Meteoritics 28, 528–537 (1993)

Consortium study of the unusual H chondrite regolith breccia, Noblesville

MICHAEL E. LIPSCHUTZ[1], STEPHEN F. WOLF[1], STEPHAN VOGT[1], EDWARD MICHLOVICH[2], MARILYN M. LINDSTROM[3], MICHAEL E. ZOLENSKY[3], DAVID W. MITTLEFEHLDT[4], CECILIA SATTERWHITE[4], LUDOLF SCHULTZ[5], THOMAS LOEKEN[5], PETER SCHERER[5], ROBERT T. DODD[6], DEREK W. G. SEARS[7], PAUL H. BENOIT[7], JOHN F. WACKER[8], ROGER G. BURNS[9] AND DUNCAN S. FISHER[9]

[1]Department of Chemistry, Purdue University, West Lafayette, Indiana 47907, USA
[2]Department of Physics, Purdue University, West Lafayette, Indiana 47907, USA
[3]Code SN2, NASA/Johnson Space Center, Houston, Texas 77058, USA
[4]C23, Lockheed Engineering and Sciences Co., Houston, Texas 77058, USA
[5]Max-Planck-Institut für Chemie, D-6500 Mainz, Germany
[6]Department of Earth and Space Sciences, SUNY-Stony Brook, New York 11794, USA
[7]Department of Chemistry/Biochemistry, University of Arkansas, Fayetteville, Arkansas 72701, USA
[8]Battelle Pacific Northwest Laboratories, Richland, Washington 99352, USA
[9]Department of Earth, Atmospheric and Planetary Sciences, MIT, Cambridge, Massachusetts 02139, USA

(Received 1992 November 11; accepted in revised form 1993 May 11)

Abstract–The Noblesville meteorite is a genomict, regolith breccia (H6 clasts in H4 matrix). Mössbauer analysis confirms that Noblesville is unusually fresh, not surprising in view of its recovery immediately after its fall. It resembles "normal" H4-6 chondrites in its chemical composition and induced thermoluminescence (TL) levels. Thus, at least in its contents of volatile trace elements, Noblesville differs from other H chondrite, class A regolith breccias. Noblesville's small pre-atmospheric mass and fall near Solar maximum and/or its peculiar orbit (with perihelion <0.8 AU as shown by natural TL intensity) may partly explain its levels of cosmogenic radionuclides. Its cosmic ray exposure age of ~44 Ma, is long, is equalled or exceeded by <3% of all H chondrites, and also differs from the 33 ± 3 Ma mean exposure age peak of other H chondrite regolith breccias. One whole-rock aliquot has a high, but not unmatched, $^{129}Xe/^{132}Xe$ of 1.88. While Noblesville is now among the chondritic regolithic breccias richest in solar gases, elemental ratios indicate some loss, especially of He, perhaps by impacts in the regolith that heated individual grains. While general shock-loading levels in Noblesville did not exceed 4 GPa, individual clasts record shock levels of 5–10 GPa, doubtless acquired prior to lithification of the whole-rock meteoroid.

INTRODUCTION

The 484-g Noblesville H chondrite fell on 1991 August 31. Even from the appearance of the whole-rock, Noblesville was recognized as a breccia in which light-colored clasts are embedded in finer-grained, grey matrix (Lipschutz *et al.*, 1993). Such breccias are unusual and, in the case of H chondrites, are often regolith breccias. About 15% of the H chondrites (fewer L and LL chondrites) contain solar gases in their dark matrix, the result of their exposure (as dust grains) to solar wind and solar flares on the surface of the parent asteroid(s) (*cf.* reviews by Scott *et al.*, 1989 and McKay *et al.*, 1989). Typically, H chondrite regolith breccias exhibit distinctive thermoluminescence (TL) properties (Haq *et al.*, 1989), petrographic characteristics and contents of volatile/mobile (*i.e.* labile) trace elements (Lipschutz *et al.*, 1983; Xiao and Lipschutz, 1991). As will be seen, Noblesville is a regolith breccia, albeit atypical in some respects.

The goal of our consortium study was to illuminate Noblesville's possible regolith history and its recent irradiation history, since it fell near the maximum in the 11-year Solar cycle. Here, we report the results of the consortium study.

EXPERIMENTAL

Samples and Curation

The meteorite was described and photographed at the Meteorite Processing Laboratory at NASA Johnson Space Center. The specimen weighed 483.7 g and measured approximately 9.5 x 8 x 3.5 cm. The exterior of the meteorite is totally fusion-crusted except for a small corner that had chipped off. The fusion crust is a dull black color everywhere except the bottom, which is red-brown. The top surface has several regmaglypts and some dirt.

The meteorite was chipped to remove 17 g for scientific research. Examination of the interior of the meteorite shows that it is a breccia consisting of abundant angular light-colored clasts in a fine-grained light grey matrix. Abundant metal fragments and a few small chondrules are visible in the matrix. The coarser-grained clasts show no chondrules.

The main mass of the meteorite (466 g) was sent to Battelle Northwest Laboratories for γ-spectroscopy and eventually returned to the owners. Meanwhile, a small chip (1.6 g) was used to prepare thin sections for characterization. After classification, the remaining 15 g of research material was processed for the first round of scientific studies that are presented here. Allocations to most investigators were of bulk meteorite, although matrix-rich samples were prepared for Lindstrom and Schultz and a clast-rich sample was prepared for Lindstrom. Further allocations of the meteorite were made in 1992 and 1993. An additional 20 g of the sample was later provided by the owners for further study.

Mineral Analysis

Using a thin section of Noblesville, we obtained mineral compositions using a CAMECA Camebax microprobe, operated at 20 nA and a focussed beam; natural mineral standards were employed. Microprobe analyses we report are accurate to within 5%, relative (Table 1).

Mössbauer Spectroscopy

The chip used for Mössbauer spectral measurements was extracted from the interior of the meteorite to avoid contamination from fusion crust (Hall and Burns, 1992). A fresh 100-mg portion was carefully pulverized under acetone to <45 μm particle size in an agate mortar and pestle to minimize oxidation of iron-bearing minerals in the meteorite during grinding. The powder was then loaded into a sealed plastic holder, and acquisition of Mössbauer spectra began immediately. Room temperature spectra were measured in two velocity ranges, ±4.5 mm s^{-1} and ±11 mm s^{-1}, with each spectrum being acquired within a 24-hour

TABLE 1. Modes (%) and mineral analyses of Noblesville matrix and clasts.

MODES	HOST	CLASTS
Olivine	35	38
Pyroxene	28	31
Plagioclase†	14	14
Metal	13	12
Sulfides‡	9	9
Chromite	1	<1
Others	<1	<1
Total	100	100
MINERAL ANALYSES		
Olivine Mean	Fo_{81}	Fo_{81}
Olivine PMD	0.6%	0.6%
Olivine CaO (wt%)	0.1–0.5	<0.1
Pyroxene Mean	En_{83}	En_{81}
Pyroxene PMD	2.8%	0.7%
Plagioclase*	ND	$Ab_{70}An_{24}O_6$ $Ab_{76}An_{17}O_7$
Metal (%)	Ni_{4-7}	Ni_{5-6}

† Includes glass for host.
‡ Pyrrhotite and pentlandite.
* Analyses have low totals.

period. The expanded velocity range enabled magnetic hyperfine sextets originating from FeS and metallic Fe phases to be identified (Table 2). However, we focussed attention on the narrower (±4.5 mm s^{-1}) velocity range in which increased resolution was achieved for the olivine and pyroxene Fe^{2+} quadrupole doublets, as well as peaks that might originate from Fe^{3+} ions.

Mössbauer spectra in the ±4.5 mm s^{-1} velocity range were resolved into component Lorentzian peaks following curve-fitting procedures adopted in earlier meteorite studies (Solberg and Burns, 1989, Burns and Martinez, 1991). Peaks constituting the magnetic sextet of troilite occur near −4.35, −2.00, 0.00, +1.60, +3.65 and +5.70 mm s^{-1} (Solberg and Burns, 1989), so that the outermost peak at 5.70 mm s^{-1} is not measured in the narrow velocity-range spectra. Similarly, for the metallic Fe phase, only the four central peaks at ±3.08 and ±0.84 mm s^{-1} (but not the outermost peaks at ±5.32 mm s^{-1}) are measurable in narrow velocity-range spectra (Burns and Martinez, 1991).

TABLE 2. Mössbauer parameters of the Noblesville meteorite.

Fe species	I.S. mm/s	Q.S. mm/s	H.W. mm/s	Area‡ %
	Mössbauer parameters†			
Fe^{2+}/olivine	1.15	2.94	0.34	48.2 ± 0.5
Fe^{2+}/pyroxene	1.14	2.10	0.34	22.3 ± 0.2
FeS/troilite	0.75	0.14	0.31	18.6 ± 0.2
metallic Fe	0	0	0.24	10.9 ± 0.1
Ratio % olivine/(ol+py)	68.5			
Ratio % pyroxene/(FeS+ol+py)	25.0			
Ratio % FeS/(FeS+ol+py)	20.9			
Ratio % Fe/(Fe+FeS)	36.9			

† Room-temperature spectra; isomer shifts (I.S.) calibrated relative to metallic Fe standard. Quadrupole splitting (Q.S.) and half-width (H.W.) are listed for each species.
‡ Area % data provide relative concentrations of each Fe species or mineral.

