Meteoritics & Planetary Science 40, Nr 5, 659–664 (2005)
Abstract available online at http://meteoritics.org

Noble gases in ten Nullarbor chondrites: Exposure ages, terrestrial ages, and weathering effects

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(Received 26 October 2004; revision accepted 16 March 2005)

Abstract–We present concentration and isotopic composition of He, Ne, and Ar in ten chondrites from the Nullarbor region in Western Australia as well as the concentrations of ^{84}Ke, ^{129}Xe, and ^{132}Xe. From the measured cosmogenic ^{14}C concentrations (Jull et al. 1995), shielding-corrected production rates of ^{14}C are deduced using cosmogenic ^{22}Ne/^{21}Ne ratios. For shielding conditions characterized by ^{22}Ne/^{21}Ne >1.10, this correction becomes significant and results in shorter terrestrial ages. The exposure ages of the ten Nullarbor chondrites are in the range of values usually observed in ordinary chondrites. Some of the meteorites have lost radiogenic gases as well as cosmogenic ^{3}He. Most of the analyzed specimens show additional trapped Ar, Kr, and Xe of terrestrial origin. The incorporation of these gases into weathering products is common in chondrites from hot deserts.

INTRODUCTION

The Nullarbor Plain, situated in the south of Australia, is an ideal place to find meteorites: the treeless limestone desert makes it possible to recognize even small "black stones" and the semi-arid to arid climate of the region guarantees preservation of meteorites over relatively long times (>30 kyr). Since about 1970, thousands of specimens from more than 300 distinct meteorites have been recovered from this region and more than 500 additional stones remain to be described, making it one of the most productive hot deserts of the world for meteorite recoveries (Bevan and Binns 1989; Grady 2000). Together with Roosevelt County in the United States, the Nullarbor is a "pioneer" for meteorite searches in hot deserts. Since 1986, the Sahara in northern Africa has also become a major source of new meteorites (e.g., Acfer in Algeria, Dar al Gani, and Hammadah al Hamra in Libya), as has the southern region of the Arabian Peninsula more recently (Dhofar and Sayh al Uhaymir in Oman).

Terrestrial age of these meteorites is one key part of understanding the alteration of meteorites on Earth and thus, for example, understanding the influence of terrestrial weathering on the noble gas record of these rocks. A knowledge of terrestrial ages and weathering rates has made it possible to estimate the flux of meteorites on the Nullarbor Plain (Bland et. al. 1996; Bevan et al. 1998).

Jull et al. (1995) and Bland et al. (2000) reported ^{14}C terrestrial ages for 36 meteorites from the Nullarbor region of Western Australia. These ages, however, have been calculated from cosmogenic ^{14}C measurements using mean production rates of ^{14}C. This could lead to an overestimation of the terrestrial age if the samples were irradiated under low shielding conditions, as shown for the Gold Basin L chondrite shower (Kring et al. 2000; Welten et al. 2001). Jull et al. (2001) reported some corrected ages of Nullarbor meteorites using ^{10}Be to normalize the ^{14}C production rate, a method valid only for meteorites with saturated ^{10}Be contents (exposure age >10 Myr). These results showed that measurements with the shielding-corrected ages based on ^{14}C/^{10}Be are more precise than those based on ^{14}C alone. However, none of the meteorites discussed in this paper are included.

Another way to make depth estimates is by ^{22}Ne/^{21}Ne ratios. We have therefore measured the noble gases of ten Nullarbor chondrites to determine the cosmogenic ^{22}Ne/^{21}Ne ratio, which is a widely used parameter for shielding. From this parameter a shielding-corrected production rate is obtained and a corrected terrestrial age is calculated.

Furthermore, gas retention ages, diffusive gas loss, exposure ages, and the degree of weathering are obtained from measured radiogenic gas components, cosmogenic gas isotopes, and the amount of trapped terrestrial gases.

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Table 1. Noble gas concentrations (in $10^{-8}cm^3STP/g$) in ten Nullabor chondrites.

