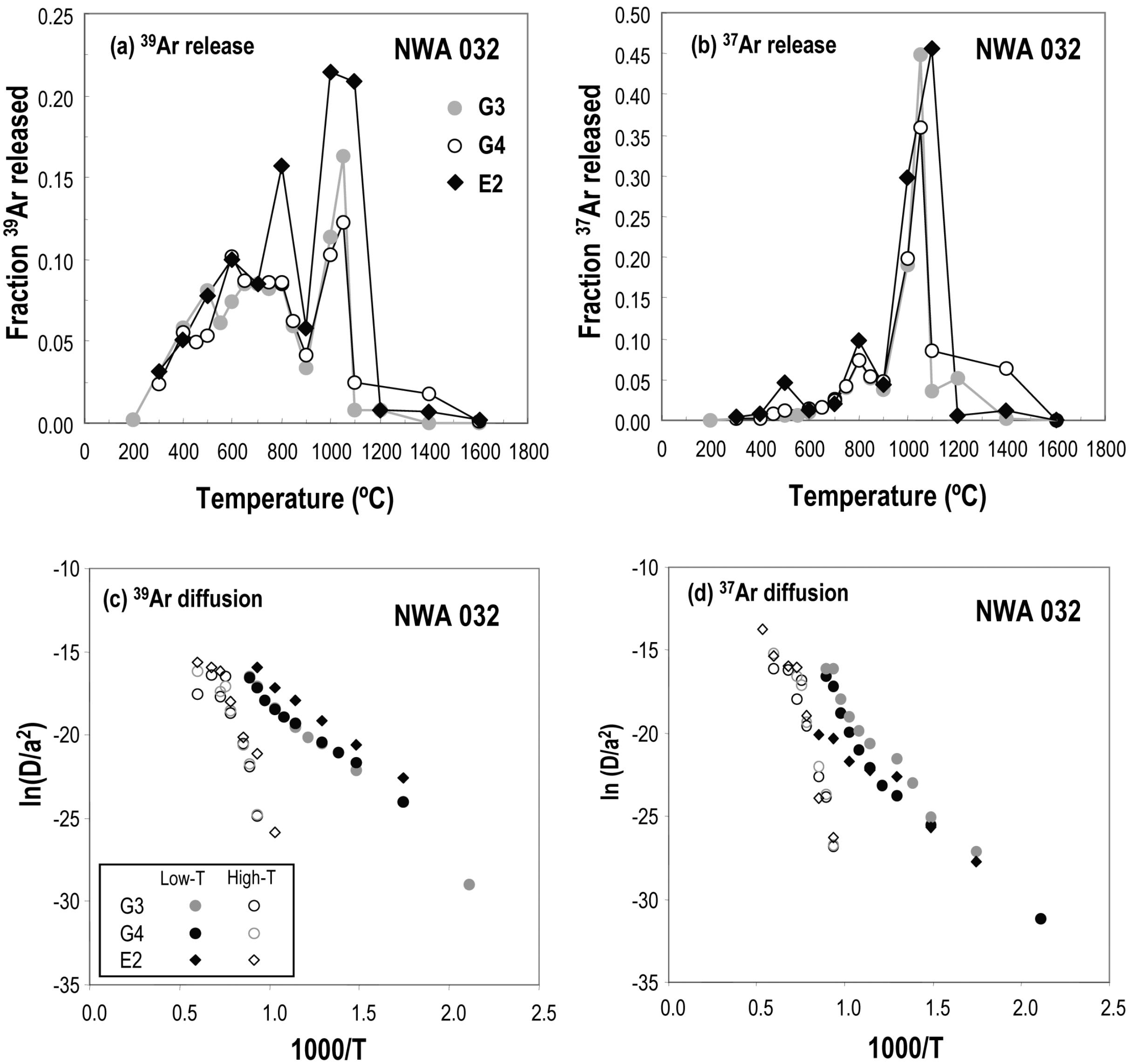

Fig. 3. Fraction of (a) ^{39}Ar and (b) ^{37}Ar released versus temperature for whole-rock NWA 032 samples. Arrhenius plots of (c) ^{39}Ar and (d) ^{37}Ar. The high temperature and the low temperature calculations are based on the partitioning of the fraction of argon released (see Figs. 2b, 3a, and 3b). A best-fit line for each temperature set of points yields the activation energy (E) for Ar diffusion. Each slope represents a distinct diffusion domain interpreted to correspond to different mineral phases.