TABLE 3. INAA data for Noblesville clast and matrix samples, and USGS standard rock BHVO-1.

	Noblesville ,12 (clast)	Noblesville ,11 (matrix)	BHVO-1	BHVO-1 lit.†
Na (mg/g)	6.60 ± 0.08	5.61 ± 0.07	16.9	16.8
K (μg/g)	620 ± 170	770 ± 90	4900	4300
Ca (mg/g)	14 ± 4	8 ± 2	80	81.5
Sc (μg/g)	7.36 ± 0.08	6.85 ± 0.08	31.0	31.8
Cr (mg/g)	4.25 ± 0.05	3.30 ± 0.04	0.286	0.289
Fe (mg/g)	271 ± 3	361 ± 4	84.6	85.5
Co (μg/g)	950 ± 10	1460 ± 20	45.3	45
Ni (mg/g)	19.5 ± 0.4	22.4 ± 0.5	0.011	0.012
As (μg/g)	2.7 + 0.2	3.6 ± 0.2	0.6	0.4
Se (μg/g)	4.4 ± 0.5	10.7 ± 0.8		
Br (ng/g)	<900	640 ± 240		
La (ng/g)	290 ± 20	250 ± 20	15400	15800
Sm (ng/g)	192 ± 7	172 ± 8	6140	6200
Eu (ng/g)	71 ± 6	67 ± 8	2040	2060
Tb (ng/g)	50 ± 30	<80	950	960
Yb (ng/g)	190 ± 40	150 ± 40	2030	2020
Lu (ng/g)	33 ± 8	25 ± 9	268	291
Hf (ng/g)	210 ± 70	160 ± 80	4420	4380
Ir (ng/g)	870 ± 30	780 ± 30		
Au (ng/g)	257 ± 4	301 ± 5		

† Recommended value (Gladney and Roelandts, 1988).

INAA

Two samples of the interior of the meteorite were obtained for INAA; one matrix-rich and one clast-rich. By hand picking, these samples yielded pure matrix (,11) and pure clast (,12) fractions weighing 46.57 and 46.46 mg, respectively. The samples were loaded into pure silica glass tubes and irradiated as part of a larger sample package at the University of Missouri Research Reactor at a flux of 5.5 x 10^{13} n cm^{-2} s^{-1} for 20 hours. The samples were counted at about 3, 8, 35 and 133 days after irradiation to obtain data for nuclides with differing half-lives. The standards and data reduction procedures used are the same as those described by Mittlefehldt and Lindstrom (1991), except that corrections for Ir and Au contents of the standard SARM-7 were performed as described by Mittlefehldt *et al.* (1992). The INAA data and their precision for the Noblesville samples are reported in Table 3 along with an analysis of USGS standard BHVO-1 (weighing 36.37 mg) from the same experiment and recommended values for it. Our data for BHVO-1 and the recommended values are identical within the uncertainty limits.

RNAA

A 218-mg whole-rock interior sample and monitors were irradiated for 64 h at a flux of 8 x 10^{13} n cm^{-2} s^{-1} at the University of Missouri Research Reactor. Chemical processing, counting, and data reduction were identical to the procedures described by Xiao (1992). Chemical yields for the sample exceeded 40% except for Bi, Cs, Rb, Ag and Sb which were 31%, 28%, 27%, 29% and 17% respectively. Monitor yields exceeded 50% for all elements except Rb and In which were 31% and 40% respectively. Data for the 14 elements of the RNAA trace element suite are listed in Table 4 with data averages for H chondrite falls (Lingner *et al.* 1987; Wolf and Lipschutz, 1992).

Thermoluminescence

Because of the small size of the Noblesville sample provided for TL (250 mg), the entire sample was homogenized and measured. The natural and induced TL were measured using techniques and apparatus described by Sears (1988). The maximum intensity of the induced TL signal (TL sensitivity) is reported relative to that of a homogenized sample of bulk Dhajala meteorite (H3.8).

TABLE 4. Elements determined by RNAA in Noblesville and other H chondrites.

Element	Noblesville	H4-6 chondrites	(No.)†
Au (ppb)	187	210 ± 48	(26)
Co (ppm)	567	790 ± 180	(58)
Ga (ppm)	6.20	5.9 ± 0.8	(55)
Rb (ppm)	3.10	2.2 + 1.1 − 0.7	(58)
Sb (ppb)	90	77 + 38 − 25	(45)
Ag (ppb)	38.9	34 + 37 − 18	(58)
Se (ppm)	8.71	8.1 ± 1.2	(58)
Cs (ppb)	131	32 + 105 − 25	(58)
Te (ppb)	401	360 ± 120	(58)
Zn (ppm)	53.9	48 ± 17	(58)
Cd (ppb)	1.9	4.8 + 29.8 − 4.1	(58)
Bi (ppb)	3.35	1.6 + 3.7 − 1.1	(58)
Tl (ppb)	1.90	0.33 + 1.73 − 0.05	(58)
In (ppb)	3.30	0.43 + 1.05 − 0.30	(58)

† Data from Lingner *et al.* (1987) and Wolf and Lipschutz (1992). Arithmetic means and associated standard deviations are indicated if one uncertainty value is listed. Otherwise, the mean is a geometric one.

Gamma-Ray Spectrometry

Counting—Two instruments were used to measure radionuclides in Noblesville: a high efficiency NaI(Tl) multiparameter gamma spectrometer (to quantify ^{22}Na, ^{26}Al, ^{46}Sc, ^{48}V, ^{54}Mn, ^{56}Co and ^{60}Co) and an anti-coincidence-shielded intrinsic Ge gamma spectrometer (for assaying ^{7}Be, ^{51}Cr, ^{54}Mn, ^{57}Co and ^{58}Co). Further details on these instruments are given by Brodzinski (1973), Perkins *et al.* (1970), Wogman *et al.* (1967, 1970), Reeves *et al.* (1984), and Miley *et al.* (1992). Noblesville was counted on the multi-parameter and Ge gamma spectrometers for total times of 19,662 and 20,674 min, respectively.

Calibration—Calibration procedures for ^{26}Al were the same as used for the analysis of Antarctic meteorites (Edwards *et al.*, 1982; Evans and Reeves, 1987). For the other radionuclides, a combination of procedures was used. Calibration data were obtained by measuring existing mock-ups (of freshly fallen meteorites) containing ^{22}Na and ^{60}Co and by using data from earlier freshly fallen meteorites that were measured on the same instruments. This procedure, although less accurate, avoided the expense of fabricating new mock-ups of Noblesville. A mixed radionuclide standard, with dimensions similar to Noblesville, was also used to calibrate the germanium diode. Finally, ^{54}Mn was measured on both instruments and was used to cross-check the results. These procedures resulted in data that are accurate to 10−15%, except for those with low signal-to-noise ratios.

Accelerator Mass Spectrometry (AMS)

The 400-mg chip (split, 10) of Noblesville received for analyses of long-lived cosmogenic radionuclides by AMS was ground in an agate ball mill and an aliquot of 100 mg of homogenized bulk material was used for ^{10}Be and ^{26}Al analyses. From the remaining material, metal was separated using a hand magnet and repeatedly etched with HF to remove any silicaceous material. A clean separate of about 30 mg was used to isolate chloride for ^{36}Cl determination, and calcium for future ^{41}Ca measurements. Chemical procedures used to separate the elements in form of suitable compounds for AMS measurements (BeO, Al_2O_3, AgCl, and CaH_2) are described by Vogt and Herpers (1988) and Fink *et al.* (1991). To meet the present requirements of the AMS facility, 2 mg of Be, 2 mg of Al, 3 mg of Cl^-, and 20 mg of Ca carrier were added to the respective samples.

The ^{10}Be, ^{26}Al, and ^{36}Cl concentrations (Table 5) were determined by AMS at Purdue's new PRIME Lab facility (Elmore *et al.*, 1992). To establish the ratio of the radioactive to stable isotope(s), the AMS system cycles between these isotopes by changing parameters of the electrostatic and magnetic selection devices. Stable isotopes are measured by the Faraday current cup located just after the analyzing magnet, at the high-energy end of the accelerator. The radioisotope is measured in the gas ionization detector, where it is distinguished from stable isobaric interference by differences in energy loss patterns. A Poisson distribution is assumed for the radioisotope counting rate. Each sample is measured several times, from which a weighted mean and standard deviation are obtained using the propagation-of-errors method described by Elmore *et al.* (1984).

The standard used for normalizing measured ^{10}Be/^{9}Be ratios was NIST standard reference material SRM 4325 for which the certified ratio of ^{10}Be/^{9}Be = (2.68 ± 0.14) x 10^{-11} was obtained using a ^{10}Be half-life of 1.34 ± 0.07 Ma. The currently accepted value for the half-life of ^{10}Be, 1.51 ± 0.06 Ma (Hofmann *et al.*, 1987), leads to a nominal ratio for SRM 4325 of ^{10}Be/^{9}Be = (3.02 ± 0.15) x 10^{-11}. Using this ratio, we obtain the ^{10}Be value in Table 1, which is compatible with published data for ^{10}Be in other meteorites. To normalize ^{26}Al and ^{36}Cl ratios, standard materials were prepared at Purdue from certified standard reference materials A0179 (ICN Chemical & Radiation Division) and SRM 4422L (NIST) by subsequent dilutions to nominal ratios of 3.75 x 10^{-12} and 1.20 x 10^{-12}, respectively. Cross-calibrations and checks of the standard materials are in progress and a more detailed description of the standard materials used will be given elsewhere, as will details of the measurements. First cross-checks with primary standard materials kindly provided by Nishiizumi show good agreement (≤3%) of the nominal ratios of the prepared dilution series with their true ratios (±4%).

