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Cosmogenic nuclides in the solar gas-rich H3–6 chondrite breccia Frontier Mountain 90174

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Abstract—We re-evaluated the cosmic-ray exposure history of the H3–6 chondrite shower Frontier Mountain (FRO) 90174, which previously was reported to have a simple exposure history, an irradiation time of about 7 Ma, and a pre-atmospheric radius of 80–100 cm (Welten et al. 2001). Here we measured the concentrations and isotopic compositions of He, Ne, and Ar in 8 aliquots of 6 additional fragments of this shower, and ¹⁰Be and ²⁶Al in the stone fractions of seven fragments. The radionuclide concentrations in the stone fractions, combined with those in the metal fractions, confirm that all samples are fragments of the FRO 90174 shower. Four of the fragments contain solar-wind-implanted noble gases with a solar ²⁰Ne/²²Ne ratio of ~12.0, indicating that FRO 90174 is a regolith breccia. The concentrations of solar gases and cosmogenic ²¹Ne in the samples analyzed by us and by Welten et al. (2001) overlap with those of the FRO H-chondrites from the 1984 season, suggesting that many of these samples are also part of the large FRO 90174 chondrite shower. The cosmogenic ²¹Ne concentrations in FRO 90174 show no simple correlation with ¹⁰Be and ²⁶Al activities. We found ²¹Ne excesses between 0.3–1.1 × 10^{–8} cm³ STP/g in 6 of the 17 samples. Since excess ²¹Ne and trapped solar gases are not homogeneously distributed, i.e., we found in one fragment aliquots with and without excess ²¹Ne and solar ²⁰Ne, we conclude that excess ²¹Ne is due to GCR irradiation of the regolith before compaction of the FRO 90174 object. Therefore, the chondrite shower FRO 90174 did not simply experience an exposure history, but some material was already irradiated at the surface of an asteroid leading to excess ²¹Ne. This excess ²¹Ne is correlated to implanted solar gases, clearly indicating that both processes occurred on the regolith.

INTRODUCTION

Large stony meteorites tend to fragment during atmospheric entry, producing large meteorite showers (Bland and Artemieva 2006). Although, relative to iron meteorites, large stones are rare, the cosmogenic nuclide records in those that have been found often provide evidence of complex exposure histories. Large chondrites, such as Jilin (Honda et al. 1982; Heusser et al. 1985), Bur Gheluai (Vogt et al. 1993), Tsarev (Nagai et al. 1993; Herzog et al. 1997), and Gold Basin (Welten et al. 2003), have complex exposure histories, which (in these cases) include a first-stage exposure on or close to the surface of the asteroid parent body, followed by a second stage exposure as a large object in space. Note that complex exposure histories might also involve more than two irradiation stages, though this would be even more difficult to recognize. In addition, a complex exposure history

might not only involve an irradiation at the surface of an asteroid followed by a 4π irradiation as a small object but it might also include a fragmentation of meteoroid sized bodies, i.e., two different 4π exposure stages. By way of contrast, reported complex exposure histories are rare among small to medium sized objects (radius <50 cm), raising the question whether large stony meteorites are more likely to experience a complex exposure history or whether complex exposure histories are simply more readily detected in large objects, perhaps enabled by multi-nuclide studies of fragments from different shielding depths (Welten et al. 2003) and/or by the fact that large meteorites and meteorite showers seem to be more attractive to study comprehensively than smaller ones. Orbital dynamics calculations suggest that ~30% of all chondrites should have complex exposure histories (Wetherill 1980), but measurements to date have not validated this hypothesis. Note that the value of 30% is

actually valid for very large meteoroids with masses of 1000 tons or more, for smaller ones the value is even higher. The apparent lack of complex exposure histories among smaller stony meteorites may indicate different transport or ejection mechanisms for different size populations. In addition, complex exposure histories can provide us with quantitative information about surface processes on asteroids, such as boulder survival rates, boulder exhumation rates, and meteoroid ejection mechanism. Finally, multi-fragment measurements in large objects help validating model calculations for cosmogenic nuclide production at high shielding conditions. Since there are only a few experimental data for energetic neutron cross sections of cosmogenic nuclides (e.g., Imamura et al. 1990), these are generally derived indirectly (e.g., Michel et al. 1995; Leya et al. 2000a, 2000b) and have large uncertainties. Therefore, experimental cosmogenic nuclide data from various shielding conditions enable testing the model calculations (e.g., Leya et al. 2000a).

Based on the terrestrial ages and cosmic-ray exposure histories for H-chondrites from the Frontier Mountains (FRO), nineteen members of a large H3–6 chondrite breccia, the FRO 90174 shower, were identified, while it was concluded that most likely more than 300 (of the 467) H-chondrites found at the FRO meteorite trap are part of this large shower (Welten et al. 2006). Petrographic observations of a thin section from FRO 90130.01, which is part of the FRO 90174 chondrite shower, show mm- to cm-sized clasts ranging from petrographic type 3 to 6 (Welten et al. 2006). This finding classifies FRO 90174 as a H3–6 breccia and indicates an origin from a heterogeneous lithology. The pre-atmospheric radius of the FRO 90174 shower was estimated to be 80–100 cm (Welten et al. 2001). Although the combined radionuclide and noble gas data suggest that eight members of the FRO 90174 shower belong to the prominent ~7 Ma exposure age peak for H-chondrites, one of the members (FRO 90207) yielded an exposure age of 10.6 ± 0.7 Ma, i.e., ~50% higher than for the other members of the shower (Welten et al. 2001). A possible explanation is that FRO 90207 has experienced a complex exposure history similar to that of the Gold Basin chondrite (Welten et al. 2003), or that some components of the FRO 90174 breccia had a pre-compaction exposure, similar to the Weston (Schultz et al. 1972) and Fayetteville chondrites (Wieler et al. 1989a). Here we report noble gas and radionuclide concentrations for eight analyzed samples from six FRO H-chondrites, for which radionuclide concentrations in the metal fractions demonstrated that these are fragments of the FRO 90174 chondrite shower (Welten et al. 2006). We re-evaluate the exposure history of the FRO 90174 shower based on combined noble gas and radionuclide results in 15 members of this shower. In addition, the new data lead to the conclusion that eight H-chondrites from the FRO 84xxx collection are also part of the FRO 90174 chondrite shower (Delisle et al. 1989).

