Terrestrial Ages of Meteorites

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The terrestrial age, or the terrestrial residence time of a meteorite, together with its exposure history provides us with useful insight into the history of the meteorite. It is easy to observe that stony meteorites can weather quickly in humid environments. However, we find that large numbers of meteorites found in semi-arid and arid environments can survive for much longer times. Meteorites in desert environments can survive for at least 50,000 yr, and there are some meteorites over 250,000 yr old from these locations. The cold and dry conditions of polar regions such as Antarctica are also good for the storage of meteorites. A considerable number of meteorites survive there for hundreds of thousands of years. Some meteorites have been found in Antarctica with ages of up to 2 m.y. In this paper, we discuss the terrestrial residence times or terrestrial ages of these meteorites. We will show the wide range of terrestrial ages from different environments.

1. INTRODUCTION

It is important to determine the terrestrial age, or residence time, of a meteorite on the surface of Earth, as this gives us useful information that can be applied to studies of infall rates, meteorite distributions, weathering of meteorites, and meteorite concentration mechanisms. Most meteorites are recovered as "finds" and not as freshly fallen material. The study of the terrestrial ages of these meteorites gives us useful information concerning the storage and weathering of meteorites, as well as the effect of local geology and climate on meteorite storage. We would expect that weathering of meteorites and their eventual destruction would be a function of the terrestrial age. A direct connection of weathering rates to the terrestrial survival times of meteorites was initially shown by *Jull et al.* (1990) and *Wlotzka et al.* (1995) and later by *Bland et al.* (1996, 1998).

1.1. Infall

It is a general assumption that meteorites fall equally all over the world (*Halliday et al.,* 1989; *Halliday,* 2001). It has been known for many years that the distribution of potential meteoroids in the solar system has an inverse power law dependence on mass, where $n \sim m^{-0.8}$. There have been a number of models and discussions of the expected infall rate onto the surface of Earth. Several models have discussed the ablation of material during fall through the atmosphere. This results in a shift to low fragment sizes and total mass of the infalling material at the surface (*Love and Brownlee,* 1993; *Cziczo et al.,* 2001).

The best description of infall is the analysis of *Halliday et al.* (1989), who formulated an equation to describe the apparent mass dependence of observed meteorite falls, based on fireball observations and other information. This equation was a refinement of earlier studies of infalling material, which showed an approximately $M^{-0.83}$ mass dependence for material in the vicinity of Earth. This is also used to predict the infall rates of objects to the surface of Earth. The infall rate was described as a function of mass where

$$\log N = a \log M + b \tag{1}$$

where N is the number of meteorites that fall per 10^6 km^2 per year, of greater than mass M in grams (see *Halliday et al.,* 1989). *Halliday et al.* (1989) determined the constants a and b to be –0.49 and +2.41 for M < 1030 g, and –0.82 and +3.41 for M > 1030 g, based on observations of meteoroids. This would result in an infall rate of M > 10 g of 83 events per 10^6 km^2/yr, or roughly one event per km^2 in 10,000 yr. Using a different approach, combining weathering rates and recovery statistics, *Bland* (2001) estimated an infall rate of 36–116 events per 10^6 km^2.

Different flux estimates have been derived from other sources. *Zolensky et al.* (1990) overestimated the infall rate, based on recovery of meteorites at Roosevelt County (New Mexico), although this was later corrected by *Zolensky et al.* (1992). *Huss* (1990) also calculated high rates of influx based on statistical analysis of the collections from different Antarctic ice fields. The model of *Huss* (1990) had assumed there was no transport of meteorites in Antarctic ice. We can explain the apparent high infall rates of *Huss* (1990) due to incorrect assumptions. Ice transport is further and the age range of Antarctic meteorites is larger than assumed by *Huss* (1990). Also, some authors have proposed that there are compositional differences in meteorites falling in different parts of the world. For example, *Lipschutz* (1989, 1990) and *Schultz et al.* (1995) discussed whether the Antarctic collection and the non-Antarctic collection sampled the same distribution of meteorites. There now appears to be little disagreement with the infall rate similar to those of *Halliday et al.* (1989), at least as a first-order approximation to the infall rate (*Bland et al.,* 1996; *Bland,* 2001). There is no evidence for fluctuations in the infall rate, at least on timescales of less than tens of millions of years (*Shoemaker,* 1997). *Karner et al.* (2003) found no changes in dust flux over the last 20 k.y., although *Farley and Patterson* (1995) and others have argued for accretionary pulses on the scale of 100 k.y. for dust-sized particles. Over longer time periods, there is possible evidence of an enhanced flux. *Schmitz et al.* (2001) found over 50 "fossil" meteorites in an Ordovician quarry in Sweden that were pseudomorphs of chondritic textures and also contained spinel grains of L-chondrite composition. The material is consistent with an age of ca. 480 Ma and their results suggest the infall rate might have been 1–2 orders of magnitude higher at that time, with the assumptions of the model used by *Schmitz et al.* (2001).