Noble Gases

Concentrations and isotopic compositions of He, Ne, Ar, Kr and Xe were determined in two bulk 40-mg samples of Noblesville (,4 and ,9 denoted as "interior chip" and "matrix", respectively) in the new mass spectrometer system "Alfred". The samples were degassed at about 1900 °C for 30 min in a W-crucible of a resistance-heated double-vacuum tantalum oven. Using a temperature-controlled charcoal trap, the purified noble gases were separated into fractions of He and Ne, Ar, Kr and Xe, respectively. The isotopic composition of each element was measured with a MAP 215 mass spectrometer. The sensitivity was

Table 5. Radionuclides in Noblesville and other H chondrite falls.

Isotope	Half-life	Noblesville (dpm/kg)	H Chondrites (dpm/kg)	Chondritic Range (dpm/kg)
^{7}Be	(53.28 d)	61 ± 10		
^{10}Be‡	(1.5 Ma)	19.1 ± 1.3	20.6 ± 1.0§	
^{22}Na	(2.601 y)	131 ± 15	60−110	60−80
^{26}Al	(0.7 Ma)	52 ± 3	56.1 ± 1.0§	
^{26}Al‡	(0.7 Ma)	47.8 ± 1.4		
^{36}Cl‡	(0.301 Ma)	22.5 ± 1.3*	22.8 ± 3.1*	
^{46}Sc	(83.8 d)	8 ± 1	5−15	~8
^{48}V	(15.97 d)	20 ± 10	15−40	~16
^{51}Cr	(27.71 d)	27 ± 5	50−130	
^{54}Mn	(312.5 d)	99 ± 11	60−110	60−105
^{56}Co	(78.5 d)	8 ± 2	5−15	
^{57}Co	(271 d)	12 ± 2	5−30	
^{58}Co	(71.3 d)	2 ± 1	2−25	
^{60}Co	(5.272 y)	0.9 ± 0.7	0 to >100	
^{40}K	(1.28 Ga)	680 ± 69		

† Near solar maximum data from Evans *et al.* (1982), Evans and Reeves (1987).
‡ Determined by AMS. All other nuclides quantified by γ-ray counting.
* Units are dpm/kg of metal (Vogt, 1990). All other data are for bulk rock.
§ Uncertainties are one population standard deviation.

determined using calibrated mixtures of noble gases of atmospheric isotopic compositions plus an additional amount of ^3He. A complete description of the apparatus is given by Loeken *et al.* (1992).

RESULTS AND DISCUSSION

Mineralogy-Petrography

Noblesville consists of approximately equal proportions of large (3–4 mm) well-defined clasts set within a significantly darker matrix (Fig. 1). In the single thin-section studied, we noted a few barred, porphyritic olivine, and glassy chondrules in the matrix; we noted no definite chondrules in the clasts. No obvious veining is evident in either the hand-specimen (*cf.* Fig. 3 of Lipschutz *et al.*, 1993) or the thin section (Fig. 1).

Small, fragmentary olivine and pyroxene grains in both Noblesville clasts and matrix show evidence of shock, this being strong undulatory extinction. However, fewer than 25% of the largest silicate grains in the matrix exhibit this phenomenon. Based upon these criteria, we set the shock level attained by Noblesville as a whole at S1, with clasts attaining S2 levels. Shock levels S1 and S2 represent low degrees of shock-loading, the corresponding shock pressures being 4 and 5–10 GPa, respectively.

The mineral modes for Noblesville matrix and clasts are approximately equal (Table 1), despite the fact that the matrix is darker and, as will be seen, contains significantly more total Fe. We note that our modes for the matrix are incorrect to some degree, due to the presence of abundant submicron-sized opaque grains. Nonetheless, the modes that we report are more consistent with an H rather than an L classification, as these are described by Dodd (1981).

Results of microprobe analyses of olivines and low-Ca pyroxenes are presented in Fig. 2 and Table 1. We were unable to obtain reliable plagioclase analyses for the Noblesville host, owing to the fine grain size and ubiquitous intergrowth with glass, pyroxene and opaques. Plagioclase analyses are given in Table 1 for the Noblesville clasts, although these analyses had low totals (94–97 wt%), and must therefore be viewed with

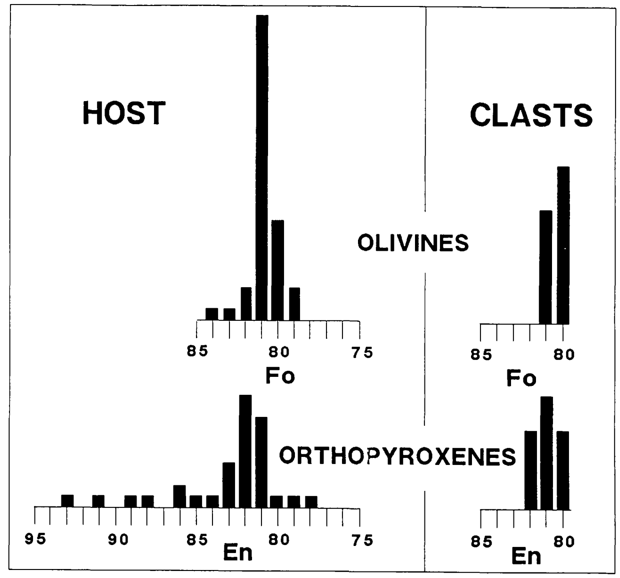

FIG. 2. Comparison of olivine and low-Ca pyroxene analyses for Noblesville host and clasts.

some suspicion. Based upon the compositional and petrographic analyses, we classify the Noblesville host as H4, and the clasts as H6 so that Noblesville is a genomict, class A breccia (Bischoff *et al.*, 1983).

Mössbauer Spectroscopy

The two ferrous quadrupole doublets in the Mössbauer spectrum of Noblesville (Fig. 3) originate from Fe^{2+} ions in olivine (Fa_{19}) and the M2 site of pyroxene (Fs_{17}). Parameters derived from the curve-fitted Mössbauer spectrum are summarized in Table 2 with the peak area data providing estimates of the relative proportions of each iron-bearing mineral in the unoxidized meteorite: 48.2% Fe^{2+} in olivine;

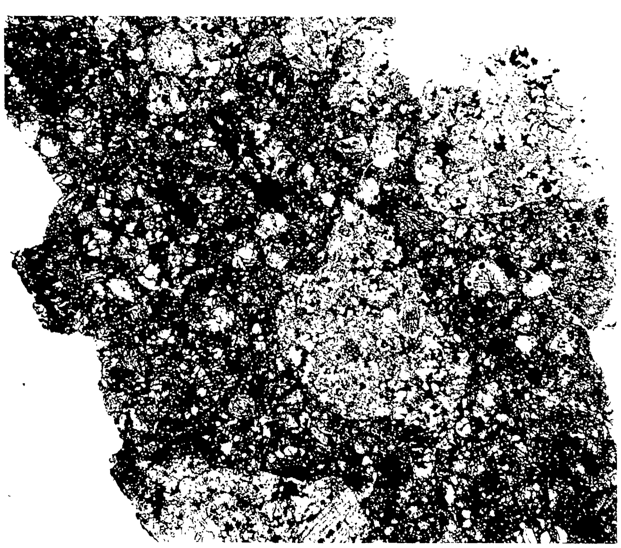

FIG. 1. View in plane-polarized light of Noblesville thin-section, measuring 1 cm across. The light-colored clasts are apparent.

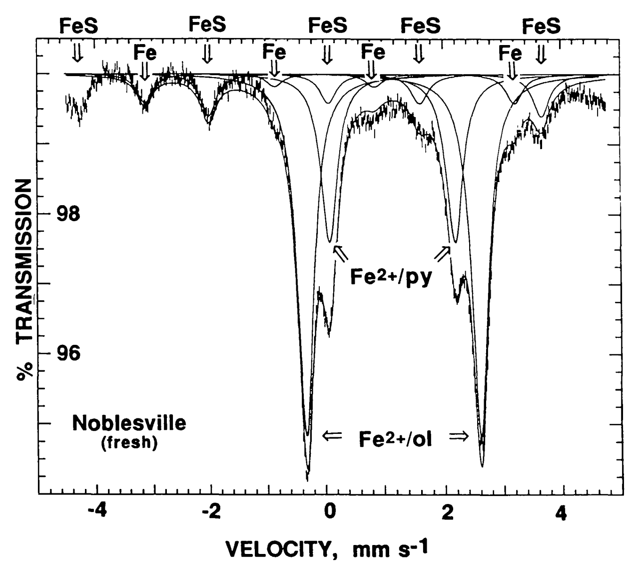

Fig. 3. Mössbauer spectrum of the Noblesville meteorite measured at room temperature.