EXPERIMENTAL

Noble Gases

We analyzed the concentrations and isotopic compositions of He, Ne, and Ar in 8 aliquots from 6 new fragments of the FRO 90174 H3–6 chondrite shower. Bulk samples, consisting of one or several chips, were used for this study. The noble gas extraction and mass spectrometry measurements were performed at the University of Bern. The methods used are standard procedures similar to the ones used previously (e.g., Eugster et al. 1993; Ammon et al. 2008; Huber et al. 2008). Briefly, the He+Ne-fraction was transferred to a static noble gas sector field mass spectrometer, while the Ar-fraction was transferred to a static noble gas tandem mass spectrometer (using two magnets separated by a slit to reduce scattered ions). System blanks were usually <1% of sample gas amounts. Typical blanks (in units of 10^{-10} cm³ STP) are 0.3, 2.5, 0.06, 0.4, and 100 for ³He, ⁴He, ²⁰Ne, ³⁶Ar, and ⁴⁰Ar, respectively. Contributions of ⁴⁰Ar²⁺ and CO₂²⁺ to ²⁰Ne and ²²Ne, respectively, are negligible while contributions of H₂¹⁸O to the ²⁰Ne signal were corrected but were always below 0.5%. The measured concentrations of He+Ne and Ar as well as their isotopic ratios are given in Tables 1 and 2, respectively. The total uncertainties (1 σ) in Ne and Ar concentrations are ~5%, while those for He concentrations are ~8%. The total uncertainties for isotopic ratios are ~2%. For solar gas-rich meteorites, FRO 90032, 95032-b, 01022, and 01048-a, the extremely high ⁴He amounts ($>1.6 \times 10^{-5}$ cm³ STP) resulted in an electronic overload of the Digital Volt Meter (DVM); for these samples only lower limits of the ⁴He concentrations are reported.

To calculate the cosmogenic (cos) and solar (sol) Ne concentrations we assume the following isotopic ratios: (²⁰Ne/²²Ne)_{sol} = 12.4 and (²¹Ne/²²Ne)_{sol} = 0.031 for solar Ne and (²⁰Ne/²²Ne)_{cos} = 0.80 and (²¹Ne/²²Ne)_{cos} = 0.91 for cosmogenic Ne. A short comment to the (²⁰Ne/²²Ne)_{sol} ratio used by us. Solar Ne in meteorites is almost always isotopically fractionated, therefore one cannot expect to find solar Ne with a ratio of 13.7 (e.g., Geiss et al. 2004; Grimberg et al. 2006). Cosmogenic ³⁸Ar concentrations are usually determined assuming a 2-component mixture of spallogenic Ar with (³⁶Ar/³⁸Ar)_{sp} = 0.65 and trapped Ar with (³⁶Ar/³⁸Ar)_{tr} = 5.32, but this approach is not valid for large meteorites such as FRO 90174, because samples from large meteorites often also contain ³⁶Ar from radioactive decay of neutron-capture produced ³⁶Cl (Bogard et al. 1995). We thus estimated cosmogenic ³⁸Ar by assuming a constant ²¹Ne/³⁸Ar ratio of ~9 (Welten et al. 2003), which allows calculating both trapped Ar contributions and neutron-capture ³⁶Ar.

Radionuclides

We dissolved non-magnetic (“stone”) fractions of seven FRO chondrites along with ~5 mg of Be and Cl carrier, in HF/

Table 1. He and Ne concentrations (10^{-8} cm³ STP/g) in bulk material from the FRO 90174 chondrite shower.

FRO	Type	Mass (mg)	³ He	⁴ He	²² Ne	²⁰ Ne/ ²² Ne	²¹ Ne/ ²² Ne	²¹ Ne _c	(²² Ne/ ²¹ Ne) _c
90032	H3.4	251.5	10.9 ± 0.6	>1600 [#]	4.28 ± 0.28	5.36 ± 0.16	0.568 ± 0.017	2.37 ± 0.24	*
95032-a	H3	101.9	19.4 ± 0.6	> 1600 [#]	13.1 ± 1.7	11.1 ± 0.22	0.155 ± 0.003	1.67 ± 0.10	*
95032-b	H3	248.2	24.4 ± 1.3	>1600 [#]	13.7 ± 1.0	9.26 ± 0.35	0.238 ± 0.009	2.94 ± 0.29	*
99014	H4	234.0	8.8 ± 0.5	1494 ± 73	2.37 ± 0.15	0.87 ± 0.02	0.948 ± 0.020	2.25 ± 0.13	1.05 ± 0.02
01022	H5	159.0	24.6 ± 1.3	>2600 [#]	20.7 ± 1.3	11.35 ± 0.81	0.155 ± 0.005	2.64 ± 0.26	*
01023	H6	198.9	5.2 ± 0.3	916 ± 45	1.93 ± 0.12	0.98 ± 0.02	0.960 ± 0.021	1.85 ± 0.18	1.03 ± 0.02
01048-a	H3/4	101.7	32.3 ± 1.7	>4000 [#]	19.7 ± 1.4	10.41 ± 0.43	0.156 ± 0.006	2.55 ± 0.25	*
01048-b	H3/4	112.7	4.1 ± 0.2	729 ± 47	1.36 ± 0.08	1.04 ± 0.05	0.900 ± 0.020	1.22 ± 0.06	1.09 ± 0.02

*Could not be determined due to the high solar Ne component. [#]Only lower limits can be given due an overload of the DVM. The given uncertainties (1σ) include the uncertainties of the ion current measurements, the blank corrections, corrections for mass fractionation effects, and possible uncertainties in the calibration standard.