Meteorite	Type	^3He	^4He	^{20}Ne	^{21}Ne	^{22}Ne	^{36}Ar	^{38}Ar	^{40}Ar	^{84}Kr	^{132}Xe	$^{129}Xe/^{132}Xe$	$^{84}Kr/^{132}Xe$
Billygoat Donga	L6	23.67	248	5.47	5.85	6.16	0.85	0.78	476	0.017	0.008	1.09	2.13
Boorabie	H5	5.03	1264	0.94	0.96	1.08	1.28	0.39	4605	0.066	0.019	1.14	3.47
Burnabbie	H5	7.47	1182	2.78	2.02	2.28	13.68	2.77	8996	0.571	0.075	1.11	7.61
Carlisle Lakes 002	H4-5	4.42	1131	1.03	1.14	1.27	1.03	0.33	4502	0.055	0.024	1.08	2.29
Cocklebiddy	H5	2.50	212	1.72	1.24	1.39	1.82	0.47	2133	0.038	0.008	1.28	4.75
Deakin 001	LL3	34.09	249	6.49	6.64	7.67	9.01	2.39	931	0.235	0.093	2.13	2.52
Forrest 007	H4	5.45	1197	1.17	1.11	1.26	1.18	0.35	4390	0.060	0.028	1.10	2.18
Forrest 009	L6	15.81	175	3.95	4.30	4.67	2.44	0.80	840	0.126	0.025	0.99	5.04
Forrest 010	L4-5	7.25	1083	1.71	1.86	2.06	1.50	0.43	4405	0.057	0.032	1.33	1.78
Kybo 001	LL5	38.94	1003	8.47	9.12	9.99	1.47	1.26	2485	0.039	0.016	1.12	2.44

EXPERIMENTAL PROCEDURES AND RESULTS

Samples of about 100 mg were wrapped in Ni foil and stored in a sample holder of the extraction system. To reduce the concentration of adsorbed atmospheric gases, the samples were heated in vacuo at about 110 °C for at least 24 hours. The samples were then dropped into a cold W crucible of a resistance-heated double vacuum Ta oven and degassed for 30 min at about 1700 °C. Purification of the noble gas mixture took place by Ti and by Zr-Al-alloy getter. Using a temperature-controlled charcoal trap, argon, Kr, and Xe were separated from He and Ne, which were first admitted into an all-metal 60° magnetic sector field mass spectrometer equipped with magnetic peak jumping controlled by a Hall probe and a desktop computer. After measurement of this fraction, the gases were pumped off and the fraction with Ar, Kr, and Xe was let into the spectrometer.

He and Ar were measured using a Faraday cup, while for Ne, ^{84}Kr, ^{129}Xe, and ^{132}Xe an electron multiplier in analogue mode was applied. Elemental abundances were determined by peak-height comparison of sample and calibration gas, extrapolated back to the time of gas inlet into the mass spectrometer.

Total extraction blanks (in units of $10^{-10}cm^3STP$) at 1700 °C were <0.04, <6, <0.2, <100, <0.04, and <0.01 for ^3He, ^4He, ^{20}Ne, ^{40}Ar, ^{84}Kr, and ^{132}Xe, respectively. Sample measurements of our laboratory standard Lakewood as well as that of a Bruderheim standard show the consistency with previous measurements in this and in other laboratories (cf. Schultz and Franke 2004).

Results of the noble gas analyses are given in Table 1. Gas concentrations are believed to be better than ±5% for He, Ne, and Ar and ±12% for Kr and Xe. Uncertainties in isotope ratios are better than 1%, with the exception of $^{129}Xe/^{132}Xe$, which should be better than 4%.

None of the analyzed chondrites contain solar gas, therefore, ^3He and ^{21}Ne are taken as purely cosmogenic. To obtain the cosmogenic $^{22}Ne/^{21}Ne$, which is used as a shielding correction for production rates, corrections have been made for a small atmospheric contribution if $^{20}Ne/^{22}Ne$ is greater than 0.82. Cosmogenic ^{38}Ar is calculated assuming a trapped component with $^{38}Ar/^{36}Ar$ = 5.32 and a cosmogenic ratio of 0.67. Details on the systematic of cosmic-ray-produced noble gases in meteorites were given recently by Wieler (2002).

Exposure ages are calculated from ^3He, ^{21}Ne, and ^{38}Ar according to procedures given by Eugster (1988), however, the production rate of ^{38}Ar used is 13% lower than that proposed by Eugster (1988) because it improves the internal concordance among all three ages (see Schultz et al. 1991). The cosmogenic $^{22}Ne/^{21}Ne$ and the calculated exposure ages are listed in Table 2.