22.3% Fe^{2+} in the pyroxene M2 site; 18.6% Fe^{2+} in troilite; 10.9% Fe in the metal. Thus, about 70% of the Fe is partitioned into ferromagnesian silicates (olivine and pyroxene), while troilite and the metallic Fe phases account for the remaining 30%. As expected, no Fe^{3+} could be resolved in the Mössbauer spectrum of the pristine meteorite.

The modal proportion of Fe^{2+} in the ferromagnesian silicates of the pristine Noblesville expressed as the ratio (%Fe^{2+} olivine/(ol+py) = 68.5), as well as the proportion of troilite (ratio %FeS/(FeS+ol+py) = 20.9), both fall within ranges determined for other chondritic meteorites (Solberg and Burns, 1989; Fisher and Burns, 1992), including specimens found in Antarctica and falls collected elsewhere soon after they arrived on Earth.

Unlike chondrites studied previously, the Noblesville meteorite contains no detectable Fe^{3+}. Iron oxide staining ("rustiness") is characteristic of all stony meteorites that contain appreciable amounts of Fe, including chondrites and ureilites collected from Antarctica and many curated specimens classified as falls in meteorite collections (Solberg and Burns, 1989; Burns and Martinez, 1991). Such iron oxide staining is commonly attributed to rusting of metallic Fe in these meteorites. The absence of detectable Fe^{3+} in Noblesville can be attributed to its availability for Mössbauer spectroscopy within a few months of its arrival on Earth.

Chemical Composition

Of the elements determined by INAA (Table 3) only three - Co, Se and Au—were also determined by RNAA (Table 4). INAA data for chalcophile Se and siderophile Co differ markedly in clast and matrix (Table 3) arguing for heterogeneous distribution of troilite (for Se) and metal (for Co) in the 50-mg samples analyzed. INAA data for Se in the Noblesville clast and matrix are 45% lower and 33% higher, respectively, than values of Wasson and Kallemeyn (1988) for mean H chondrites or the RNAA datum (Table 4). The RNAA Se datum for Noblesville does not differ greatly from the mean value for 58 "normal" (*i.e.* non-regolith breccia) H4-6 chondrites (Table 4). This suggests that the 200-mg Noblesville sample analyzed by RNAA contains the "normal" troilite complement of H4-6 chondrites. A 1:2 mixture of clast:matrix Se (Table 3) would fit the RNAA value.

The RNAA data for Au and Co are 10-30% lower than mean values for "normal" H4-6 chondrites (Table 4) while the INAA data for these elements and other siderophiles are higher in both clast and matrix (Table 3). Except for Fe, which in chondrites shows lithophile, siderophile and chalcophile character, siderophiles in the clast are 15–30% high and in the matrix are 30–80% higher than in average H chondrites (Wasson and Kallemeyn, 1988). The Fe and Ni data alone (the most significant contributors to the metal content of a chondrite) indicate a metal enrichment in the matrix of 30–40%. *In toto* then, it appears that the sample analyzed by RNAA contained 10–30% less metal than average H chondrite while the clast and matrix contained, respectively, 20 and 35% more metal than average. Such distributional heterogeneity of metal in 50–200 mg chondrite samples is not unknown.

In Fig. 4, the INAA data (Table 3) are normalized to mean H chondrite (Wasson and Kallemeyn, 1988) and are ordered by decreasing nebular condensation temperature within each geochemical group. As can be seen, there is no correlation of abundance with volatility among the siderophile elements in either clast or matrix. The absence of effects of volatility-controlled fractionation is again consistent with the explanation of heterogeneous metal distribution. The siderophile element/Fe ratios calculated for Noblesville clast and matrix are within the ranges of whole-rock H chondrites determined by Sears and Weeks (1986) on samples of 120–210 mg. Typical H chondrites show siderophile element/Fe ratios varying within ±40% of mean H chondrites (Sears and Weeks, 1986).

The Noblesville clast is quite similar to an average H chondrite in lithophile element contents except for Cr, which is about 16% too high (Fig. 4). Mean lithophile element contents in the matrix sample are about 90% those of average H chondrite material (Fig. 4). This probably reflects the higher metal and troilite contents of the matrix sample, causing dilution of lithophile elements. Since metal + troilite make up between 20–25% of a typical H chondrite (*e.g.*, see mean H chondrite analysis in Jarosewich, 1990), increasing the metal + troilite content by 35% will result in a dilution of lithophile elements by 7–9% (~0.2 x 0.35), roughly in accord with our matrix analysis.

In its contents of labile trace elements, Noblesville does not differ greatly from "normal" (*i.e.* non-regolith breccia) H4-6 chondrites (Table 4). Like the "dog in the night" of Sherlock Holmes, this is strange since Noblesville is manifestly a very gas-rich regolith breccia, as discussed below. Lipschutz *et al.* (1983) found that dark and/or light portions of the six other such H chondrite breccias that have been studied thus far (Cangas de Onis, Fayetteville, Leighton, Pantar, Tysnes Is., and Weston) are enriched in Rb, Cs, Te, Bi, Tl and In relative to "normal" H4-6 chondrites and somewhat depleted in Ag. It is true that the Rb and Cs contents of Noblesville lie at the high end of the "normal" H4-6 chondrite ranges, so that these could accord with Rb and Cs contents of other H chondrite regolith breccias. However, Ag is not depleted and contents of Bi, Tl and In, while

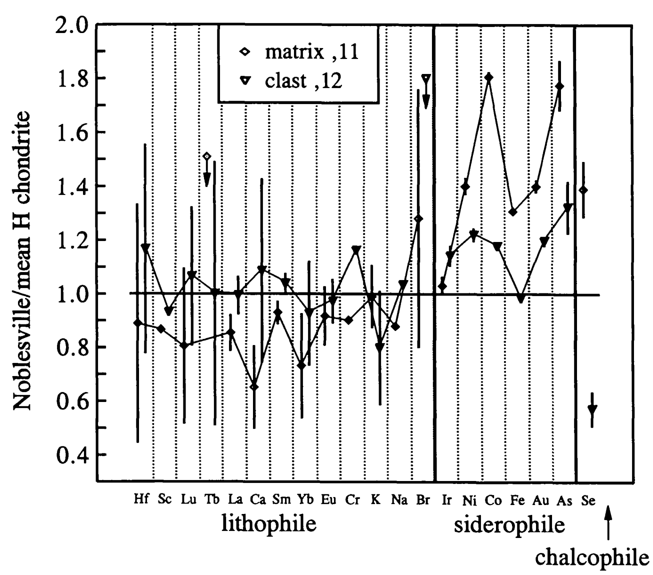

FIG. 4. Lithophile, siderophile and chalcophile concentrations determined by INAA in Noblesville matrix and clast normalized to mean H chondrite (Wasson and Kallemeyn, 1988). The elements are arranged in order of decreasing nebular condensation temperature (Wasson, 1985) within each geochemical family.

somewhat high for "normal" H chondrites, are not impossibly so. Certainly, contents of these three labile elements do not unambiguously correspond to those of mature H chondrite regolith breccias like Fayetteville or Leighton which contain comparable quantities of solar gases, or even Tysnes Island with a factor of 10 less ^{4}He (Schultz and Kruse, 1992).

Thermoluminescence

Induced TL–A single sample of Noblesville has a TL sensitivity value of 3.6 ± 0.2 relative to Dhajala. This value is similar to those of type 4 ordinary chondrites and a factor of 5–10 lower than most equilibrated (type 5 and 6) ordinary chondrites (Sears *et al.*, 1980). However, since Noblesville is a regolith breccia, another factor may be affecting its TL sensitivity. Regolith gardening causes TL sensitivity to decrease by up to a factor of 4–5, most probably due to destruction of feldspar and formation of agglutinates (Fig. 5; *cf.* Haq *et al.*, 1989). Thus, the ratio of the TL sensitivity of the matrix to that of the clasts decreases with regolith maturity, while the contents of trapped solar gases, C, In, Tl and Bi, increase. Since our TL sample almost certainly contained mainly matrix and the trapped solar gas content indicates a high level of regolith maturity, we would infer a matrix/clast TL sensitivity ratio of about 0.2 and thus clast values of about 7 (Dhajala = 1), which is comparable to type 5 or 6 ordinary chondrites (Sears *et al.*, 1980). The clasts in Noblesville are type 6.

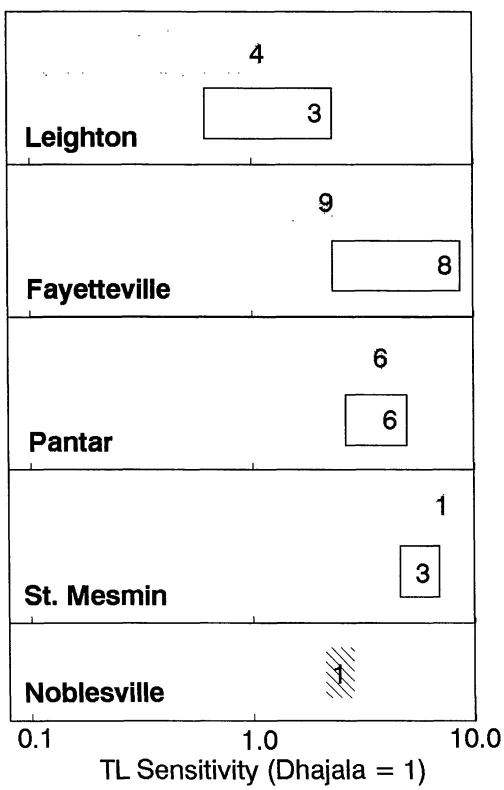

FIG. 5. Induced TL sensitivity data for four regolith breccias and Noblesville. Open rectangles show range of clast material; dots show range of matrix material. Number within the boxes give number of samples used to delineate the range. Data for meteorites other than Noblesville are from Haq *et al.* (1989).