1.2. Find Locations

In warm and humid regions, recovering meteorites of any significant terrestrial age is a difficult task. Meteorites weather rapidly in warm and humid conditions, especially in the presence of Cl^- (*Buchwald,* 1975). However, there are many places where large concentrations of meteorites can be recovered. In such regions, particularly arid environments such as deserts and cold, dry polar regions, we can expect that weathering rates are much reduced and so meteorites can be preserved for longer periods of time. In addition, in polar regions, meteorites may be concentrated by ice flow, as observed in Antarctica (*Cassidy,* 2003).

Great numbers of meteorites have been recovered from many areas of the world (*Koblitz,* 2003). The largest single source is Antarctica (estimated >20,000 individual specimens), but large numbers have been recovered from North African deserts, including Morocco (>2000), Libya (over 1270 meteorites recovered), and Algeria (~500 meteorites), the deserts of Oman (>1100), and the Arabian peninsula (*Franchi et al.,* 1995; *Hofmann et al.,* 2003). In addition, some 300 meteorites have been recovered from the Nullarbor Plain of Australia (*Bevan and Binns,* 1989a,b; *Bevan et al.,* 1998; *Bland et al.,* 2000). Roosevelt County, New Mexico (*Sipiera et al.,* 1987), where 105 individuals have been recovered, was the first area of large-scale recovery in North America. *Kring et al.* (1999, 2001) have discussed the large strewnfield of the Gold Basin meteorite, where thousands of individual fragments have been recovered. *Verish et al.* (1999) have discussed the Lucerne Valley meteorites recovered from a dry lakebed in California. It is now common to hear of organized searches of meteorites, arranged by scientists, meteorite enthusiasts, and collectors, especially to the deserts of North Africa, North America, southern Africa, and the Middle East (Fig. 1). To add to the interest, many rare and valuable achondrites, identified as being from Mars or the Moon, have been recovered from these locations. A total of about 32 meteorites from Mars (representing 24 discrete falls) and the same number from the Moon were known as of 2003 (*Cassidy,* 2003; *Hofmann et al.,* 2003).

Although one could assume the length of time a meteorite has resided on Earth's surface affects its degree of weathering, this correlation is not direct, as has been shown by the study of *Bland et al.* (1996). Desert meteorites can be particularly weathered, due to the extreme conditions of storage *(Welten et al.,* 1999a). Weathering of meteorites received much less attention before the recovery of large numbers of desert meteorites. Although the Roosevelt County meteorites, collected from the semi-arid areas of eastern New Mexico, were very weathered, studies on Antartic meteorites initially assumed that meteorites collected from Antarctica were pristine. This became an issue in studies of carbonates of apparently martian origin in the sher-

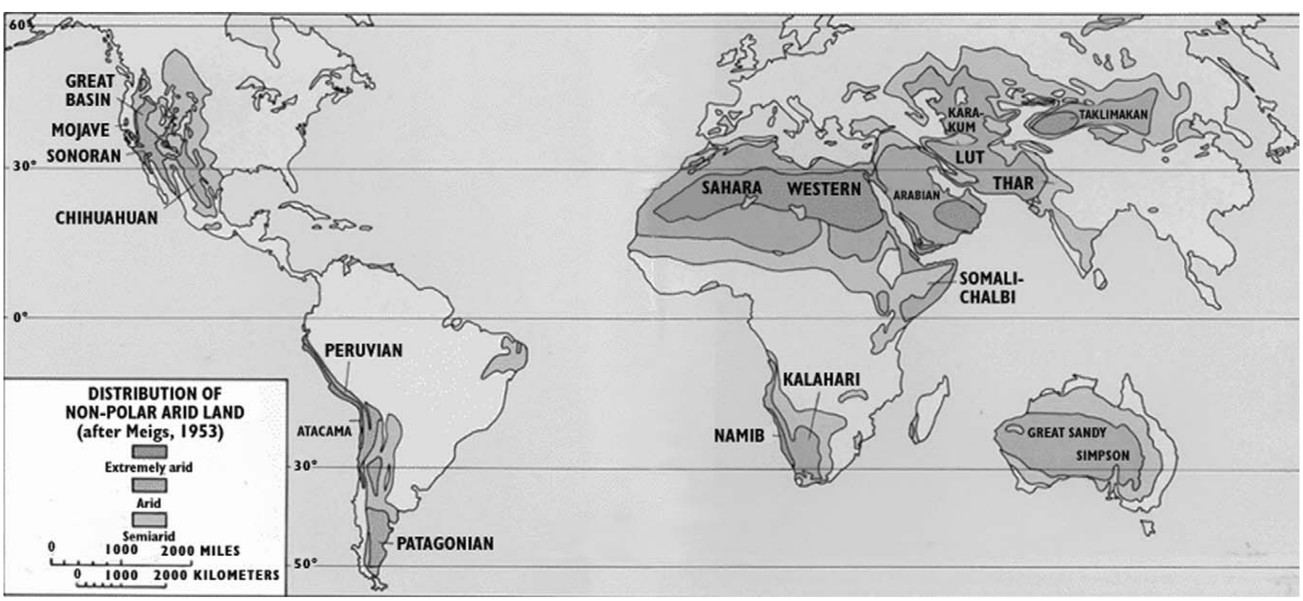

Fig. 1. Map of desert regions of the world based on rates of precipitation (*Fraser,* 1997). Courtesy of the U.S. Geological Survey.