Table 2. Argon concentrations (10^{-8} cm³ STP/g) in bulk material from the FRO 90174 chondrite shower.

FRO	Type	Mass (mg)	³⁸ Ar	³⁶ Ar/ ³⁸ Ar	⁴⁰ Ar	³⁸ Ar _c ^a	³⁸ Ar _c ^b
90032	H3.5	251.5	0.545 ± 0.027	4.21 ± 0.17	1983 ± 85	0.13	0.27 ± 0.03
95032-a	H3	101.9	3.08 ± 0.20	4.70 ± 0.13	5847 ± 316	0.40	0.19 ± 0.02
95032-b	H3	248.2	1.15 ± 0.06	4.57 ± 0.19	2008 ± 86	0.18	0.33 ± 0.03
99014	H4	234.0	0.512 ± 0.025	4.36 ± 0.13	2131 ± 91	0.10	0.25 ± 0.02
01022	H5	159.0	1.69 ± 0.08	4.85 ± 0.19	3137 ± 134	0.17	0.29 ± 0.03
01023	H6	198.9	0.276 ± 0.017	2.92 ± 0.17	2508 ± 107	0.14	0.21 ± 0.02
01048-a	H3/4	107.7	2.00 ± 0.08	4.68 ± 0.18	4903 ± 209	0.27	0.29 ± 0.03
01048-b	H3/4	112.7	0.862 ± 0.052	4.25 ± 0.09	4390 ± 236	0.20	0.16 ± 0.02

^aAssuming Ar is a mixture of spallogenic Ar (³⁶Ar/³⁸Ar = 0.65) and trapped Ar (³⁶Ar/³⁸Ar = 5.32); ^bAssuming cosmogenic ²¹Ne/³⁸Ar = 9; ³⁸Ar_c: cosmogenic ³⁸Ar.

Table 3. Cosmogenic ¹⁰Be and ²⁶Al in the FRO 90174 chondrite shower.

FRO	Metal (%)	Mass (mg)	Fe (%)	Ni (%)	¹⁰ Be (s)	²⁶ Al (s)	¹⁰ Be (m)	²⁶ Al (m)	¹⁰ Be (b)	²⁶ Al (b)
90032	9.0	126.0	18.3	0.78	17.3 ± 0.5	50.4 ± 1.1	3.22 ± 0.07	2.44 ± 0.12	16.7 ± 0.5	50.9 ± 1.5
95032	9.4	124.8	19.1	0.82	17.6 ± 0.5	56.4 ± 1.1	2.88 ± 0.06	2.05 ± 0.08	16.9 ± 0.5	56.6 ± 1.6
99014	10.8	120.7	17.7	0.75	17.4 ± 0.4	58.5 ± 1.2	3.43 ± 0.07	2.38 ± 0.09	16.7 ± 0.4	57.9 ± 1.6
01022	10.6	128.7	17.3	0.68	16.2 ± 0.4	57.7 ± 1.3	2.66 ± 0.06	1.88 ± 0.09	15.4 ± 0.4	57.1 ± 1.7
01023	6.9	124.4	19.0	0.99	16.0 ± 0.3	49.2 ± 1.6	3.30 ± 0.07	2.45 ± 0.08	15.9 ± 0.3	50.8 ± 1.9
01044	10.8	136.8	17.9	0.75	18.5 ± 0.4	57.9 ± 1.3	3.19 ± 0.07	2.38 ± 0.09	17.7 ± 0.4	57.3 ± 1.7
01048	7.9	126.3	19.4	0.91	16.7 ± 0.5	47.6 ± 1.1	3.66 ± 0.07	2.58 ± 0.08	16.4 ± 0.5	48.6 ± 1.4

Radionuclide concentrations in bulk (b) (dpm/kg meteorite) are calculated from those in the stone fraction (s; this work) (dpm/kg stone) and metal fraction (m; Welten et al. 2006) (dpm/kg metal). Bulk concentrations are corrected for radioactive decay during the terrestrial residence time of 100 ± 20 ka.

HNO₃. After separation of Cl as AgCl, a small aliquot was taken for chemical analysis by atomic absorption spectrometry. Be and Al fractions were separated and purified using anion-cation exchange and solvent-solvent extraction techniques and converted to BeO and Al₂O₃ for measurement by accelerator mass spectrometry (AMS). The ¹⁰Be and ²⁶Al AMS measurements were carried out at Purdue University (Sharma et al. 2000). The measured ¹⁰Be/Be ratios of (3–11) × 10⁻¹² and ²⁶Al/Al ratios of (5–20) × 10⁻¹² were corrected for blanks (3 × 10⁻¹⁴ for ¹⁰Be/Be and 1 × 10⁻¹⁵ for ²⁶Al/Al) and normalized to AMS standards (Nishiizumi 2004; Nishiizumi et al. 2007). The results are reported in Table 3. The quoted 1σ uncertainties include the uncertainties in the AMS measurements of samples, blanks, and standards, but not the uncertainties in the absolute ratios of the AMS standards,

which are, depending on the isotope, a few percent. For the ¹⁰Be measurements we used a half-life of 1.36 Ma (Nishiizumi et al. 2007). Since we give the radionuclide concentrations in dpm/kg the results do not depend on the half-life used.