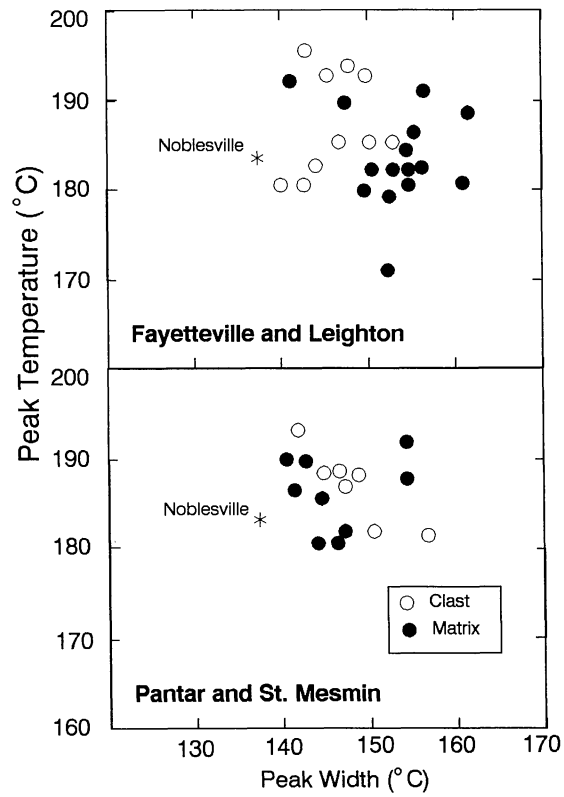

FIG. 6. Induced TL peak temperature and peak width data for regolith breccias. Immature breccias (Pantar and St. Mesmin) have similar induced TL parameters for clasts and matrix. Mature breccias (Fayetteville and Leighton) show a fairly clear separation between the two components, with matrix having higher peak widths. Data other than that for Noblesville are from Haq *et al.* (1989).

If our sample was from the matrix, which the trapped gases (but not In, Tl or Bi) indicate to be of high maturity, then our previous measurements on six gas-rich regolith breccias indicate that the induced TL peak widths should be >150 °C, much larger than the value we observe (Fig. 6). Most probably our sample was contaminated with clast material in sufficient amount to affect the glow curve width but insufficient to seriously affect the TL sensitivity data. We guess that 10–30 v/v% would suffice. Our present data are insufficient to evaluate this further.

Natural TL–Unlike induced TL data, natural TL data are generally insensitive to inhomogeneities in meteorite components. The natural TL level of a meteorite reflects its recent (<10^5 year) thermal and radiation history. Noblesville has a natural TL level of 7.0 ± 0.1 krad, which is low relative to most ordinary chondrite falls (typically 30–60 krad). Approximately 15% of ordinary chondrites and achondrites have such low levels and calculations show that the likely cause is draining of natural TL during close solar passages (<0.8 AU, Benoit *et al.* 1991). The fact that Noblesville's natural TL has not been completely drained indicates either that its perihelion prior to Earth impact was not much less than 0.8 AU or that its TL was drained in a heating episode about 10^4 years ago and has since partially regenerated in an orbit closer to 1 AU. Another possibility, that Noblesville was exposed to cosmic rays less than

10^4 years prior to Earth impact, can be ignored in view of its contents of cosmogenic nuclides and its cosmic ray exposure age (see below).

Radionuclides

The following radionuclides have been detected in Noblesville: cosmogenic ^{7}Be, ^{10}Be, ^{22}Na, ^{26}Al, ^{36}Cl, ^{46}Sc, ^{48}V, ^{51}Cr, ^{54}Mn, ^{56}Co, ^{57}Co, ^{58}Co, ^{60}Co, and ^{40}K. The results are given in Table 5. While the ^{26}Al activity of 52 dpm/kg determined by γ-spectroscopy is within the normal range for H chondrites (Evans and Reeves, 1987) and agrees with the value obtained by AMS (Table 5), both of these and the ^{10}Be value are somewhat low relative to average secular-equilibrium production rates of 56.1 ± 1.0 (Hampel *et al.*, 1980) and 20.6 ± 1.0 dpm/kg, respectively (Vogt, 1990). Effects of meteoroid size and sample depth within the object, commonly referred to as shielding conditions, or a relatively recent multiple-stage exposure to cosmic rays could explain the lower-than-average activities. The ^{26}Al/^{10}Be ratio, which is rather insensitive to shielding effects in ordinary chondrites (Vogt, 1990), corresponds to the calculated production value so that a multi-stage exposure during about the past 5 Ma can be ruled out. Low ^{10}Be and ^{26}Al activities have been reported for small H-chondrites with pre-atmospheric radii of less than 20 cm (Vogt, 1990), and predicted under high shielding conditions for large meteoroids (Michel *et al.*, 1991; Reedy, 1985). The measured ^{36}Cl content agrees fairly well with its production rate in the metal phase of ordinary chondrites for preatmospheric radii of at least up to 45 cm (Reedy *et al.*, 1993). This not only precludes the likelihood of a recent multiple exposure, but also supports the idea that the Noblesville meteoroid was small since the low ^{60}Co activity of 0.9 ± 0.7 dpm/kg implies a pre-atmospheric mass for Noblesville of 1 to 10 kg (Eberhardt *et al.*, 1963; Spergel *et al.*, 1982). Hence, the recovered Noblesville specimen likely represents the major portion of the fall, and, probably, of the pre-atmospheric meteoroid in space. Cosmogenic Ne data are inconclusive on this point because of the high solar Ne content of Noblesville (see below).

The activities of relatively short-lived (<1 year) ^{46}Sc, ^{48}V and ^{54}Mn are all within the normal range for chondritic meteorites (Evans *et al.*, 1982). However, the longer-lived ^{22}Na (2.60 years) activity of 131 dpm/kg, is considerably above the expected 60–110 dpm/kg range for chondritic meteorites. Noblesville fell just past the most recent Solar maximum, during which the ^{22}Na production rate should have been at its minimum due to Solar modulation of the galactic cosmic ray flux. H-chondrites that fell during the 1969 solar maximum had ^{22}Na activities in the range of 60–80 dpm/kg, whereas those falling during the 1976 Solar minimum had activities in the range of 80–110 dpm/kg (Evans *et al.*, 1982). Comparison of the 1969 and 1991 maxima, using both Zürich-smoothed sunspot numbers and Deep River neutron monitor data (both obtained from the National Geophysical Data Center, Boulder, Colorado), shows that the 1991 maximum was more intense than the 1969 one, so that a low, not high, ^{22}Na activity would be expected.

The ^{22}Na activity of Noblesville exceeds even the range observed in H-chondrites that fell near Solar minima. Several possibilities can be eliminated. The high ^{22}Na activity is not an instrumental artifact since normal ^{22}Na activities have been measured recently in other freshly fallen specimens, such as Chela (an H5 that fell on 1988 July 12 and had ^{22}Na and ^{26}Al activities of 97 ± 12 and 68 ± 8 dpm/kg). Mineralogy and trace element analyses show typical H-chondrite-like abundances for Mg, Si, and Na, which are the main targets for production of ^{22}Na. Exposure to solar cosmic rays (SCR) is unlikely due to the relatively low ^{56}Co activity (Evans *et al.*, 1987, Nishiizumi *et al.*, 1990). One possibility is suggested by the low natural TL level, 7.0 ± 0.1 krad, which could imply an eccentric orbit, leading to higher-than-normal ^{22}Na production. But even an orbit with an aphelion of >3 AU would be unlikely to lead to a 30–50% increase in ^{22}Na production (*e.g.*, Cressy and Rancitelli, 1974). A high-inclination orbit could also produce high ^{22}Na (Goswami *et al.*, 1988; Traub-Metlay and Benoit, 1992), but the move to such an orbit must have occurred recently, otherwise high ^{26}Al activity would also be observed. Unusual ^{22}Na activities with otherwise normal activities for other radionuclides have been previously observed in meteorites such as Kiffa, Dwaleni and Acapulco (Evans *et al.*, 1982); Noblesville fits the same pattern, albeit with an even more unusually elevated activity. However, the source of the high ^{22}Na activities in these meteorites remains a mystery.

In addition to cosmogenic radionuclides, a bulk K concentration of 680 ± 69 ppm was determined based on the measured ^{40}K activity and assuming terrestrial isotopic composition. The K concentration agrees well with values of 620 and 770 ppm determined for clasts and matrix, respectively, by INAA (Table 3).