032; 1.147 for NWA 773 cumulate; and 1.044 for NWA 773 breccia. The CRE ages (Fig. 5 and Tables 1–3) have errors that only include analytical precision. They do not include uncertainties in production rates, which are a function of shielding depth in the lunar regolith. The stated ages should, therefore, be considered minimum values.

Apparent CRE ages for NWA 032 are shown in Fig. 5a. The ^{38}Ar/^{36}Ar ratios for all the NWA 032 fragments analyzed have a cosmogenic value of 1.54 consistent with a negligible trapped ^{36}Ar content in this meteorite. The $^{38}Ar_c$/Ca ratios are relatively high for the low temperature steps of NWA 032, possibly due to the presence of reactor-derived $^{38}Ar_{Cl}$ formed from Cl-bearing terrestrial contaminants. Between 80–90% of the ^{37}Ar is released above 800°C in all samples of NWA 032 and NWA 773 and is inferred to be dominantly from pyroxene. All samples of NWA 032 give a flat spectrum of CRE ages (Fig. 5a), and the total release CRE ages are indistinguishable within an average of 212 ± 11 Myr. CRE ages from G2 subfragments are broadly similar with a range between 217–256 Myr and an average of 232 ± 8 Myr.

The cumulate lithology of NWA 773 gives a flat CRE age spectrum (Fig. 5b) with a total release exposure age of 73 ± 2 Myr. The exposure age spectrum of the breccia is complicated showing a maximum of 233 Myr and declining at high temperature to 99 Myr. The complex spectrum implies release of cosmogenic ^{38}Ar from at least two different phases,

Table 3. Summary of ^{40}Ar-^{39}Ar age data for Northwest Africa 773 lunar meteorite obtained by stepped heating.

Sample	Weight (mg)	K[a] (ppm)	Ca[a] (%)	Age (Ga)	CRE age (Myr)
Ta-Furnace step-heating					
Cumulate	3.203	412 ± 6	5.11 ± 0.03	2.66 ± 0.02	73 ± 2
Breccia	10.876	1238 ± 9	7.39 ± 0.04	2.92 ± 0.01	154 ± 3

[a]K and Ca content reported were calculated based on the ^{39}Ar and ^{37}Ar released during laser heating.

occurring at low and high temperature. The total release 2π exposure age is 154 ± 3 Myr. This exposure age is in broad agreement with a previous report of ~160 Myr (Eugster and Lorenzetti 2001) based on noble gas studies. Thus, it is appears that the cumulate and breccia portions of the NWA 773 experienced different degrees of exposure/burial in the lunar regolith. The higher exposure age of the breccia is consistent with the relatively high trapped Ar content of this lithology.

Implications and Source Areas

The Ar-Ar ages obtained in this study of 2.8 and 2.9 Gyr for NWA 032 and NWA 773, respectively, are the youngest ages reported so far for lunar samples. This is the first prima facie evidence that lunar volcanism continued beyond the age of the youngest mare dated at 3.1 Gyr. Based on crater counts, young mare units of <3.0 Gyr have been predicted to be present in most of the large lunar basins on the near side (Hiesinger et al. 2000; Schultz and Spudis 1983). Many of the younger extrusions are of significant aerial extent, and their distribution is not always restricted to the margins of the basins (Hiesinger et al. 2000).

The most useful approach in determining possible source regions for lunar meteorites is attempting to match chemical and age data obtained from the meteorite, with remotely obtained global chemical maps and crater count age determinations. Chemical maps are currently restricted to FeO, TiO_2, and Th abundances. Using this approach, Fagan et al. (2002) identified the following likely source areas for NWA 032, in descending order of probability, to be Mare Humorum, Mare Fecunditatis, western Mare Serenitatis, Mare Crisium, and far western Oceanus Procellarum. More recently, Lawrence et al. (2002), by refining the FeO data obtained by the Lunar Prospector, were able to suggest that NWA 032 most likely derives from the Western Oceanus Procellarum where surfaces of <3 Gyr age have been suggested to occur (Hiesinger et al. 2000).