Cosmic-Ray Exposure Ages

Since the production rates of cosmogenic noble gases in large chondrites are not correlated with the cosmogenic ²²Ne/²¹Ne ratio (e.g., Masarik et al. 2001; Huber et al. 2008), we rely on the ¹⁰Be/²¹Ne and ²⁶Al/²¹Ne methods that are relatively independent of shielding (Graf et al. 1990) to calculate the cosmic-ray exposure ages of the FRO samples.

Fig. 1. Concentrations of ^{10}Be and ^{26}Al in stone fractions as a function of ^{10}Be in the metal phase for 16 fragments of the FRO 90174 shower. Note that ^{10}Be in the metal decreases from left to right, reflecting increasing shielding.

Fig. 2. Neon-3-isotope plot for FRO 90174 H-chondrite samples. Also shown are the isotopic compositions of solar wind (SW), atmospheric (air), and cosmogenic (cos) neon. Extrapolation of the linear correlation (dashed line) to a $^{21}\text{Ne}/^{22}\text{Ne}$ ratio of ~ 0.03 yields a trapped $^{20}\text{Ne}/^{22}\text{Ne}$ ratio of ~ 12.4 .

RESULTS

Radionuclides

The concentrations of ^{10}Be and ^{26}Al in the stone fractions of the seven FRO samples analyzed here are within the range of other members of the FRO 90174 shower, as expected from the data of the metal fractions (Welten et al. 2001, 2006). The ^{10}Be and ^{26}Al concentrations in bulk samples (b) are calculated from those in stone and metal fractions by simple mass balance of non-magnetic and magnetic fractions. Those bulk concentrations, corrected for radioactive decay during a

terrestrial residence of 100 ± 20 ka (Welten et al. 2001), are given in Table 3 as $^{10}\text{Be}(b)$ and $^{26}\text{Al}(b)$. Figure 1 shows ^{10}Be and ^{26}Al in the stone fraction as a function of ^{10}Be in the metal fraction for 16 FRO 90174 samples (this work and Welten et al. 2001). The concentration of ^{10}Be in the metal fraction decreases with increasing shielding depth (i.e., from left to right), at least in large objects, making it a reliable shielding indicator. The radionuclide data clearly indicate that ^{10}Be in the stone fraction varies only very minor with depth, whereas the ^{26}Al concentrations in the stone fraction slightly increase with shielding.

Trapped Noble Gases

The high ^{20}Ne contents and high $^{20}\text{Ne}/^{22}\text{Ne}$ ratios in FRO 90032, 95032, 01022, and 01048 (aliquot a) indicate large contributions of trapped Ne. In a Ne-3-isotope plot these samples fall on a mixing line between cosmogenic and solar Ne (Fig. 2). The correlation yields a trapped $^{20}\text{Ne}/^{22}\text{Ne}$ ratio of ~ 12.4 at $^{21}\text{Ne}/^{22}\text{Ne} = 0.03$. The solar ^{20}Ne concentrations (in 10^{-8} cm³ STP/g) of the samples analyzed here range from ~ 21 in FRO 90032 to ~ 234 in FRO 01022 (Table 4). Note that of the nine previously analyzed samples from the FRO 90174 shower, only one, i.e., FRO 90012, contains a large amount of solar Ne (Welten et al. 1999). However, that FRO 90174 contains regolithic material was already known from earlier studies (c.f., Delisle et al. 1989; Welten 1999, 2001). Since we were unable to measure ^4He for the solar gas-rich FRO samples, we estimated the solar ^3He concentrations by determining the correlation line of cosmogenic ^3He versus cosmogenic ^{21}Ne for the solar gas free samples. We then estimated the solar ^3He concentrations from the deviation of the data for the solar gas-rich samples from that correlation line. This approach yields solar ^3He concentrations (in 10^{-8} cm³ STP/g) ranging from 2.6 in FRO 90032 to 23.4 in FRO 01048 (Table 4). To check this procedure for robustness we also estimated the solar ^3He concentrations from the deviations of the observed $^3\text{He}/^{21}\text{Ne}$ ratios from the correlation of cosmogenic $^3\text{He}/^{21}\text{Ne}$ versus $^{21}\text{Ne}/^{22}\text{Ne}$, i.e., from the “Bern-line” (Fig. 3). This procedure gives very similar trapped gas concentrations as the more precise procedure describe before. Based on a solar $^4\text{He}/^3\text{He}$ ratio of ~ 3000 (Wieler et al. 1989a), we estimate trapped ^4He concentrations (in 10^{-8} cm³ STP/g) of ~ 8000 in FRO 90032 to $\sim 70,000$ in FRO 01048, which explains the overloading of the DVM. The trapped ^{36}Ar concentrations (in 10^{-8} cm³ STP/g) in the solar gas-rich samples range from ~ 1.5 in FRO 90032 to ~ 9 in FRO 01048. The trapped ^{36}Ar is a mixture of atmospheric, solar, and planetary. Note that due to the presence of H3 material planetary Ar, e.g. Ar-Q, cannot be excluded. However, there is no clear trend between the amount of trapped ^{36}Ar and the metamorphic grade of the meteorite. For example, FRO 90032, which is of type H3.4 has the lowest amount of trapped ^{36}Ar among all meteorites studied here, whereas FRO 01022, which is of type H5, has the second highest amount of

Table 4. Trapped He, Ne, and Ar concentrations ($10^{-8} \text{ cm}^3 \text{ STP/g}$) in solar-gas-rich samples from the FRO 90174 shower.