Noble Gases

Noble gases in chondrites represent a mixture of several different components and in Noblesville, solar He and Ne dominate contributions from all other sources (Table 6). Because of this, radiogenic ^{4}He cannot be determined: however, ^{40}Ar is entirely radiogenic so that a K-Ar age for Noblesville can be calculated. Assuming a K content of 800 ppm, K-Ar ages for ,4 and ,9 are 4.5 and 4.6 Ga, respectively. All gas-rich meteorites have such high ages, reflecting retention of ^{40}Ar because of the absence of severe shock. Other properties (increased feldspar content, and hypothetical parentless Ar) may factor into these high ages.

The high concentrations of solar noble gases in Table 6 demonstrate that Noblesville is a regolith breccia. Only the H chondrites Fayetteville (Manuel and Kuroda, 1964), Weston (*cf.* Schultz and Kruse, 1992), and Acfer 111 (Pedroni and Weber, 1991) have comparable solar gas concentrations in whole-rock samples. The ^{20}Ne/^{22}Ne ratio of 12.5 ± 0.2 obtained from a three-isotope-plot of neon (Fig. 7) is essentially solar, and is characteristic of meteoritic gases that are a mixture of incorporated solar wind ions and solar energetic particles. Fayetteville and Weston – the other regolith breccias containing solar gases in amounts comparable to those of Noblesville for which shock data are available – like Noblesville, are of class S1, <5 GPa (Bischoff *et al.*, 1993).

Using a value for solar ^{22}Ne/^{21}Ne of 32, cosmogenic ^{21}Ne is calculated to be 13.3 x 10^{-8} cm^{3}STP/g and 14.3 x 10^{-8} cm^{3}STP/g, in ,4 and ,9 respectively. With a production rate of 0.31 x 10^{-8} cm^{3}STP/g Ma (Eugster, 1988), exposure ages of 42.9 and 46.3 Ma are calculated for ,4 and ,9 respectively. Because cosmogenic ^{22}Ne/^{21}Ne is masked by the solar Ne, the mean exposure age of about 44 Ma is not corrected for shielding. To calculate this, we assumed a mean shielding characterized by

TABLE 6. Concentrations and isotopic compositions of noble gases in Noblesville.

	^{4}He†	$^{4}He/^{3}He$	^{20}Ne†	$^{20}Ne/^{22}Ne$	$^{22}Ne/^{21}Ne$	^{36}Ar†	$^{36}Ar/^{38}Ar$	$^{40}Ar/^{36}Ar$
,4	896000	3058	5470	12.05	16.82	225	4.90	27.8
	±45000	±34	±274	±0.05	±0.09	±11	±0.05	±0.4
,9	863000	3049	5310	12.24	15.84	216	4.98	32.1
	±43000	±34	±266	±0.06	±0.09	±10	±0.05	±0.4

	^{84}Kr†	^{78}Kr	^{80}Kr	^{82}Kr	^{83}Kr	^{84}Kr	^{86}Kr
,4	0.107	0.76	10.8	22.4	20.9	≡100	30.8
	±0.015	±0.02	±0.4	±0.4	±0.4		±0.6
,9	0.105	0.72	7.4	21.1	20.7	≡100	30.4
	±0.015	±0.02	±0.2	±0.4	±0.4		±0.6

	^{132}Xe†	^{124}Xe	^{126}Xe	^{128}Xe	^{129}Xe	^{130}Xe	^{131}Xe	^{132}Xe	^{134}Xe	^{136}Xe
,4	0.058	0.50	0.49	9.0	188.2	16.3	82.2	≡100	38.3	32.1
	±0.009	±0.02	±0.01	±0.1	±0.9	±0.1	±0.5		±0.3	±0.2
,9	0.062	0.51	0.48	8.4	136.4	16.2	81.4	≡100	37.8	31.8
	±0.009	±0.02	±0.01	±0.1	±0.7	±0.1	±0.5		±0.3	±0.2

† Units are 10^{-8} cm^3 STP/g.

cosmogenic $^{22}Ne/^{21}Ne$ = 1.11. If the shielding were higher or lower (*i.e.* $^{22}Ne/^{21}Ne$ = 1.08 or 1.18, respectively), the exposure age would be about 40 or 56 Ma, respectively. However, levels of cosmogenic radionuclides–especially ^{60}Co–eliminate the possibility of higher shielding. Hence, shielding was low, suggesting an exposure age >44 Ma. Thus, for any reasonable assumption, the exposure age of Noblesville is rather high compared to other H chondrites; less than 3% of all H-chondrites have exposure ages in excess of 44 Ma (Fig. 8).

If we assume a cosmogenic ^{3}He content corresponding to the calculated amount of cosmogenic ^{21}Ne, the solar $^{4}He/^{3}He$ is about 3800, a value that accords reasonably well with other estimates of this ratio (Swindle, 1988). Similarly, a quite reasonable value for the solar $^{36}Ar/^{38}Ar$ ratio of about 5.15 can be calculated.

The calculated solar nuclide ratio of $^{4}He/^{20}Ne$ = 164 is smaller than the measured value for the solar wind (= 570; Geiss, 1973) indicating fractionation of individual light noble gases. This fractionation could have occurred by shock-heating of individual grains in the regolith prior to lithification of Noblesville's parent material. Some fractionation by heating during the close Solar approach indicated by the natural TL is possible, but it cannot have been severe since no evidence is observed for cosmogenic ^{3}He loss. On the other hand, mild ^{3}He loss could be masked by implanted solar He.

Assuming bulk solar elemental ratios (Anders and Grevesse, 1989), the measured ^{132}Xe is almost completely of the planetary type; this same conclusion is also suggested by its isotopic composition (Table 6). In this case, the concentration of planetary ^{132}Xe is comparable to values observed in chondrites of petrographic type 4, *i.e.* the Noblesville matrix.

In H3 and H4 chondrites, $^{129}Xe/^{132}Xe$ ratios are typically 1.2–1.5 as is evident in Fig. 9. Although the ,9 sample of Noblesville is well within the usual range of $^{129}Xe/^{132}Xe$ values, that of ,4 is distinctly higher, 1.88. Such a high value has not previously been observed in a whole-rock chondrite sample although similar values have been reported for Xe released at higher temperatures during stepwise heating of Fayetteville (Manuel, 1967). Presumably, it derives from *in-situ* decay of primordial 16 Ma ^{129}I or represents incorporation of Xe in which the ^{129}Xe decay-product had not homogenized with ambient Xe.

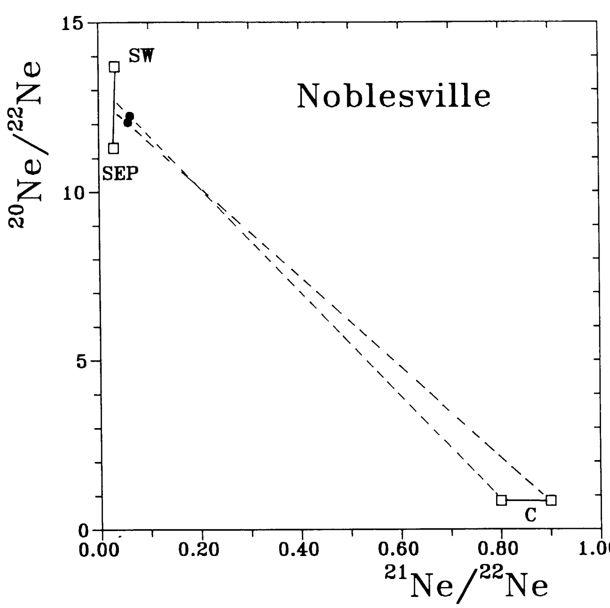

FIG. 7. Three-isotope plot for Ne. The Noblesville data plot near the points for solar wind (SW) and solar energetic protons (SEP) indicating that nearly all Ne in it is of Solar origin. Regolith breccias typically yield such a result and in such meteorites, solar Ne is thought to have been implanted in dust grains in the regolith of a parent body with essentially no indigenous atmosphere. Such grains and others would later be lithified by impacts into breccias like Noblesville. The isotopic composition range of spallation Ne present in Noblesville is indicated at C.

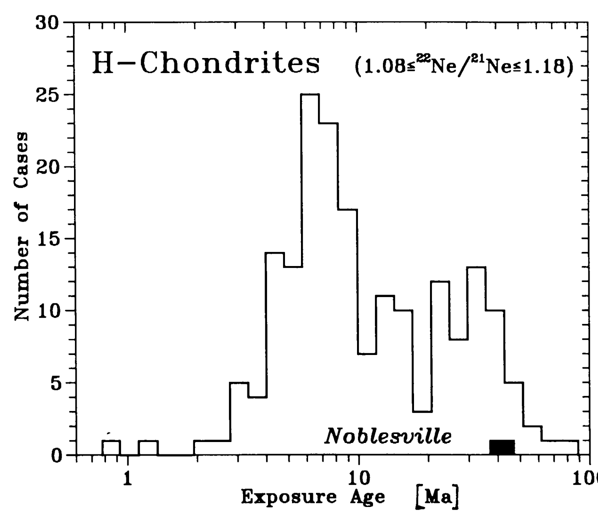

FIG. 8. Histogram of cosmic ray exposure ages of H chondrites estimated from cosmogenic ^{21}Ne. The age of Noblesville, ~44 Ma, is estimated assuming "normal" shielding for the meteoroid during cosmic ray bombardment, although other information suggests lower shielding, hence a somewhat longer age. In any event, the Noblesville exposure age is unusually long for an H chondrite.