The cumulate lithology of NWA 773 has FeO = 18.1 wt%, TiO_2 = 0.24 wt% (Jolliff et al. 2003), a Th content of 14 ppm (J. Bridges personal communication), and an age of 2.9 Gyr. The high Th and Fe content constrain the source area to the near side within the Procellarum-KREEP terrain. Regions with Th >10 ppm are predominantly found within central areas of mare basins (Chevrel et al. 2002). Interestingly, this includes eastern areas of Oceanus Procellarum (Jolliff et al. 2001), but an origin from many other basins cannot be excluded based on available data. Thus, both NWA 032 and NWA 773 are most likely to have been derived from within the PKT region, where the youngest lava flows have been identified using crater counts. The source region in the mantle

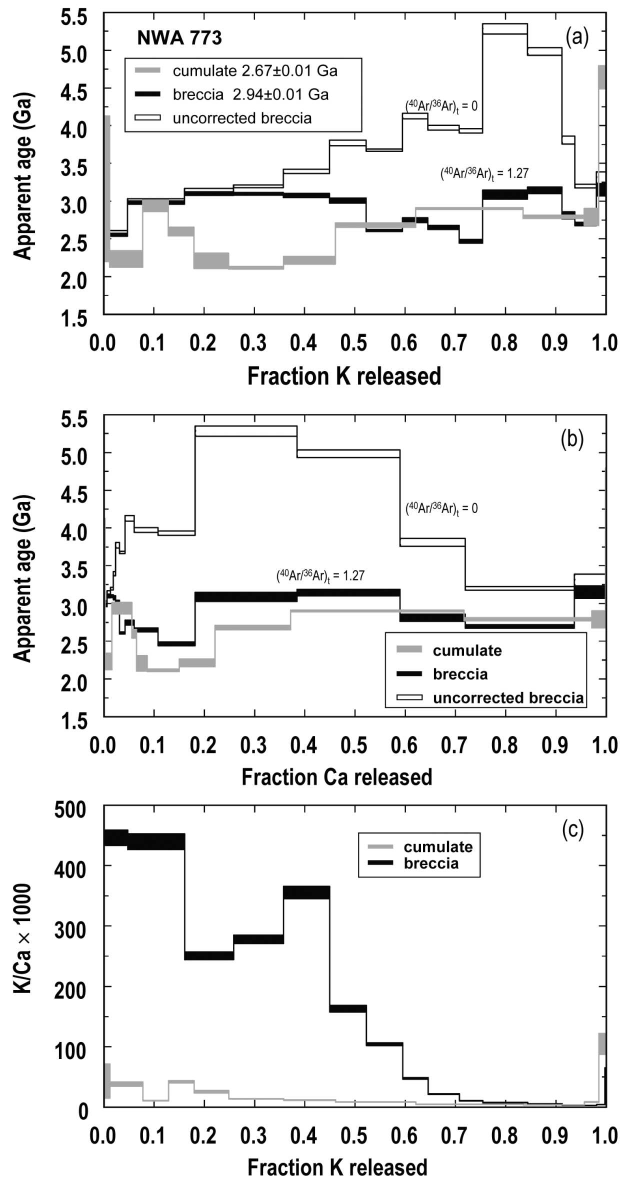

Fig. 4. NWA 773 step-heating results: a) apparent age versus fraction of ^{39}Ar released; b) apparent age versus fraction of ^{37}Ar released; and c) K/Ca versus fraction of ^{39}Ar released.