FRO	$^3\text{He}(\text{tr})$	$^{20}\text{Ne}(\text{tr})$	$^{36}\text{Ar}(\text{tr})^{\text{d}}$	$^{36}\text{Ar}(\text{nc})$	$^3\text{He}/^{20}\text{Ne}$	Ref.
8405	50	406.8	17.5	e	0.123	a
8409	50	812.0	32.9	e	0.062	a
8413	40	297.4	9.9	e	0.134	a
8423	30	268.1	15.0	e	0.112	a
8425	73	708.9	31.7	e	0.103	a
8426	31	292.3	15.9	e	0.106	a
90012	10	93.6	4.5	e	0.107	b
90032	3	21.4	2.2	0.63	0.238	c
95032-a	14	124.3	14.4	e	0.123	c
95032-b	14	143.2	5.0	0.66	0.126	c
01022	15	234.2	8.0	0.57	0.081	c
01048-b	24	202.8	9.2	0.04	0.128	c

a) Delisle et al. (1989); b) Welten et al. (1999); c) This work; d) The trapped ^{36}Ar components are in all cases calculated via $^{21}\text{Ne}/^{38}\text{Ar} = 9$. They might contain some neutron capture produced ^{36}Ar . e) The calculated $^{36}\text{Ar}_{\text{nc}}$ is lower than 0, indicating that there is no neutron capture produced ^{36}Ar and/or that the assumption of cosmogenic $^{21}\text{Ne}/^{38}\text{Ar} = 9$ is not strictly valid.

Fig. 3. Cosmogenic $^3\text{He}/^{21}\text{Ne}$ versus $^{22}\text{Ne}/^{21}\text{Ne}$ in FRO samples. Also shown is the Bern-line. The data for samples without solar gases are shown as open and closed symbols. For the solar gas rich samples only the $^3\text{He}/^{21}\text{Ne}$ ratios are indicated because the large amount of trapped gases prevents the determination of cosmogenic $^{22}\text{Ne}/^{21}\text{Ne}$ ratios.

trapped ^{36}Ar . We therefore conclude that the majority of the trapped Ar is of solar origin. Note, however, that the concentrations given below for solar Ar might include some (minor) amounts of planetary Ar as well. The solar-gas free FRO samples contain $(0.7 \text{ to } 3.5) \times 10^{-8} \text{ cm}^3 \text{ STP/g}$ of atmospheric ^{36}Ar , introduced during terrestrial weathering. Assuming an average trapped atmospheric ^{36}Ar content of $\sim 2 \times 10^{-8} \text{ cm}^3 \text{ STP/g}$, we thus estimate solar ^{36}Ar concentrations (in $10^{-8} \text{ cm}^3 \text{ STP/g}$) ranging from 0.2 (FRO 90032) to 12.2 (FRO 95032). Note that six out of 11 H-chondrites from the FRO 1984 collection also contain solar gases (Delisle et al. 1989), suggesting that they are also part of the FRO 90174 shower. Based on the noble gas concentrations (Delisle et al. 1989), the solar-gas-rich H-chondrites FRO 8405, 8409, 8413, 8423, 8425, and 8426 most likely belong to the FRO

Fig. 4. Trapped ^3He and ^{20}Ne in the solar gas-rich H-chondrites Fayetteville (open triangles; Wieler et al. 1989), FRO 90174, including FRO 84 samples (closed circles, this work and Welten et al. 1999; open circles, Delisle et al. 1989), and Acfer 111 (open diamonds, Pedroni and Begemann 1994).

90174 shower; as well as the solar gas-free H-chondrites FRO 8404, 8406, and 8421. However, one cannot be certain about this pairing without detailed cosmogenic radionuclide measurements. For the following discussion we assume that FRO 8404, 8405, 8406, 8409, 8413, 8421, 8423, 8425, and 8426 are also part of the FRO 90174 H3-6 chondrite shower. The trapped He, Ne, and Ar concentrations are given in Table 4.

Figure 4 shows trapped ^3He and ^{20}Ne concentrations in the solar-gas-rich FRO samples, including the gas-rich FRO 84 samples mentioned above, in comparison to those measured in the solar-gas rich matrix of the H3-6 chondrite Fayetteville (Wieler et al. 1989a) and in various step-wise heating and etch steps of the H3-6 meteorite Acfer 111 (Pedroni and Begemann 1994). Although the solar gas

Fig. 5. Cosmogenic ^{21}Ne versus ^{10}Be (panel a) and ^{26}Al (panel b) in bulk fragments of the FRO 90174 chondrite shower. ^{10}Be and ^{26}Al concentrations represent bulk values at the time of fall. Twelve of the 17 samples (represented by filled symbols and solid lines) show constant $^{21}\text{Ne}/^{10}\text{Be}$ and $^{21}\text{Ne}/^{26}\text{Al}$ ratios of 25.5 ± 1.6 and 17.2 ± 0.9 atoms/atoms, respectively. The remaining samples (open symbols) show excesses of ^{21}Ne , ranging from $(0.3\text{--}1.1) \times 10^{-8} \text{ cm}^3 \text{ STP/g}$. Note that almost all gas-rich samples have high $^{21}\text{Ne}/^{26}\text{Al}$ and $^{21}\text{Ne}/^{10}\text{Be}$ ratios and those with low gas concentrations are also low in $^{21}\text{Ne}/^{26}\text{Al}$ and $^{21}\text{Ne}/^{10}\text{Be}$. The dashed line represents a ^{21}Ne excess of $0.8 \times 10^{-8} \text{ cm}^3 \text{ STP/g}$. Note that for some samples two aliquots have been measured, resulting in 19 data for 17 samples.