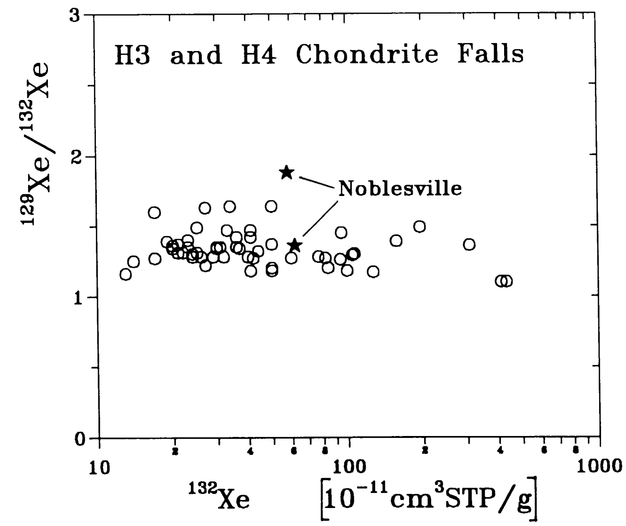

FIG. 9. $^{129}Xe/^{132}Xe$ ratios in H3 and H4 chondrite samples exhibit a 50-fold ^{132}Xe (and, thus, ^{129}Xe) variation arguing that both ^{129}Xe and ^{132}Xe were introduced into such chondrites in similar proportions (Schultz *et al.*, 1990). The Noblesville aliquot ,4 is clearly anomalously rich in ^{129}Xe.

Noblesville does not belong to the cluster of meteorites having exposure ages of 33 ± 3 Ma where Acfer 111, Fayetteville, Weston and other H-chondrites containing solar gas are found. The question of a possible complex irradiation history for Noblesville cannot be answered from these bulk measurements alone. Additional studies are clearly required.

CONCLUSIONS

Although compositionally, Noblesville is an average H chondrite, mineralogically, it is genomict and consists of H6 clasts in an H4 matrix. Its induced TL properties essentially reflect the dominant nature of its matrix. The prompt recovery and recognition of Noblesville as meteoritic and the prompt analysis of it provides a new standard of "freshness" for Mössbauer and other studies.

The natural TL intensity indicates that Noblesville's orbit was unusual, with a perihelion ≤0.8 AU, similar to that of but 15% of all ordinary chondrites. This unusually close passage to the Sun, coupled with its apparently small pre-atmospheric size and fall near the maximum in the 11-year Solar cycle, result in unusual levels of some cosmogenic radionuclides. The causes of these anomalies are uncertain at present and could involve some combination of an orbit that was highly inclined and/or eccentric or a relatively recent change in the orbit and/or amount of shielding in the meteoroid. It is clear, however, that Noblesville has a long cosmic ray exposure age for a chondrite, an age equaled or exceeded by <3% of all H chondrites.

The meteorite is undoubtedly a regolith breccia–indeed one of the most mature ones known, if maturity is defined by solar gas content. Yet, it shows none of the trace element trends previously thought to be characteristic of such regolith breccias. At some point during exposure of Noblesville's parent material to solar particles, its noble gas contents, especially of He, were even higher.

It may be that the Noblesville meteoroid was formed more-or-less as it now is, shortly after Solar System formation as indicated by its high K-Ar age. Other regolith breccias acquired TL changes and addition of volatiles from above or below in their parent body. If Noblesville received an earlier irradiation, ambient chemical conditions could well have been different from later ones. This possibility can only be evaluated by detailed noble gas studies of additional samples of Noblesville and these will occur in the near future.

Acknowledgements–We thank Drs. A. Bischoff, R. Hutchison, E. R. D. Scott and D. M. Shaw for advice and suggestions. Various aspects of this study were supported by the following NASA grants: NAG 9-48 and NAG 9-580 (to M. E. L.); NAS 9-17538 (to J. F. W.); NAG 9-81 (to D. W. G. S.); NAGW-2049 (to R. G. B.), and RTOP 152-13-40-21 (to M. M. L.). Other parts of the study were supported by NSF grant DPP-8817569 (to D. W. G. S.), DOE grant DE-FG07-80ER1 072SJ (to M. E. L.) and NATO grant 0252/89.

Editorial handling: D. Shaw

REFERENCES

ANDERS E. AND GREVESSE N. (1989) Abundances of the elements: Meteoritic and solar. *Geochim. Cosmochim. Acta* **53**, 197–214.

BENOIT P. H., SEARS D. W. G. AND MCKEEVER S. (1991) The natural thermoluminescence of meteorites. II. Meteorite orbits and orbital evolution. *Icarus* **94**, 311–325.

BISCHOFF A., RUBIN A. E., KEIL K. AND STÖFFLER D. (1993) Lithification of gas-rich chondrite regolith breccias by grain boundary and localized shock melting. *Earth Planet. Sci. Lett.* **66**, 1–16.

BRODZINSKI R. L. (1973) The use of gold as a backscatter absorber in multidimensional gamma ray spectrometers. *Radiochem. Radioanal. Lett.* **3**, 375–380.

BURNS R. G. AND MARTINEZ S. L. (1991) Mössbauer spectra of olivine-rich achondrites: Evidence for preterrestrial redox reactions. *Proc. Lunar Planet. Sci.* **21st**, 331–340.

CRESSY P. J. AND RANCITELLI L. A. (1974) The unique cosmic-ray history of the Malakal chondrite. *Earth Planet. Sci. Lett.* **22**, 275–283.

DODD R. T. (1981) *Meteorites, A Petrologic-Chemical Synthesis.* Cambridge Univ. Press, New York, New York. 368 pp.

EBERHARDT P., GEISS J. AND LUTZ H. (1963) Neutrons in meteorites. In *Earth Science and Meteoritics* (eds. J. Geiss and E. D.Goldberg), pp. 143–168. North-Holland, Amsterdam.

EDWARDS D. R., REEVES J. H. AND BRODZINSKI R. L. (1982) Preparation of lunar sample and meteorite mockups: Or how to make rocks. *Nucl. Instrument Methods* **196**, 507–509.

ELMORE D., CONARD N., KUBIK P. W. AND FABRYKA-MARTIN J. (1984) Computer controlled isotope ratio measurements and data analysis. *Nucl. Instrum. Methods* **B5**, 233–237.

ELMORE D., RICKEY F. A., SIMMS P. C., LIPSCHUTZ M. E., MUELLER K. A. AND MILLER T. E. (1992) PRIME Lab: A dedicated AMS Facility at Purdue University. *Proc. 14th Int. Radiocarbon Conf.* **34**, 447–451.

EUGSTER O. (1988) Cosmic ray production rates for ^{3}He, ^{21}Ne, ^{38}Ar, ^{83}Kr and ^{126}Xe in chondrites based on ^{81}Kr-Kr exposure ages. *Geochim. Cosmochim. Acta* **52**, 1649–1662.

EVANS J. C. AND REEVES J. H. (1987) ^{26}Al survey of Antarctic meteorites. *Earth Planet. Sci. Lett.* **82**, 223–230.

EVANS J. C., REEVES J. H., RANCITELLI L. A. AND BOGARD D. D. (1982) Cosmogenic radionuclide variations in recently fallen meteorites: Evidence for galactic cosmic ray variations during the period 1967–1978. *J. Geophys. Res.* **87 (B7)**, 5577–5591.

EVANS J. C., REEVES J. H. AND REEDY R. C. (1987) Solar cosmic ray produced radionuclides in the Salem meteorite (abstract). *Lunar Planet. Sci.* **18**, 271–272.

FINK D., KLEIN J., MIDDLETON R., VOGT S. AND HERZOG G. F. (1991) ^{41}Ca in iron falls, Grant and Estherville: Production rates and related exposure age calculations. *Earth Planet. Sci. Lett.* **107**, 115–128.

FISHER D. S. AND BURNS R. G. (1992) Mössbauer spectra of H-5 chondrites from Antarctica (abstract). *Lunar Planet. Sci.* **23**, 367–368.

GEISS J. (1973) Solar wind composition and implications about the history of the solar system. *13th Int. Cosmic Ray Conf.* **5**, 3375–3398.

GLADNEY E. S. AND ROELANDTS I. (1988) 1987 compilation of elemental concentration data for USGS BHVO-1, MAG-1, QLO-1, RGM-1, SCO-1, SDC-1, SGR-1 and STM-1. *Geostandards Newslett.* **12**, 253–262.

GOSWAMI J. N., MCGUIRE R. E., REEDY R. C., LAL D. AND JHA R. (1988) Solar flare protons and alpha particles during the last three solar cycles. *J. Geophys. Res.* **93**, 7195–7205.

HALL T. M. AND BURNS R. G. (1992) Fusion crusts of achondrites: Changes of mineralogy of iron in outermost surfaces of meteorites (abstract). *Lunar Planet. Sci.* **23**, 475–476.

HAMPEL W., WÄNKE H., HOFMEISTER H., SPETTEL B. AND HERZOG G. F. (1980) ^{26}Al and rare gases in Allende, Bereba and Juvinas: Implications for production rates. *Geochim. Cosmochim. Acta* **44**, 539–547.