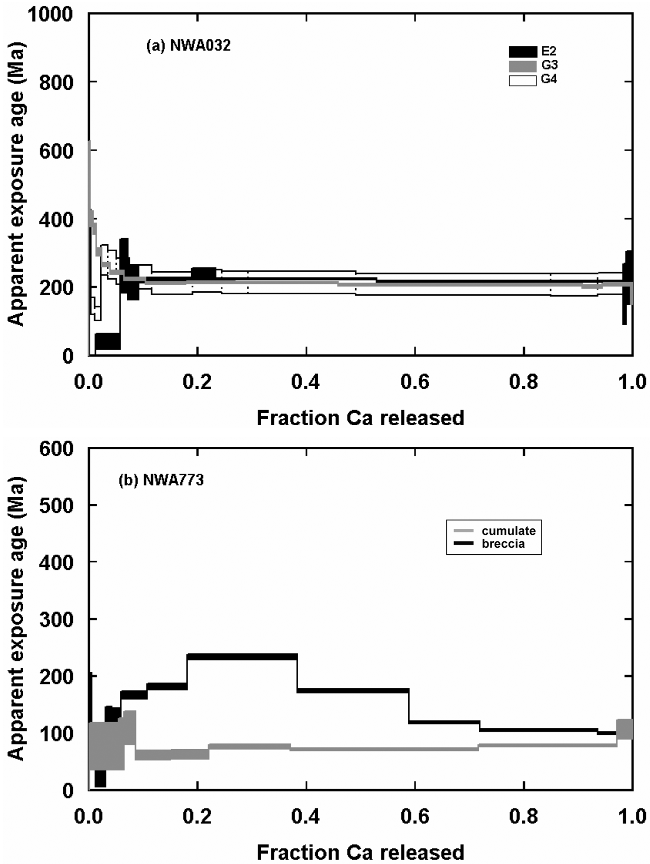

Fig. 5. Cosmic ray exposure age (CRE-age) versus fraction of ^{37}Ar released for (a) NWA 032 fragments G3, G4, and E2 and (b) NWA 773 breccia and cumulate lithologies.

for these basalts was probably heated over an extended period due to the existence of a reservoir of an overturned incompatible-element-rich layer similar to that suggested by Hess and Parmentier (1995, 2001) and Wieczorek and Phillips (2000). Both lunar meteorites have relatively high Th contents compared with Apollo and Luna samples. Further refinement of Lunar Prospector and Clementine datasets, in addition to those that may become available from the SMART-1 mission, may shed further light on the source region of these meteorites.

CONCLUSIONS

The basaltic lunar meteorite Northwest Africa 032 has an age of 2.8 Gyr, an age in the Erathosthenian Period of the lunar chronostratigraphy. The age spectra show a relatively undisturbed pattern at intermediate and high temperature steps, which suggests that the age is a crystallization age and makes it the youngest lunar basalt analyzed. It contains a negligible trapped Ar component and has a cosmogenic $^{38}Ar/^{36}Ar$ value (~1.54). Laser fusion experiments on small (<0.1 mg) subfragments show that glass veins present within this meteorite are unlikely to be influencing the age information either by ^{39}Ar recoil or shock implantation of pre-existing radiogenic ^{40}Ar. Diffusion calculations, based on the argon released during the step-heating experiments, confirm that this meteorite did not experience any thermal disturbance that could have significantly affected the argon distribution within the sample, as the high and low temperature results show a well constrained change in phases dominating the release.

The age obtained from the high temperature steps from the cumulate lithology of NWA 773 is 2.91 Gyr. The age of the breccia, while partially compromised by the presence of trapped solar wind Ar and retrapped ^{40}Ar, appears to be broadly consistent with this estimate. This suggests coeval formation of the two lithologies of NWA 773, which are notably similar in age to NWA 032. We argue that the relatively young age of NWA 773 is unlikely to be related to shock given the difference in exposure age and the presence of trapped Ar in the breccia. If a major shock event at 2.9 Gyr affected both lithologies and assembled the meteorite in its present form, it would have been expected to reset the exposure ages and degass the breccia of solar wind Ar components. We suggest, instead, that the cumulate olivine-gabbro, and VLT basalt, crystallized contemporaneously at 2.9 Gyr.

The high Fe and Th contents of NWA 032 and NWA 773, combined with their young ages, indicate a source region from within the large lunar basins on the PKT region on the near side of the Moon.