TABLE 1. Radionuclides of interest for terrestrial-age studies.

	Half-life	Phase	Saturated Activity (dpm/kg) L	H	References
^{39}Ar	269 yr	metal	25	21	*Begemann et al.* (1969)
^{14}C	5.73 k.y.	bulk	51	46	*Jull et al.* (1998b); *Jull* (2001)
^{41}Ca	100 k.y.	metal	24		*Fink et al.* (1991); *Herzog et al.* (1997)
^{59}Ni	108 k.y.*	metal	~350		*Schnabel et al.* (1999a)
^{81}Kr	229 k.y.	bulk	0.003–0.0045†		*Freundel et al.* (1986); *Eugster* (1988a)
^{36}Cl	300 k.y.	metal	22.8		*Nishiizumi et al.* (1989a); *Herzog et al.* (1997)
^{26}Al	700 k.y.	bulk	60	56	*Evans et al.* (1982); *Vogt et al.* (1990)
^{60}Fe	1.49 m.y.				*Knie et al.* (1999); *Goel and Honda* (1965)
^{10}Be	1.5 m.y.	bulk	22	20	*Nishiizumi et al.* (1989a); *Nishiizumi* (1995)
^{53}Mn	3.7 m.y.	metal	434		*Nishiizumi et al.* (1977, 1989a)

Data adapted from *Jull* (2001).
* *Ruhm et al.* (1994).
† Based on the average production rates for ^{81}Kr of 6–9 × 10^{-14} cm^3/g/m.y. (*Eugster,* 1988a); depends on composition.

gottite EETA 79001 and later some other martian meteorites. The degree of terrestrial alteration of EETA 79001 carbonates (*Jull et al.,* 1997) was shown to be considerable. However, this discussion became much more important due to a much larger debate over Allan Hills 84001 (ALH 84001), since *McKay et al.* (1996) asserted that they observed fossil-bacterial forms as well as evidence for organic material in this meteorite. This initiated a considerable debate about weathering and contamination effects. As part of this discussion, *Jull et al.* (1998a) and *Bada et al.* (1998) showed that over the terrestrial age of ALH 84001 of some 13,000 yr, there had been weathering and adsorption of organic materials.

1.3. Weathering

The original scheme for collection of meteorites from Antarctica assumed that weathering might be an indication of terrestrial residence time. However, it is well known to many meteoriticists that weathering is dependent on the composition of the meteorites, particularly for irons and that the presence of Cl^-, incorporated into the meteorite from the environment, seems be an important catalyst for the oxidation of meteoritic metal (*Buchwald,* 1975). A common observation is that certain compositions seem to be more susceptible to weathering than others. The weathering criteria used by the U.S. Antarctic Search for Meteorites (ANSMET) uses a simple A-B-C scale for hand specimens, which does not correlate easily with terrestrial age (*Jull et al.,* 1998b). *Wlotzka et al.* (1995) devised a five-step scale, which more broadly follows terrestrial age, at least for meteorites from Roosevelt County, New Mexico.

1.4. How We Can Determine Terrestrial Age

Although some thermoluminescence (TL) measurements have been used to estimate terrestrial ages (*McKeever,* 1982; *Ninagawa et al.,* 1983; *Benoit et al.,* 1993), this method is of limited use because of the number of variables involved, and thus is not easily utilized for terrestrial ages. In one case, *Benoit et al.* (1993) were able to show a fair correlation of TL vs. terrestrial age for some meteorites from the southwestern U.S. However, attempts to apply TL to Antarctic meteorites have not been very successful.

The best approach for measurements of terrestrial age has been to study the amounts of cosmic-ray-produced radionuclides (Table 1). This was originally demonstrated in 1962, when terrestrial ages were measured by *Suess and Wänke* (1962) and about the same time by *Goel and Kohman* (1962) on large meteorite samples (10–100 g), using 5.73-k.y. ^{14}C β-decay counting. A decade later, *Boeckl* (1972) used ^{14}C to estimate terrestrial ages of meteorites from the central and southwestern U.S., using ~10-g samples. In meteorites, the longer-lived nuclide ^{36}Cl, with a half-life of 300 k.y., was also first measured by decay counting (*McCorkell et al.,* 1968; *Chang and Wänke,* 1969). *Chang and Wänke*'s (1969) pioneering work was the first attempt to systematically determine terrestrial ages of iron meteorites using ^{36}Cl; these authors also showed that some meteorites could apparently survive for very long times on the surface of Earth. *Chang and Wänke* (1969) determined that the iron meteorite Tamarugal (Chile) had a terrestrial age of ~2.7 Ma. *McCorkell et al.* (1968) studied six different radionuclides in three iron meteorites, two of unknown age (Hoba and Deelfontein), and estimated their terrestrial age. As we will discuss later, the entire field of measurement of many long-lived radionuclides was revolutionized by the introduction of accelerator mass spectrometry (AMS) in 1977 (see *Tuniz et al.,* 1998; *Fifield,* 1999). In general, ^{14}C is most useful for the terrestrial age of stony meteorites and ^{36}Cl for iron meteorites. The radionuclide ^{81}Kr, with a half-life of 229 k.y., is measured by noble-gas mass spectrometry (*Freundel et al.,* 1986; *Miura et al.,* 1993; *Eugster et al.,* 1997). This is accomplished by comparing the ^{81}Kr-^{83}Kr apparent exposure age to an independent measure of exposure age, such as ^{38}Ar.