concentrations in the FRO samples are one order of magnitude lower than in Fayetteville matrix, they show the same $^3\text{He}/^{20}\text{Ne}$ ratio of ~ 0.10 . The solar $^{20}\text{Ne}/^{36}\text{Ar}$ ratios of ~ 20 in the FRO samples are also similar to those in Fayetteville, although the ratios in the FRO samples show significantly more scatter probably due to contributions of atmospheric ^{36}Ar . The lower solar gas contents suggest that either the solar-gas rich samples of the FRO H3–6 breccia contain 10–100 times less solar gas-rich grains as the Fayetteville matrix or that the solar gas-rich grains in FRO were exposed to the solar wind 10–100 times shorter than the solar gas-rich grains in Fayetteville. In comparison with the solar gases in the H3–6 chondrite Acfer 111, the solar gases in FRO 90174 and Fayetteville are slightly more fractionated, i.e., showing $\sim 40\%$ lower $^3\text{He}/^{20}\text{Ne}$ and 20–50% lower $^{20}\text{Ne}/^{36}\text{Ar}$ ratios.

Cosmogenic Noble Gases

The $^{21}\text{Ne}_{\text{cos}}$ concentrations (the index cos labels the cosmogenic component, i.e., corrected for trapped gases) in the 8 aliquots of the 6 new FRO samples studied here are within the range of $^{21}\text{Ne}_{\text{cos}}$ concentrations of the 9 previously studied FRO 90174 samples (Welten et al. 1999), except for FRO 01048-b, which has a lower $^{21}\text{Ne}_{\text{cos}}$ concentration. Figure 5 shows the $^{21}\text{Ne}_{\text{cos}}$ concentration as a function of ^{10}Be (panel a) and ^{26}Al (panel b) in bulk samples at the time of fall. In addition to the data as part of this work results from Welten et al. (2001) and Delisle et al. (1989) are plotted. Only the solar gas-free samples, i.e., FRO 8405 and 8421 from the latter two works are shown. For FRO 8404, which is also a solar gas-free meteorite from the 1984 collection, there are no radionuclide data. For some samples two aliquots have been measured, resulting in 19 data for 17 samples. Although the data scatter significantly, the $^{21}\text{Ne}_{\text{cos}}$ concentrations can be divided into two groups, a major group with $^{21}\text{Ne}_{\text{cos}}$ concentrations lower than about $2 \times 10^{-8} \text{ cm}^3 \text{ STP/g}$ and a minor group with $^{21}\text{Ne}_{\text{cos}}$ concentrations higher than $2 \times 10^{-8} \text{ cm}^3 \text{ STP/g}$. The $^{21}\text{Ne}_{\text{cos}}/^{10}\text{Be}$ and $^{21}\text{Ne}_{\text{cos}}/^{26}\text{Al}$ ratios of the samples having low $^{21}\text{Ne}_{\text{cos}}$ concentrations are constant at 25.5 ± 1.6 and 17.2 ± 0.9 atoms/atoms, respectively, which gives a 4π cosmic-ray exposure age of $7.2 \pm 0.5 \text{ Ma}$ (Welten et al. 2001). The remaining samples show excesses of $^{21}\text{Ne}_{\text{cos}}$, e.g., excess $^{21}\text{Ne}_{\text{cos}}$ relative to the highest $^{21}\text{Ne}_{\text{cos}}$ for the solar gas-poor samples, ranging from $(0.3\text{--}1.1) \times 10^{-8} \text{ cm}^3 \text{ STP/g}$. To summarize, the cosmogenic radionuclide and noble gas concentrations can be explained by a simple cosmic-ray exposure of $7.2 \pm 0.5 \text{ Ma}$ as an object with a radius of 80–100 cm, followed by a terrestrial age of $\sim 100 \text{ ka}$ (Welten et al. 2001). However, there are some samples that show excess $^{21}\text{Ne}_{\text{cos}}$. Note that almost all gas-rich samples have high $^{21}\text{Ne}_{\text{cos}}/^{26}\text{Al}$ and $^{21}\text{Ne}_{\text{cos}}/^{10}\text{Be}$ ratios and those with low gas concentrations are also low in $^{21}\text{Ne}_{\text{cos}}/^{26}\text{Al}$ and $^{21}\text{Ne}_{\text{cos}}/^{10}\text{Be}$ (Fig. 5). The question therefore is, what caused the excess $^{21}\text{Ne}_{\text{cos}}$ in the solar gas-rich fragments of the FRO 90174 chondrite shower? Two possible scenarios are discussed below.

DISCUSSION

We discuss our measurements in the context of two different scenarios. Note that we use for the discussion below the term “complex exposure” in a relatively specific way. While some authors argue that complex exposures can be due to 1) collisions of meteorites in space, 2) regolith exposure, 3) early presolar exposure or 4) interstellar exposure (e.g., Herzog 2005), the complex exposure scenarios discussed below mean two 4π irradiations or a 2π irradiation of the later meteorite on an asteroid followed by a 4π irradiation. The motivation for this limitation is the observation that a large group of chondrites experienced the latter type of complex

exposures (2π followed by 4π) and it is worth checking whether FRO 90174 belongs to this group.

Scenario 1. In this scenario we assume that FRO 90174 experienced a complex exposure history with a first exposure stage on or close to the surface of the asteroid parent body.