Acknowledgments–We thank Tim Fagan and Marvin Kilgore for generously supplying us with the samples of NWA 032 and NWA 773, respectively. Dave Blagburn and Bev Clementson are thanked for technical support in the noble gas laboratory. Reviews by Barbara Cohen and an anonymous reviewer and the editorial assistance of Rainer Wieler led to significant improvement of the original manuscript. We thank John Bridges, Randy Korotev, Silvio Lorenzetti, and Ryan Zeigler for helpful discussions. Financial support was provided by an EEC-TMR fellowship to V. A. Fernandes.

Editorial Handling—Dr. Rainer Wieler

REFERENCES

Bogard D. D. and Hirsch W. C. 1978. Noble gases in Luna 24 core soils. *In Mare crisium: The view from Luna 24*, edited by Merill R. B. and Papike J. J. New York: Pergamon Press. pp. 105–116.

Burgess R. and Turner G. 1998. Laser ^{40}Ar-^{39}Ar age determinations of Luna 24 mare basalts. *Meteoritics & Planetary Science* 33: 921–935.

Chevrel S. D., Pinet P. C., Daydou Y., Maurice S., Lawrence D. J., Feldman W. C., and Lucey P. G. 2002. Integration of the Clementine UV-VIS spectral reflectance data and the Lunar Prospector gamma-ray spectrometer data: A global multielement analysis of the lunar surface using iron, titanium, and thorium