HAQ M., HASAN F. A., SEARS D. W. G., MOORE C. B. AND LEWIS C. F. (1989) Thermoluminescence and the origin of the dark matrix of Fayetteville and similar meteorites. *Geochim. Cosmochim. Acta* **53**, 1435–1440.

HOFMANN H. J., BEER J., BONANI G., VON GUNTEN H. R. RAMAN S., SUTER M., WALKER R. L. WÖLFLI W. AND ZIMMERMANN D. (1987) ^{10}Be half-life and AMS-standards. *Nucl. Instr. Methods* **B29**, 32–36

JAROSEWICH E. (1990) Chemical analyses of meteorites: A compilation of stony and iron meteorite analyses. *Meteoritics* **25**, 323–337.

LINGNER D., HUSTON T. J., HUTSON M. AND LIPSCHUTZ M. E. (1987) Chemical studies of H chondrites–I. Mobile trace elements and gas retention ages. *Geochim. Cosmochim. Acta* **51**, 727–739.

LIPSCHUTZ M. E., BISWAS S. AND MCSWEEN H. Y., Jr. (1983) Chemical characteristics and origin of H chondrite regolith breccias. *Geochim. Cosmochim. Acta* **47**, 169–179.

LIPSCHUTZ M. E., SPAULDING B., KINZIE B. D. AND GARTENHAUS S. (1993) Fall and recovery of the Noblesville (Indiana, U.S.A.) H chondrite. *Meteoritics* **28**, 240–242.

LOEKEN T., SCHERER P. AND SCHULTZ L. (1992) Noble gases in 18 stone meteorites. *Chem. Erde* **52**, 249–259.

MANUEL O. K. (1967) Noble gases in the Fayetteville meteorite. *Geochim. Cosmochim. Acta* **31**, 2413–2431.

MANUEL O. K. AND KURODA P. K. (1964) Isotopic composition of the rare gases in the Fayetteville meteorite. *J. Geophys. Res.* **69**, 1413–1419.

MCKAY D. S., SWINDLE T. D. AND GREENBERG R. (1989) Asteroidal regoliths: What we do not know. In *Asteroids II* (eds. R. P. Binzel, T. Gehrels, and M. J. Matthews), pp. 617-642. Univ. of Arizona Press, Tucson, Arizona.

MICHEL R., DRAGOVITSCH P., CLOTH P., DAGGE G. AND FILGES F. (1991) On the production of cosmogenic nuclides in meteoroids by galactic protons. *Meteoritics* **26**, 221–242.

MILEY H. S., BRODZINSKI R. L. AND REEVES J. H. (1992) Low background counting systems. *J. Radioanal. Nuc. Chem.* **160**, 371–385.

MITTLEFEHLDT D. W. AND LINDSTROM M. M. (1991) Generation of abnormal trace element abundances in Antarctic eucrites by weathering processes. *Geochim. Cosmochim. Acta* **55**, 77–87.

MITTLEFEHLDT D. W., SEE T. H. AND HÖRZ F. (1992) Dissemination and fractionation of projectile materials in the impact melts from Wabar Crater, Saudi Arabia. *Meteoritics* **27**, 361–370.

NISHIIZUMI K., NAGAI H., IMAMURA M., HONDA M., KOBAYASHI K., KUBIK P. W., SHARMA P., WEIER R., SIGNER P., GOSWAMI J. N., SINHA N., REEDY R. C. AND ARNOLD J. R. (1990) Solar cosmic ray produced nuclides in the Salem meteorite (abstract). *Meteoritics* **25**, 392.

PEDRONI A. AND WEBER H. W. (1991) Exceptionally unfractionated solar noble gases in the H3-H6 chondrite Acfer 111 (abstract). *Meteoritics* **26**, 383–384.

PERKINS R. W., RANCITELLI L. A., COOPER J. A., KAYE J. H. AND WOGMAN N. A. (1970) Cosmogenic and primordial radionuclide measurements in Apollo 11 lunar samples by nondestructive analysis. *Proc. Apollo 11 Lunar Sci. Conf.*, 1455–1469.

REEDY R. C. (1985) A model for GCR-particle fluxes in stony meteorites and production rates of cosmogenic nuclides. *Proc. Lunar Planet. Sci. Conf.* **15th**, Part 2, *J. Geophys. Res.* **90**, C722–C728.

REEDY R. C., MASARIK J., NISHIIZUMI K., ARNOLD J. R., FINKEL R. C., CAFFEE M. W., SOUTHON J., JULL A. J. T. AND DONAHUE D. J. (1993) Cosmogenic radionuclide profiles in Knyahinya: New measurements and models (abstract). *Lunar Planet. Sci.* **24**, 1195–1196.

REEVES J. H., HENSLEY W. K., BRODZINSKI R. L. AND RYGE P. (1984) An ultralow background germanium gamma-ray spectrometer using superclean materials and cosmic ray anticoincidence. *IEEE Trans. Nuclear Sci.* **NS-31**, 697.

SCHULTZ L. AND KRUSE H. (1992) Helium, neon, and argon in meteorites–A data compilation. *Meteoritics* **24**, 155–171 and unpublished data.

SCHULTZ L., WEBER H. W. AND BEGEMANN F. (1990) Planetary noble gases in H3- and H4-chondrite falls (abstract). *Meteoritics* **25**, 405–406.

SCOTT E. R. D., TAYLOR G. J., NEWSOM H. E., HERBERT F., ZOLENSKY M. AND KERRIDGE J. F. (1989) Chemical, thermal, and impact processing of asteroids. In *Asteroids II* (eds. R. P. Binzel, T. Gehrels and M. J. Matthews), pp. 701–739. Univ. of Arizona Press, Tucson, Arizona.

SEARS D. W. G. (1988) Thermoluminescence of meteorites: Shedding light on the cosmos. *Nucl. Tracks Radiat. Meas.* **14**, 5–17.

SEARS D. W. G. AND WEEKS K. S. (1986) Chemical and physical studies of type 3 chondrites–VI: Siderophile elements in ordinary chondrites. *Geochim. Cosmochim. Acta* **50**, 2815–2832.

SEARS D. W. G., GROSSMAN J. N., MELCHER C. L., ROSS L. M. AND MILLS A. A. (1980) Measuring metamorphic history of unequilibrated ordinary chondrites. *Nature* **287**, 791–795.

SOLBERG T. C AND BURNS R. G. (1989) Iron Mössbauer spectral study of weathered Antarctic and SNC meteorites. *Proc. Lunar Planet. Sci. Conf.* **19th**, 313–322.

SPERGEL M. S., ROY R. C., LAZARETH O. W. AND LEVY P. W. (1982) Cosmic-ray-produced cobalt-60 in chondrites (abstract). *Lunar Planet. Sci.* **13**, 756–757.

SWINDLE T. D. (1988) Trapped noble gases in Meteorites. In *Meteorites and the Early Solar System* (eds. J. F. Kerridge and M. S. Matthews), pp. 535–564. Univ. of Arizona Press, Tucson, Arizona.

TRAUB-METLEY S. G. AND BENOIT P. H. (1992) The natural thermoluminescence of meteorites with high ^{26}Al contents: Unusual orbital histories in ordinary chondrites? (abstract). *Lunar Planet. Sci.* **23**, 1443–1444.

VOGT S. (1990) Cosmogenic radionuclide production rates in meteorites. In *Workshop on Cosmogenic Production Rates* (eds. P. A. J. Englert, R. C. Reedy and R. Michel), pp. 112–118. LPI Tech. Rpt. 90-05. Lunar and Planetary Institute, Houston, Texas.

VOGT S. AND HERPERS U. (1988) Radiochemical separation techniques for the determination of long-lived radionuclides in meteorites by means of accelerator mass spectrometry. *Fresenius Z. Anal. Chem.* **331**, 186–188.

WASSON J. T. (1985) *Meteorites–Their Record of Early Solar-System History*. W. H. Freeman and Co., New York, New York. 267 pp.

WASSON J. T. AND KALLEMEYN G. W. (1988) Compositions of chondrites. *Phil. Trans. R. Soc. Lond.* **A325**, 535–544.

WOGMAN N. A., ROBERTSON D. E. AND PERKINS R. W. (1967) A larger detector, anticoincidence shielded multidimensional gamma-ray spectrometer. *Nucl. Instrum. Methods* **50**, 1–10.

WOGMAN N. A., PERKINS R. W. AND KAYE J. H. (1970) An all sodium iodide anticoincidence shielded multidimensional gamma-ray spectrometer for low activity samples. *Nucl. Instrum. Methods* **83**, 277–282.

WOLF S. F. AND LIPSCHUTZ M. E. (1992) Multivariate statistical analysis of labile trace elements in H chondrites: Evidence for meteoroid streams (abstract). *Meteoritics* **27**, 308–309.

XIAO X. (1992) Trace Element Study of Formation Processes of Carbonaceous Chondrites and Regolith Processes on Fayetteville Parent Body. Ph.D. Dissertation, Purdue University.

XIAO X. AND LIPSCHUTZ M. E. (1991) Chemical studies of H chondrites –III. Regolith evolution of the Fayetteville chondrite parent. *Geochim. Cosmochim. Acta* **55**, 3407–3415.