1.5. Radionuclide Production

Radionuclides are produced in meteorites by interactions of primary cosmic rays (mostly protons and α particles) and the secondary particle cascade resulting from this irradiation (*Tuniz et al.,* 1998). The two main modes of production of nuclides are by spallation and neutron-capture reactions. Spallation is a result of disintegration of a nucleus as a result of a collision with a high-energy cosmic-ray particle. Secondary particles produced by such interactions include many neutrons, which peak at a depth of about 50 g/cm^2 (an expression of depth in the units of length times density), equivalent to ~17 cm in material of meteoritic composition. These interactions occur at high energies above about 10–20 MeV. A depth profile of a radionuclide produced purely by spallation in an infinitely large object will increase to about 50 g/cm^2 and then decrease by a factor of ~2 every 100 g/cm^2. We refer to this as a "2π irradiation." For smaller object such as meteorites, since the irradiation occurs from all solid angles, the production rate will continue to increase into the center of the object until we approach a certain size of object, which has a radius of about 150 g/cm^2 (i.e., 50 cm). We refer to this situation as a "4π irradiation." When we study larger objects, the production-rate maximum will occur before the center and we will eventually reach a condition where the cosmic rays can only penetrate from one side, that is, we eventually reach a "2π irradiation."

The secondary neutrons will eventually slow to thermal energies with depth in the sample, if they do not react or escape from the object. The nuclear reactions of these thermal neutrons with some target nuclei gives rise to reactions at greater depths, due to neutron capture or other thermal neutron reactions. In this case, production rate for the neutron-produced radionuclides will increase with depth and the size of the meteoroid, up to about a depth of 200 g/cm^2 (2π). Cobalt-60 is an example of a short-lived radionuclide produced by thermal neutrons, and most of the ^{36}Cl and ^{41}Ca produced in silicates is from thermal-neutron reactions, as is ^{59}Ni in meteoritic metal. It is also important that we can estimate the depth of a meteorite sample in its parent meteoroid in space during irradiation, which is usually unknown. We have to estimate this depth, often termed "shielding depth," from ratios of isotopes sensitive to depth, such as $^{22}Ne/^{21}Ne$ (*Cressy and Bogard,* 1976). Alternatively, shielding-independent age measurements can be obtained by using pairs of different radionuclides of different half-life, but similar production reactions.

After the collection of meteorites from Antarctica, there was a renewed interest in understanding the terrestrial ages of these meteorites. This began with the work of *Fireman* (1978). *Kigoshi and Matsuda* (1986) also made some ^{14}C measurements on Antarctic meteorites using similar β-counting methods. All these early measurements required the use of gas or solid counters and usually required large samples and gave low count rates. Aluminum-26 measurements were performed by counting the annihilation γ-rays from ^{26}Al on whole-rock specimens *(Evans and Rancitelli,* 1979; *Evans et al.,* 1982, 1992), but it was found that determining this nuclide alone could not be easily used to determine terrestrial age.

Few measurements of terrestrial age were available, because of the size of sample needed and the slow nature of the counting process. This was changed radically by the development of accelerator mass spectrometry (AMS), which allowed the use of much smaller samples. *Nishiizumi et al.* (1979) were the first to exploit the usefulness of this new technology for meteoritics. A review of the extensive literature up to 2001 has been discussed by *Jull et al.* (1998b) and *Jull* (2001). In the last several years, the number of meteorites recovered from arid desert regions has continued to increase rapidly and many more measurements on various meteorites have been made. An example of this focus is the recovery of a number of lunar and martian meteorites (*Nishiizumi et al.,* 2002, 2004). Apart from some rare cases of very old achondrites (*Nishiizumi et al.,* 2002), it is still true that for desert meteorites, ^{14}C is the most useful radionuclide for terrestrial-age determinations (*Jull et al.,* 2002; *Welten et al.,* 2003, 2004).