DISCUSSION

Radiogenic Gases and Gas Loss

^{40}Ar in chondrites is predominantly of radiogenic origin, but adsorbed atmospheric Ar is common in stones from hot deserts (Scherer et al. 1994). This is the case for Burnabbie. The ^{36}Ar concentration is 13.7 · $10^{-8}cm^3STP/g$, which is very high for H5 chondrites, which generally have less than 0.7 · $10^{-8}cm^3STP^{36}Ar/g$ (Schultz et al. 1990). It is assumed that the ^{36}Ar in this meteorite is mostly atmospheric. This reduces the concentration of radiogenic ^{40}Ar to approximately 5.1 · $10^{-5}cm^3STP/g$, which is a reasonable value. For Deakin 001, however, the ^{36}Ar concentration is in the range of types 3 to 4 chondrites. This meteorite has no appreciable amounts of adsorbed atmospheric gases. Three meteorites, Billygoat Donga, Deakin 001, and Forrest 010, show very low radiogenic ^{40}Ar concentrations; the ^{40}Ar of Cocklebiddy and Kybo are also rather low. For these five meteorites, the radiogenic ^4He is also low.

The loss of radiogenic gases takes place during thermal events on the parent body of chondrites. These events are most likely impacts, which release meteoroids from their parent bodies. For example, Kybo 001 is a severely shocked LL5 chondrite containing melt pockets, and a heating episode resulting from an impact may account for the loss of ^{40}Ar in this meteorite.

However, radiogenic gas loss also occurs in meteoroids

Table 2. The cosmogenic shielding indicator $^{22}Ne/^{21}Ne$, exposure ages calculated from ^{3}He (T3), ^{21}Ne (T21), ^{38}Ar (T38), and the mean value (T_{mean}), as well as the terrestrial ages terrestrial ages T_J given by Jull et al. (1995) and the shielding-corrected ages T_L according to Leya et al. (2000).

		T3	T21	T38	T_{mean}	T_J	T_L
Meteorite	$^{22}Ne/^{21}Ne$	Exposure ages (10^6 yr)				Terrestrial ages (10^3 yr)	
Billygoat Donga	1.045	14.4	12.4	15.9	14.3 ± 1.5	7.6 ± 1.3	
Boorabie	1.127	3.1	3.3	3.9	3.4 ± 0.4	0.9 ± 1.3	−1.9
Burnabbie	1.078	4.6	5.6	4.9	5.0 ± 0.5	23.1 ± 1.4	
Carlisle Lakes 002	1.115	2.7	3.8	3.6	3.7 ± 0.1[a]	2.8 ± 1.3	1.0
Cocklebiddy	1.069	1.5	3.3	3.1	3.2 ± 0.1[a]	1.9 ± 1.3	
Deakin 001	1.151	21.4	23.7	21.1	22.1 ± 1.4	27.1 ± 1.4	22.4
Forrest 007	1.119	3.4	3.7	3.4	3.5 ± 0.2	3.4 ± 1.3	1.2
Forrest 009	1.084	9.7	11.4	9.5	10.2 ± 1.0	5.9 ± 1.3	
Forrest 010	1.104	4.5	5.4	4.1	4.7 ± 0.7	17.9 ± 1.3	16.9
Kybo 001	1.093	24.0	25.3	27.1	25.5 ± 1.6	2.2 ± 1.3	

[a]T21 and T38 only.