Doing so, we assume that the $^{21}\text{Ne}_{\text{cos}}$ contents in the 12 samples with low $^{21}\text{Ne}_{\text{cos}}/^{10}\text{Be}$ and $^{21}\text{Ne}_{\text{cos}}/^{26}\text{Al}$, i.e., with $^{21}\text{Ne}_{\text{cos}}$ concentrations below $\sim 2 \times 10^{-8} \text{ cm}^3 \text{ STP/g}$, are entirely due to the second 4π exposure as a body with a radius of 80–100 cm lasting for $7.2 \pm 0.5 \text{ Ma}$, whereas the 7 remaining samples show excess $^{21}\text{Ne}_{\text{cos}}$, e.g. excess $^{21}\text{Ne}_{\text{cos}}$ relative to the highest $^{21}\text{Ne}_{\text{cos}}$ for the solar gas-poor samples, from a previous exposure on or close to the surface of the H-chondrite parent body (Welten et al. 2001). The $^{21}\text{Ne}_{\text{cos}}$ excesses from the first exposure stage are between 0.3 and $1.1 \times 10^{-8} \text{ cm}^3 \text{ STP/g}$, while the other 12 samples contain $< 0.1 \times 10^{-8} \text{ cm}^3 \text{ STP/g}$. The factor of at least 10 variation in $^{21}\text{Ne}_{\text{cos}}$ production during 2π irradiation requires variations in depth of $> 1 \text{ m}$, which is quite plausible for an object with a diameter of 160–200 cm. Assuming maximum $^{21}\text{Ne}_{\text{cos}}$ production rates of 0.15 – $0.19 \times 10^{-8} \text{ cm}^3 \text{ STP/g per Ma}$ for the 2π irradiation (Graf et al. 1990; Leya et al. 2001), the maximum $^{21}\text{Ne}_{\text{cos}}$ excess yields a minimum 2π exposure age of 6–7 Ma. However, there are two data strictly contradicting this “complex exposure scenario”, FRO 95032 and FRO 01048. The results for these two samples clearly demonstrate that excess $^{21}\text{Ne}_{\text{cos}}$ is not homogeneously distributed in individual fragments of this meteorite, as expected if $^{21}\text{Ne}_{\text{cos}}$ were produced on the surface of an asteroid. In detail, one aliquot of 01048 is extremely low in $^{21}\text{Ne}_{\text{cos}}$ and free of solar gases and the other aliquot of the same fragment is extremely rich in $^{21}\text{Ne}_{\text{cos}}$ and is also solar gas-rich. Similarly, both aliquots of fragment 95032 are solar gas-rich, but one has excess $^{21}\text{Ne}_{\text{cos}}$ and the other not. Note that for these two samples a dark-light contrast was visible (the others were not studied for such a contrast). Based on the inhomogeneity of the excess $^{21}\text{Ne}_{\text{cos}}$ measured within cm-sized fragments of the FRO 90174 chondrite shower, the variations cannot be explained as the result of a complex exposure history in which the first exposure occurred within a large boulder on or close to the surface of an asteroid.

Scenario 2. Here we argue that the excess $^{21}\text{Ne}_{\text{cos}}$ is due to irradiation of the regolith before compaction of the FRO 90174 meteoroid and is therefore connected to the occurrence of solar gases. As already discussed, petrographic observations of a thin section from FRO 90130.01, which is part of the FRO 90174 chondrite, show mm- to cm-sized clasts ranging from petrographic type 3 to 6 (Welten et al. 2006). This finding classifies FRO 90174 as a H3–6 breccia and indicates an origin from a heterogeneous lithology. The noble gas data indicate that some parts of this breccia are solar gas-rich, clearly indicating that certain components of this meteorite were exposed as a regolith to the solar wind. Since solar ^{20}Ne has been implanted at the surface of the regolith, an appreciable amount of cosmogenic ^{21}Ne should have been

Fig. 6. Variations of trapped solar ^{20}Ne and cosmogenic ^{21}Ne in 8 fragments of the FRO 90174 H-chondrite shower (this work) and in 12 H-chondrites from the FRO 84xx collection (Delisle et al. 1989). Similar ^{20}Ne and ^{21}Ne contents suggest that most of the FRO 84 chondrites are probably also part of the FRO 90174 shower. Note that all gas-rich FRO 90174 shower samples, except 95032 and 84023, contain more than $2.0 \times 10^{-8} \text{ cm}^3 \text{ STP/g}$ of cosmogenic ^{20}Ne .

produced in the regolith as well. The amount of produced $^{21}\text{Ne}_{\text{cos}}$, however, depends on the regolith thickness, mixing times, and exposure times and is therefore hard to estimate. Therefore, at least some of the excess $^{21}\text{Ne}_{\text{cos}}$ can be explained by cosmic-ray irradiation of the regolith of the H-chondrite parent body before compaction into the FRO 90174 chondrite breccia. Note that samples rich in solar gases often show excess cosmogenic ^{21}Ne (Fig. 6). Note further that excess $^{21}\text{Ne}_{\text{cos}}$ in clasts is well known also for the solar gas-rich H-chondrites Weston (Schultz et al. 1972), Djernaia (Lorin and Pellas 1979), and Fayetteville (Wieler et al. 1989a). Schultz and coworkers observed that there were clasts of Weston containing excess $^{21}\text{Ne}_{\text{cos}}$ with and without association of solar ^{20}Ne . Caffee et al (1987), although they interpreted their data in terms of an active early sun, also observed excesses of cosmogenic ^{21}Ne in both chondrules and olivines from Weston and olivine grains from Fayetteville. These excesses ranged from 50–100% of the average ^{21}Ne inventory. The constituents with excess cosmogenic ^{21}Ne also had solar flare tracks and solar wind implanted noble gases. These earlier findings are in agreement with our data. For example, the two aliquots of the fragment FRO 01048, which represent different petrographic types, clearly indicate that in this fragment solar ^{20}Ne and excess cosmogenic ^{21}Ne are correlated. While one aliquot is solar gas-free and low in $^{21}\text{Ne}_{\text{cos}}$, the other aliquot of the same fragment is rich in solar gases and shows excess $^{21}\text{Ne}_{\text{cos}}$. On the other hand, there is no strict correlation between trapped ^{20}Ne and excess cosmogenic ^{21}Ne in FRO 95032, both aliquots are rich in solar gases but only one aliquot shows a significant

cosmogenic ^{21}Ne excess. In summary, our measurements, consistent with other studies of solar gas-rich H-chondrites, indicate a regolith exposure of some clasts of FRO 90174 before consolidation of the parent body. After the final consolidation of this parent body all subsequent exposure to cosmic-rays occurred in a single stage, immediately prior to collision with Earth.