2. ACCELERATOR MASS SPECTROMETRY METHODS

In accelerator mass spectrometry (AMS), the atoms of the radionuclide of interest are counted directly using mass spectrometry combined with nuclear accelerator techniques (*Tuniz et al.,* 1998). The sample size requirements are correspondingly reduced by factors of 1000 to 10,000 compared to decay counting of β particles or γ rays and the counting time is also reduced from days or weeks to a measurement time by AMS of ~20–30 min. At the Arizona AMS laboratory, the detection limit for ^{14}C is ~2×10^{-15} $^{14}C/^{12}C$ and for ^{10}Be ~5×10^{-15} $^{10}Be/^{9}Be$. Detection limits for other radionuclides are similar (*Tuniz et al.,* 1998; *Fifield,* 1999). For typical sample and carrier, this is about 10^5 atoms for both nuclides. In the case of meteorite samples, blanks are typically higher for ^{14}C, ~10^6 atoms, due to chemical processing and high-temperature of extraction of the CO_2 from the sample. Although the chemistry used to extract the nuclide of interest varies considerably, the principles are very similar to other radionuclide methodology. The sample is processed and a carrier of the element of interest is usually added. A concentration step allows the separation of the carrier and the radionuclide and the final product is a solid target consisting of 0.1–1 mg of the element of interest in a suitable compound. In all cases of AMS measurements, a solid target material is pressed into a target holder and negative ions are produced from the sample by Cs sputtering. The negative ions are accelerated, stripped of several electrons, and then further accelerated. These positive ions are then separated by mass and energy, to the final detector (see *Tuniz et al.,* 1998; *Fifield,* 1999).

3. PRODUCTION AND DECAY OF RADIONUCLIDES

3.1. Principles

The buildup and decay of the radionuclides in meteorites are the same as for any other radioactive process. The buildup of the nuclide is controlled by the production rate of the given nuclide in the meteorite, at the location of the sample within the larger meteoroid. In most cases, the meteoroid has been exposed in space for longer than several mean lives of the radionuclide and the nuclide reaches a saturation equilibrium, termed "saturation," where the rate of production equals the rate of decay. We show some typical production rates of radionuclides in ordinary chondrites in Table 1.

We can relate the amount of any radionuclide remaining at time t by integrating the basic radioactive decay equation $dN/dt = -\lambda N$. The equations below are given in number of atoms present, but similar equations can be derived for activity (dN/dt)

$$t = -\frac{1}{\lambda}\ln\left(\frac{N}{N_0}\right) \qquad (2)$$

where N_0 is the initial number of atoms, N is the number of atoms remaining, and λ is the decay constant. Except for samples exposed at altitudes above a few kilometers (*Tuniz et al.,* 1998), the exposure to cosmic radiation after the meteorite fell to Earth is negligible and is not used for most calculations of terrestrial ages. However, this radioactivity can become significant in cases where most of the radionuclide produced in space has decayed. This allows us to calculate an age from this equation, defining N_0 as P_s/λ

$$N = \frac{P_s}{\lambda}e^{-\lambda t} + \frac{P_t}{\lambda}(1 - e^{-\lambda t}) \qquad (3)$$

Here, P_s is the production rate in space and P_t is the production rate in the meteorite after it fell to Earth. P_s is a function that depends on the position of the sample in the parent meteoroid and the original size of that object (*Graf et al.,* 1990a,b). We can apply this equation to any radionuclide. In some cases, we can get better precision in the age measurement by using the ratio of two radionuclides with different half-lives, since the effects of shielding on both nuclides is minimized (*Nishiizumi et al.,* 1997)

$$\frac{N_1}{N_2} = \frac{P_1\lambda_2}{P_2\lambda_1}e^{(\lambda_2 - \lambda_1)t} \qquad (4)$$

where the subscripts 1 and 2 refer to the two radionuclides with different half-lives. Nishiizumi and co-workers have used the combinations of ^{10}Be-$^{36}Cl/^{10}Be$ and ^{36}Cl-$^{41}Ca/^{36}Cl$ to calculate terrestrial ages.

3.2. Production Rates

We can estimate the dependence of different radionuclides in small meteoroids from calculations using computer modeling codes (*Reedy,* 1987, 2000; *Vogt et al.,* 1990). *Reedy* (1985) adopted the original *Reedy and Arnold* (1972) model for use with meteorites. *Graf et al.* (1990a,b) developed models for both the size of the meteoroid and depth dependence of major radionuclides. This work was also utilized by *Wieler et al.* (1996). There are three computer codes currently in use: HERMES (*Leya et al.,* 2000, 2004), the LAHET code system (*Reedy and Masarik,* 1995), and MCNPX *(Kim and Reedy,* 2003).