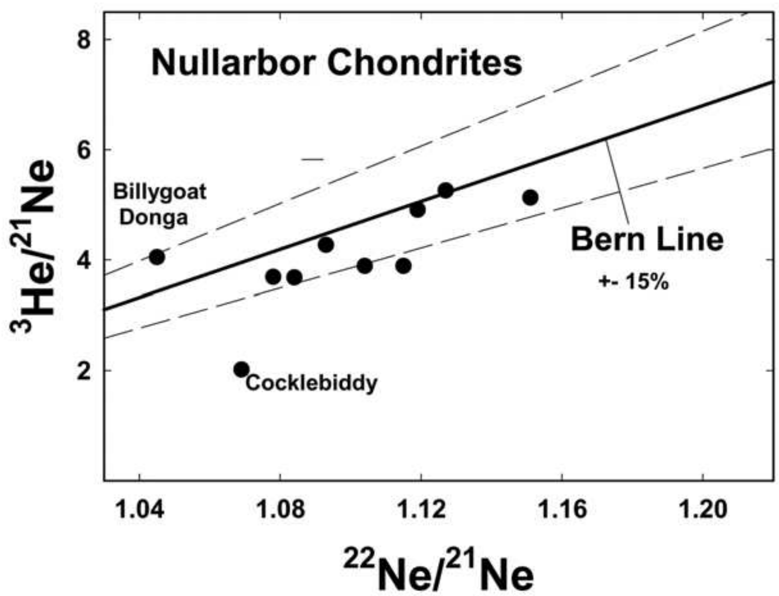

Fig. 1. Cosmogenic $^{3}He/^{21}Ne$ versus $^{22}Ne/^{21}Ne$. The solid lines represent a best fit for ordinary chondrite and the dashed lines indicate a ±15% band covering the variations caused by different shielding to cosmic rays. Cocklebiddy plots below this band, indicating a loss of ^{3}He, possibly caused by solar heating of its meteoroid on an orbit with small perihelion distance.

with small perihelion distances due to solar heating (e.g., Hintenberger et al. 1966). Such a loss is generally accompanied with a deficit of cosmogenic ^{3}He, caused by direct loss of ^{3}He, or of tritium (a precursor of cosmogenic ^{3}He). A deficit of ^{3}He is recognized in a $^{3}He/^{21}Ne$ versus $^{22}Ne/^{21}Ne$ diagram, the so-called Bern plot (Eberhardt et al. 1966), which is shown for the Nullarbor chondrites in Fig. 1.

Most of the chondrites plot within the ±15% band covering the variation caused by different chemical composition or different shape, but the general trend implies smaller $^{3}He/^{21}Ne$ ratios than most chondrites. In meteorites from hot deserts, this ratio can be influenced by weathering effects because the oxidation of the metal with the loss of cosmogenic gases would result in relatively lower ^{3}He concentrations (e.g., Nyquist et al. 1973). Only Cocklebiddy may have lost cosmogenic ^{3}He (and possibly the radiogenic gases) due to solar heating as a meteoroid on an orbit with small perihelion distance.

The position of Billygoat Donga with an extremely low $^{22}Ne/^{21}Ne$ ratio may be caused by a large shielding in a meteoroid with rather large mass. Another reason may be deviation from the mean chemical composition of L chondrites.

Exposure Ages

The exposure ages of the ten Nullarbor chondrites range from about 3 Myr to about 25 Myr. This is in the usual range

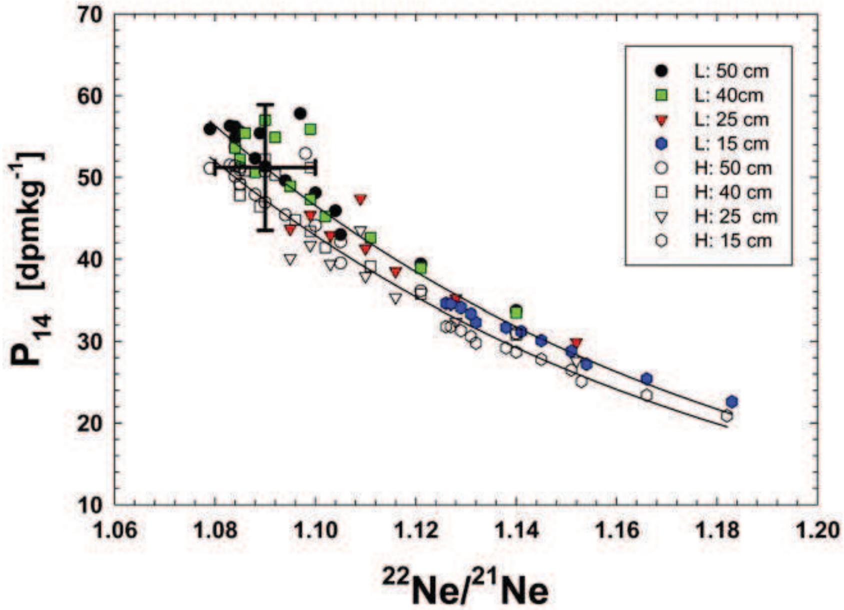

Fig. 2. The production rate of ^{14}C (P_{14}) as a function of the cosmogenic shielding indicator $^{22}Ne/^{21}Ne$ according to Leya et al. (2000). Data are given for L and H chondrites with pre-atmospheric radii of 15, 25, 40, and 50 cm. For shielding characterized by $^{22}Ne/^{21}Ne > 1.10$ (radius less than ~20 cm or the outer parts of larger meteoroids), the production rate P_{14} deviates from observed mean values.