abundances. *Journal of Geophysical Research* 107:5132.
Eugster O. and Michel T. 1995. Common asteroid break-up events of eucrites, diogenites, and howardites and cosmic-ray production rates for noble gases in chondrites. *Geochimica et Cosmochimica Acta* 59:177–199.
Eugster O., Beer J., Burger M., Finkel R. C., Hoffmann H. J., Krähenbühl U., Michel T., Synal H. A., and Wölfli W. 1991. History of the paired lunar meteorites MAC88104 and MAC88105 derived from noble gas isotopes, radionuclides, and some chemical abundances. *Geochimica et Cosmochimica Acta* 55:3139–3148.
Eugster O. and Lorenzetti S. 2001. Exposure history of some differentiated and lunar meteorites (abstract). *Meteoritics & Planetary Science* 36:A54.
Fagan T. J., Bunch T. E., Wittke J. H., Jarosewich E., Clayton R. N., Mayeda T., Eugster O., Lorenzetti S., Keil K., and Taylor G. J. 2000. Northwest Africa 032, a new lunar mare basalt. *Meteoritics & Planetary Science* 35:A51.
Fagan T. J., Taylor G. J., Keil K., Bunch T. E., Wittke J. H., Korotev L., Jolliff B. L., Gillis J. J., Haskin L. A., Jarosewich E., Clayton R. N., Mayeda T. K., Fernandes V. A., Burgess R., Turner G., Eugster O., and Lorenzetti S. 2002. Northwest Africa 032: Product of lunar volcanism. *Meteoritics & Planetary Science* 37: 371–394.
Fagan T. J., Keil, K., Taylor G. J., Hicks T. L., Kilgore M., Bunch T. E., Wittke J. H., Eugster O., Lorenzetti S., Mittlefehldt D. W., Clayton R. N., and Mayeda T. 2001. New lunar meteorite Northwest Africa 773: Dual origin by cumulate crystallization and impact brecciation. *Meteoritics & Planetary Science* 36: A55.
Fechtig H. and Kalbitzer S. 1966. The diffusion of argon in potassium bearing solids. In *Potassium-Argon dating,* edited by Schaeffer O. A. and Zahringer J. H. Amsterdam: Springer-Verlag. pp. 68–106.
Fernandes V. A., Burgess R., and Turner G. 2000. Laser ^{40}Ar-^{39}Ar studies of Dar al Gani 262 lunar meteorite. *Meteoritics & Planetary Science* 35:1355–1364.
Grossman J. N. and Zipfel J. 2001. The Meteoritical Bulletin, No. 85. *Meteoritics & Planetary Science* 36:A293–322.
Haskin L. A. 1998. The Imbrium impact event and the thorium distribution at the lunar highlands surface. *Journal of Geophysical Research* 103:1679–1689.
Hess P. C. and Parmentier E. M. 1995. A model for the thermal and chemical evolution of the moon's interior: Implications for the onset of mare volcanism. *Earth and Planetary Science Letters* 134:501–514.
Hess P. C. and Parmentier E. M. 2001. Thermal evolution of a thicker KREEP liquid layer. *Journal of Geophysical Research* 106: 28,023–28,032.
Hiesinger H., Jaumann R., Neukum G., and Head J. W. 2000. Ages of mare basalts on the lunar nearside. *Journal of Geophysical Research* 105:29,239–29,275.
Jolliff B. L., Korotev R. V., Zeigler R. A., Floss C., and Haskin L. A. 2003. Northwest Africa 773: Lunar mare breccia with a shallow-formed olivine cumulate component, very low-Ti heritage and a KREEP connection (abstract #1935). 34th Lunar and Planetary Science Conference. CD-ROM.
Korotev R. L. 2000. The 'Great Lunar Hot Spot' and the composition and origin and origin of the Apollo mafic ('LKFM') impact-melt breccias. *Journal of Geophysical Research* 105:4317–4345.
Korotev R. L., Jolliff B. L., Wang A., Gillis J. J., Haskin L. A., Fagan T. J., Taylor G. J., and Keil K. 2001. Trace-element concentrations in Northwest Africa 032 (abstract #1451). 32nd Lunar and Planetary Science Conference. CD-ROM.
Korotev R. L., Zeigler R. A., Jolliff B. L. and Haskin L. A. 2002. Northwest Africa 773—An unusual rock from the lunar maria (abstract). *Meteoritics & Planetary Science* 37:A81.
Langseth M. G., Keihm S. J., and Peters K. 1976. Revised lunar heat-flow values. Proceedings, 7th Lunar and Planetary Science Conference. pp. 3143–3171.
Lawrence D. J., Feldman W. C., Elphic R. C., Little R. C., Prettyman T. H., Maurice S., Lucey P. C., and Binder A. B. 2002. Iron abundances on the lunar surface as measured by the Lunar Prospector gamma-ray and neutron spectrometers. *Journal of Geophysical Research* 107:5130.
McConville P., Kelley S., and Turner G. 1988. Laser probe ^{40}Ar-^{39}Ar studies of the Peace River shocked L6 chondrite. *Geochimica Cosmochimica Acta* 52:2487–2499.
Schultz P. H. and Spudis P. D. 1983. Beginning and end of lunar mare volcanism. *Nature* 302:233–236.
Turner G. 1979. A Monte Carlo fragmentation model for the production of meteorites: Implications for gas retention age. Proceedings, 10th Lunar and Planetary Science Conference. pp. 1917–1941.
Turner G. 1981. Argon-argon age measurements and calculations of temperatures resulting from asteroidal break-up. *Proceedings of the Royal Society of London A* 374:281–298.
Turner G. and Cadogan P. H. 1974. Possible effects of ^{39}Ar recoil in $^{40}Ar/^{39}Ar$ dating. Proceedings, 3rd Lunar and Planetary Science Conference. *Geochimica et Cosmochimica Acta* 2:1613–1622.
Turner G., Enright M. C., and Cadogan P. H. 1978. The early history of chondrite parent bodies inferred from ^{40}Ar-^{39}Ar ages. Proceedings, 9th Lunar and Planetary Science Conference. pp. 989–1025.
Turner G., Huneke J. C., Podosek F. A., and Wasserburg G. J. 1971. ^{40}Ar-^{39}Ar ages and cosmic ray exposure ages of Apollo 14 samples. *Earth and Planetary Science Letters* 12:19–35.
Wieczorek M. A. and Phillips R. J. 2000. The "Procellarum KREEP Terrane:" Implications for mare volcanism and lunar evolution. *Journal of Geophysical Research* 105:20,417–20, 430.
Wieczorek M. A., Zuber M. T., and Phillips R. J. 2001. The role of magma buoyancy on the eruption of lunar basalts. *Earth and Planetary Science Letters* 185:71–83.