Graf et al. (1990a,b) compared measured and calculated levels of cosmogenic nuclides in Knyahinya to show the production rates as a function of depth. In the case of ^{14}C, *Jull et al.* (1994), *Jull* (2001), and *Wieler et al.* (1996) have discussed the variation in production rate at different depths in meteorites of different sizes. Recent falls generally show activities of ^{14}C equivalent in a range of production rates from about 38–58 atoms/min/kg, with an average value of 51 ± 1 dpm/kg for L chondrites (*Jull,* 2001). It was estimated by *Wieler et al.* (1996) that in H chondrites with pre-atmospheric radii from 20 to 45 cm, the saturated activity (or production rate) should vary from about 38 to 52 dpm/kg. Smaller objects have lower production rates of ^{14}C. *Jull et al.* (1994) measured samples from different depths in the Knyahinya L chondrite (Fig. 2), which had a preatmospheric radius ~45 cm. These measurements gave values of 37 at the surface to 58 dpm/kg at the center of the meteorite (*Jull et al.,* 1994). In most cases, nearly all ^{14}C is produced from spallation of O, only about 3% produced from Si (*Sisterson*

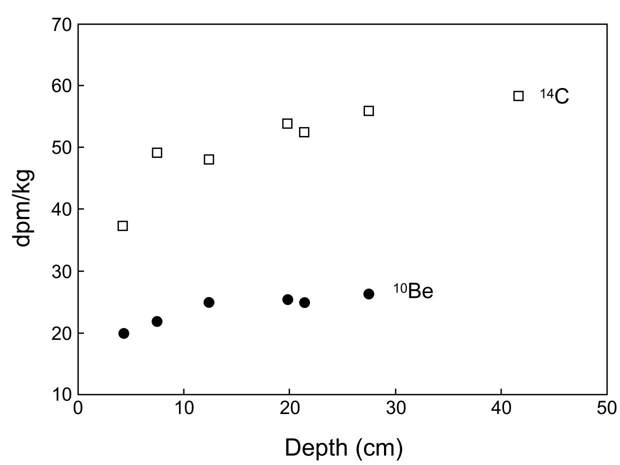

Fig. 2. Depth dependence of ^{14}C and ^{10}Be in samples of Knyahinya (*Jull et al.,* 1994, 2004a). The increase with depth is due to the buildup of secondary-neutron production of the radionuclides.

et al., 1995). Hence, we can use the O content as a scaling parameter. We estimate the saturated activity for a given class of meteorite by normalizing the mean value of the ^{14}C content of Bruderheim (51 ± 1 dpm/kg) to the O content of the meteorite determined from bulk chemistry or from average compositions (*Mason,* 1979).

4. OTHER RADIONUCLIDE TERRESTRIAL-AGE DATING METHODS

4.1. Carbon-14–Beryllium-10 Dating

A limitation of using ^{14}C for terrestrial ages is that shielding corrections may be required if the original meteoroid was very large or small. One way to make these depth estimates is by $^{22}Ne/^{21}Ne$ ratios (*Welten et al.,* 2003). An excellent method is to use the production rate of a more long-lived nuclide such as ^{10}Be to normalize to the ^{14}C production rate. Since both of these radionuclides are produced by spallation reactions on O, we can assume their production ratio in meteorites to be reasonably constant. We assume that the exposure age of the meteorite is sufficient to saturate ^{10}Be and that the $^{14}C/^{10}Be$ production ratio is reasonably constant. In the past, we have taken the production ratio $^{14}C/^{10}Be$ to be 2.5 ± 0.1 (*Kring et al.,* 2001; *Welten et al.,* 2001; *Jull et al.,* 2001), based on a few irradiation experiments, as well as observations of the $^{14}C/^{10}Be$ in recently fallen meteorites. We first observed the stability of the ^{14}C-^{10}Be system for Knyahinya (*Jull et al.,* 1994). Later, we were able to show the utility of the ^{14}C-^{10}Be method for the large fall of the Gold Basin (Arizona) meteorites (*Kring et al.,* 2001) and for Frontier Mountain (Antarctica) meteorites (*Welten et al.,* 2001). In Fig. 3, we show the behavior of the ^{14}C-^{10}Be ratio for average chondrites [where we have taken $^{14}C/^{10}Be$ = 2.5 (*Jull et al.,* 2004a)] and also Knyahinya (L5), which gives a ratio of ~2.1 (*Jull et al.,* 2004a). For comparison, we also plot the results for the Gold Basin meteorite shower (*Kring et al.,* 2001). For Gold Basin, we can observe the much lower ratio due to the decay of ^{14}C over the 15-ka terrestrial age of these meteorite fragments.

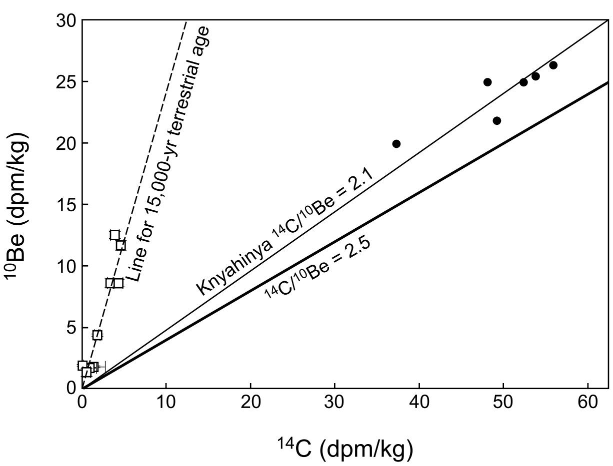

Fig. 3. Behavior of ^{14}C and ^{10}Be for chondrites of average size, with a production rate of ~2.5, Knyahinya ($^{14}C/^{10}Be$ = 2.1) and Gold Basin. For Gold Basin, the low $^{14}C/^{10}Be$ is due to the decay of ^{14}C over its 15-ka terrestrial age.