of exposure ages of stony meteorites (e.g., Wieler and Graf 2001). None of the five analyzed H chondrites belong to the main cluster around 7 Myr that includes about 30% of all H chondrites, which are produced as meteoroids in a major collision event. All Nullarbor H chondrites have exposure ages of less than 5 Myr and thus belong to the 15% in this age range of that chondrite type. A possible pairing of these meteorites is excluded, however, because their find locations are too far apart to be members of a shower (e.g., Bevan and Binns 1989).

The exposure age of Billygoat Donga of 14.3 Myr may be a lower limit because the production rate could be overestimated due to the low cosmogenic $^{22}Ne/^{21}Ne$. Cosmogenic radionuclide data are needed to verify that this meteorite came from a very large object.

Terrestrial Ages

The terrestrial ages of Nullarbor meteorites calculated from cosmogenic ^{14}C have been given by Jull et al. (1995) and Bland et al. (2000) and are listed in Table 2 under T_J. ^{14}C in chondrites is produced mainly from oxygen; therefore, the saturation activity of ^{14}C depends on the class of the meteorite investigated. In addition, the production rate of ^{14}C for small meteorites is dependent on shielding. More detailed discussions are given by Jull (2001) and Jull et al. (2000).

The terrestrial ages T_J are calculated by Jull et al. (1995) with constant production rates for each meteorite class (L and LL: 51.1 dpmkg^{-1}; H: 46.5 dpmkg^{-1}) because no shielding indicator was available at that time. With the cosmogenic $^{22}Ne/^{21}Ne$ ratio, we can compensate the shielding dependence of the production rate of ^{14}C. Leya et al. (2000) have calculated depth-dependent and size-dependent production rates of cosmogenic nuclides from a physical model with a normalization to measured saturation activities. From their tables, the dependence of the production rate of ^{14}C (P_{14}) is evaluated in Fig. 2 for measured cosmogenic $^{22}Ne/^{21}Ne$ of H and L chondrites of pre-atmospheric radii between 15 and 50 cm.

The use of a constant P_{14} is justified for ratios <1.10 because under these shielding conditions, the production rates cluster around the mean values used by Jull et al. (1995) independent from the radius of meteoroids. For larger $^{22}Ne/^{21}Ne$ values, however, a correction is appropriate. Such a correction would lead to smaller P_{14}, which results in larger numbers of terrestrial ages.

Best-fit lines through the data of H or L chondrites are shown in Fig. 2. These lines have the form:

$$P_{14} = a \cdot \exp(-b \cdot {}^{22}Ne/{}^{21}Ne) \quad (1)$$

with a = 1.639 · 10^6 and b = 9.592 for H chondrites. For L chondrites, a and b are 1.673 · 10^6 and 9.536, respectively.

Five of the investigated Nullarbor chondrites have $^{22}Ne/^{21}Ne$ ratios >1.10. Their terrestrial ages, calculated with the production rates according to Equation 1 are given in Table 2 under T_L.

It is confirmed that Boorabie is a recent fall. The calculated negative terrestrial age may also indicate that Leya et al. (2000) have systematically underestimated the ^{14}C