Based on our data we can elaborate on the regolith history of FRO 90174. The average trapped $^{20}\text{Ne}/^{36}\text{Ar}$ ratio of 20 is in good agreement with the data for, e.g., Fayetteville (18.5–21.1, Wieler et al. 1989a), ALH 85119 (34.7 ± 7.8 , Nakashima et al. 2006), MAC 88136 (31.5 ± 2.1 , Nakashima et al. 2006), and with the value for the lunar ilmenite 12001 (26.8 ± 5.4 , Eberhardt et al. 1972). However, the FRO 90174 data show considerably more scatter, probably due to the presence of atmospheric ^{36}Ar . Note that the lack of correlation between trapped $^{20}\text{Ne}/^{36}\text{Ar}$ and ^{36}Ar indicates that neither ^{20}Ne nor ^{36}Ar are in saturation. The solar $^{20}\text{Ne}/^{22}\text{Ne}$ endmember ratio of 12.4 for FRO 90174 is consistent with endmember ratios of 11.6–11.9 measured by Wieler et al. (1989a) for Fayetteville. Note that solar Ne in meteorites is almost always isotopically fractionated, therefore one cannot expect to find solar Ne with a ratio of 13.7 (e.g., Geiss et al. 2004; Grimberg et al. 2006). From excess cosmogenic ^{21}Ne we can calculate upper limits for the duration of the regolith exposure. Assuming a maximum production rate of $0.15\text{--}0.19 \times 10^{-8} \text{ cm}^3 \text{ STP/g per Ma}$ for the 2π irradiation (Graf et al. 1990; Leya et al. 2001) yields a minimum 2π exposure age of 6–7 Ma, which is within the range of exposure times determined for inclusions from Weston, St. Mesmin, Djermaja, and Fayetteville (cf. Wieler et al. 1989a, 1989b). Note that these authors interpreted regolith exposure times in the range of ten or more Ma as an indication that the surface of asteroid parent bodies seem to be rather similar to the lunar regolith (e.g., Wieler et al. 1989a). Finally, following the idea by Anders (1975) and Nakashima et al. (2006) we can give some constraints on the heliocentric distance of the FRO 90174 parent body. By comparing $^{36}\text{Ar}_s/^{21}\text{Ne}_{\text{cos}}$ ratios for FRO 90174 with lunar material, whereas S indicates solar and cos cosmogenic, we can estimate an upper limit for the heliocentric distance for the FRO 90174 parent body of about 6 AU, which is in reasonable agreement with the value of 2.3 AU determined by Wieler et al. (1989b) and Pedroni (1989) for Fayetteville and Kapoeta, respectively. In his original work Anders (1975) deduced that meteorites were irradiated at a distance of more than 1 AU from the Sun but probably less than 4–8 AU and in a recent study Nakamura et al. (2006) determined a heliocentric distance for the parent body of E-chondrites greater than 1.3 AU.

CONCLUSIONS

The measured cosmogenic nuclide concentrations in FRO 90032, 95032, 99014, 01022, 01023, and 01048 confirm that these H-chondrites are members of the FRO 90174

shower and that this meteorite were exposed to galactic cosmic-rays as a 80–100 cm-sized object for about 7 Ma. Five of the eight samples analyzed in this study show trapped solar gases with ratios of $^{20}\text{Ne}/^{22}\text{Ne} \sim 12.0$, $^{20}\text{Ne}/^3\text{He} \sim 10$ and $^{20}\text{Ne}/^{36}\text{Ar} \sim 20$. Although the concentrations of trapped solar gases in FRO 90174 are 10 times lower than in the solar gas-rich matrix of the Fayetteville H-chondrite, their noble gas elemental ratios are very similar. Besides solar gases some samples also show excess ^{21}Ne of between 0.3 and $1.1 \times 10^{-8} \text{ cm}^3 \text{ STP/g}$. Since excess ^{21}Ne is not homogeneously distributed, and is often (but not always) correlated with solar ^{20}Ne , we conclude that excess ^{21}Ne is due to GCR irradiation of individual clasts within the regolith before compaction of the FRO 90174 object and is therefore correlated to the implanted solar gases. Consequently, the exposure history of FRO 90174 is a little more complex than assumed so far. Instead of a simple exposure history determined by Welten et al. (2001) we found that some parts of this meteorite were irradiated within the regolith before compaction. However, this scenario, though not simple, differs from the complex exposure histories observed for a variety of other larger chondrites, i.e., a 2π irradiation of the later meteorite on or close to the surface of an asteroid followed by a 4π irradiation. This shows that large chondrites not always have (this type of) complex exposure histories. Finally, based on similar cosmogenic and trapped noble gas concentrations in some H-chondrites from the FRO 84xx collection, we conclude that about seven of these, i.e., FRO 8404, 8405, 8409, 8413, 8421, 8425, and 8426, are also part of the FRO 90174 shower.

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