Western Australian meteorites (*Jull et al.,* 2001) generally show lower shielding and higher ^{10}Be production in the range 13–18 dpm/kg ^{10}Be. Recently, it has become apparent that there may be other meteorites where the $^{14}C/^{10}Be$ is not as well constrained. We have therefore undertaken a new set of modeling studies using the MCNPX code system to model the dependence of ^{14}C and ^{10}Be production as a function of depth and size of the meteoroid (*Jull et al.,* 2004a). The calculated ratios range from ~1.2 at the surface of small meteoroids to ~3.0 for deep samples in larger meteoroids for R = 10–1000 cm. Most of the ratios ranged from 1.8 to 3.0 and include the measured ratios of 2.5 ± 0.1 adopted by *Jull et al.* (2001). However, meteoroids with pre-atmospheric radii of ~25–100 cm, the most common size for chondrites, scatter around 2.5 but with a spread greater than 0.1. Our calculations (*Jull et al.,* 2004a) indicate that using the $^{14}C/^{10}Be$ ratio to get a rate for ^{14}C would yield slightly higher values for cases of low shielding (near surface locations or very small pre-atmospheric size) and slightly lower values for very large radii.

4.2. Chlorine-36–Calcium-41 and Chlorine-36–Beryllium-10 Dating

Welten et al. (2001) have developed a new method of dating using both ^{41}Ca and ^{36}Cl measured in the metal phase of chondrites and small irons. They found good agreement of terrestrial ages derived from these ratios compared to ^{14}C ages. This is possible due to the near-constant production ratio of these two radionuclides in the metal phase (*Nishiizumi and Caffee,* 1998). Also, these nuclides have the potential to cover the range beyond ^{14}C (>50,000 yr) and below ^{36}Cl (<150,000 yr). This method was first used for lunar meteorites, where a range of radionuclides were measured (*Nishiizumi et al.,* 1996; *Nishiizumi and Caffee,* 1998). *Nishiizumi et al.* (1997) have also reported on an alternative method for normalizing shielding corrections for iron meteorites using the combination of ^{36}Cl-^{10}Be. *Nishiizumi et al.* (1999) have claimed that using these two radionuclide combinations can reduce the uncertainty in the terrestrial age to about ±40 ka.

4.3. Other Radionuclides

Two other radionuclides of potential interest are ^{59}Ni and ^{60}Fe. Nickel-59 is a potentially useful nuclide with a half-life of ~100,000 yr, similar to ^{41}Ca. However, this radionuclide has only been used in some very limited cases and cannot be considered a routine measurement. Accelerator mass spectrometry measurements would require the use of very large accelerators. Recently, AMS measurements of ^{59}Ni and ^{60}Fe have become feasible using very large accelerators at Munich and Canberra. *Knie et al.* (1999) have studied ^{60}Fe in two iron meteorites and *Schnabel et al.* (1999a) determined ^{59}Ni in fragments of Canyon Diablo. This nuclide is potentially useful for large iron meteorites, where the production rate of the spallogenic nuclides is least useful. For example, using decay counting, *Kaye* (1963) measured ^{59}Ni in fragments of the Cañon Diablo (Arizona) iron meteorite, from which he derived a terrestrial age of $<4 \times 10^4$ yr. This result can be compared to the age estimate of Meteor Crater of ~50 ka, which is discussed below in section 5.5. In another early counter study, *McCorkell et al.* (1968) estimated the terrestrial age of Hoba to be <80,000 yr. This value was determined from the levels of ^{59}Ni present, 355 ± 100 dpm/kg, which suggested little decay of ^{59}Ni, compared to a known fall (Sikhote-Alin, Russian Far East), which gave 285 ± 70 dpm/kg.

Another radionuclide of potential interest for meteoritics is ^{39}Ar ($t_{1/2}$ 269 yr). *Begemann and Vilcsek* (1969) reported on some measurements using gas counters. Improvements in small gas-counter technology make it feasible that such studies might be done in the future. Perhaps future technical improvements will allow these three radionuclides to be added to the stable of techniques available to us for cosmogenic-nuclide dating.

5. TERRESTRIAL AGES OF METEORITES FROM DIFFERENT REGIONS

Although meteorites are found everywhere, the arid and polar regions of the world appear to be the best locations for storage of meteorites. They can survive for long periods of time in such environments (*Nishio and Annexstad,* 1980; *Nishiizumi et al.,* 1989b, 2002; *Jull et al.,* 1990, 1993a, 1995, 1998b).