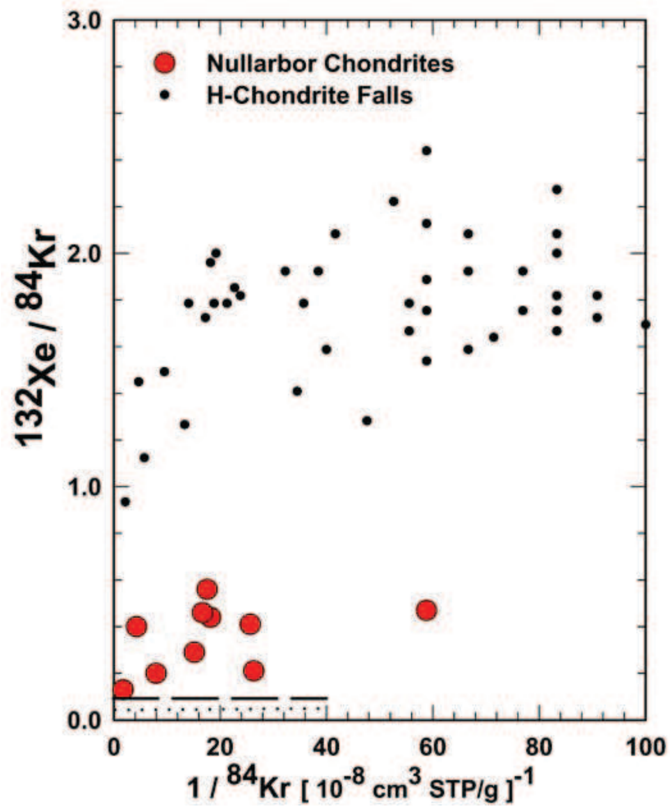

Fig 3. $^{132}Xe/^{84}Kr$ versus $1/^{84}Kr$ in meteorites from the Nullarbor region and modern falls. While the falls cluster around the average value observed for planetary gases in chondrites ($^{132}Xe/^{84}Xe$ ~1.7) meteorites from the Nullarbor region contain much smaller values due to an addition of adsorbed atmospheric gases ($^{132}Xe/^{84}Kr = 0.036$). The two lines indicate the values for the terrestrial atmosphere (dotted) and for dissolved gases in water (~0.076).

production rate for low shielding conditions. The terrestrial ages of Carlisle Lakes 002, Deakin 001, Forrest 007, and Forrest 010 are, however, considerably shorter than those calculated without shielding-corrected production rates. Because cosmogenic $^{22}Ne/^{21}Ne$ ratios >1.15 are not uncommon in chondrites from hot deserts or the Antarctic, such a correction, or one using radioactive nuclide ratios, should be applied for terrestrial age determinations.

Terrestrial Weathering

Scherer et al. (1994) have discussed the influence of adsorbed atmospheric gases on the concentrations of Ar, Kr, and Xe in chondrites from different find locations (hot deserts, Antarctic meteorites, and modern falls). The $^{132}Xe/^{84}Kr$ ratio is especially affected by the addition of atmospheric gases because the terrestrial air value is 0.036, compared to a value of about 1.7 usually observed in chondrite falls. This is demonstrated in Fig. 3, which shows a comparison of measurements of H chondrite falls (Schultz et al. 1990) and the Nullarbor meteorites.

The addition of terrestrial atmospheric gases in meteorites with weathering products causes higher concentrations and thus lower $1/^{84}Kr$ and $^{132}Xe/^{84}Kr$ values, which are close to values observed in the atmosphere (dotted line) or those of gases dissolved in water (dashed line). This is a typical pattern of gases in meteorites from hot deserts, a feature which is much smaller in those from Antarctica (Scherer et al. 1994).

According to Scherer et al. (1994), the $^{132}Xe/^{84}Kr$ ratio is also roughly correlated to the weathering grade as defined by Wlotzka (1993). According to this criteria, Burnabbie and Forrest 009 are the most weathered chondrites among this suite of Nullarbor chondrites.

CONCLUSION

From the measurement of the cosmogenic noble gases in ten chondrites from the Nullarbor Plain in Australia, we can conclude that their noble gas record is comparable to that of meteorites from other hot desert areas. This concerns exposure ages, loss of radiogenic gases and of cosmogenic ^{3}He, and of adsorbed terrestrial atmospheric gases.

The production of cosmogenic ^{14}C in chondrites is dependent on the size of the meteoroid and the position of the sample within this object. Using the shielding parameter $^{22}Ne/^{21}Ne$ and model calculations by Leya et al. (2000), we have shown that mean production rates of ^{14}C should be corrected for shielding characterized by $^{22}Ne/^{21}Ne$ >1.10. This influences the calculation of terrestrial ages of meteorites from measured ^{14}C concentrations.

Acknowledgments–This paper has benefited from constructive reviews by Dr. Tim Jull and Dr. Kees Welten. L. Schultz thanks Drs. John de Laeter, Bob Loss, and Kevin Rosman for their hospitality during his stay at Curtin University of Technology, Perth, Western Australia.

Editorial Handling—Dr. Marc Caffee

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