5.1. Antarctic Meteorites

Beginning in 1969, Japanese researchers recovered a number of meteorites from Antarctica. They have continued to recover meteorites annually. In 1976, Cassidy and Olsen undertook an expedition to Antarctica to recover meteorites from the Allan Hills blue icefield, located in easy range of the U.S. base at McMurdo (*Cassidy,* 2003). This program has since developed into the U.S. Antarctic Search for Meteorites (ANSMET), and at least 20,000 meteorites have been recovered from Antarctica by various international teams (*Marvin and Mason,* 1984; *Marvin and MacPherson,* 1989, 1992; *Grossman,* 1994; *Cassidy*, 2003). Figure 4 shows a map of the various recovery locations.

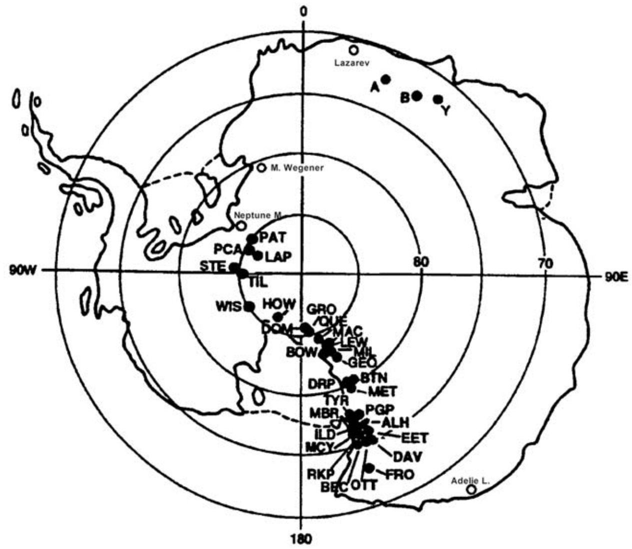

Fig. 4. Map of Antarctica showing the primary recovery locations for meteorites. The sites are encoded as follows: A — Asuka, ALH — Allan Hills, B — Belgica Mountains, BEC — Beckett Mountains, BOW — Bowden Neve, BTN — Bates Nunataks, DAV — David Glacier, DOM — Dominion Range, DRP — Derrick Peak, EET — Elephant Moraine, GEO — Geologists Range, GRO — Grosvenor Mountains, HOW — Mt. Howe, ILD — Inland Forts, LAP — LaPaz Icefield, LEW — Lewis Cliff, MAC — MacAlpine Hills, MBR — Mount Baldr, MCY — MacKay Glacier, MET — Meteorite Hills, MIL — Miller Range, OTT — Outpost Nunatak, QUE — Queen Alexandra Range, PAT — Patuxent Range, PCA — Pecora Escarpment, PGP — Purgatory Peak, RKP — Reckling Peak, STE — Stewart Hills, TIL — Thiel Mountains, TYR — Taylor Glacier, WIS — Wisconsin Range, Y — Yamato Mountains. Adapted from the *Antarctic Meteorite Newsletter,* courtesy of NASA Johnson Space Center.

The U.S. collection contained 8792 meteorites in 2002 with a total weight of close to 2 metric tons. In principle, we would expect that the cold and dry conditions would allow the storage of meteorites with low rates of weathering and meteorite destruction. The observation of old terrestrial ages, some at the limit of ^{14}C dating, was initially shown by *Fireman* (1978), *Fireman and Norris* (1981), and *Kigoshi and Matsuda* (1986), using β-decay counting. This also confirmed the long terrestrial ages of *Nishizumi et al.* (1979). The change to AMS measurements had already begun to have its effect and Fireman worked with other colleagues (*Brown et al.,* 1984) on the first AMS ^{14}C measurements on meteorites. Subsequently, there is considerable literature on ^{14}C terrestrial age measurements using smaller sample sizes (0.1–0.7 g) and AMS measurements on Antarctic meteorites, as summarized by *Jull et al.* (1998b) and *Jull* (2001). As we have already discussed, the longer-lived isotopes ^{81}Kr and ^{36}Cl can determine longer terrestrial ages, beyond the useful range of ^{14}C of ~40,000 yr. The combination of two nuclide measurements can constrain the age of the meteorite; for example, a meteorite with no ^{14}C, but close to saturated ^{36}Cl, can be constrained to be between >40 and <80 ka. *Nishiizumi et al.* (1989a), *Cresswell et al.* (1993), *Jull et al.* (1993b, 1998b, 1999a), and *Michlovich et al.* (1995) have shown that the age distributions of meteorites at the Allan Hills (Victoria Land) and Yamato (Queen Maud Land) collection sites in Antarctica can be very different, as seen in Fig. 5. *Nishiizumi et al.* (1989a) reported that many meteorites from the Allan Hills Main Icefield have long terrestrial ages, as determined by ^{36}Cl ($t_{1/2}$ =

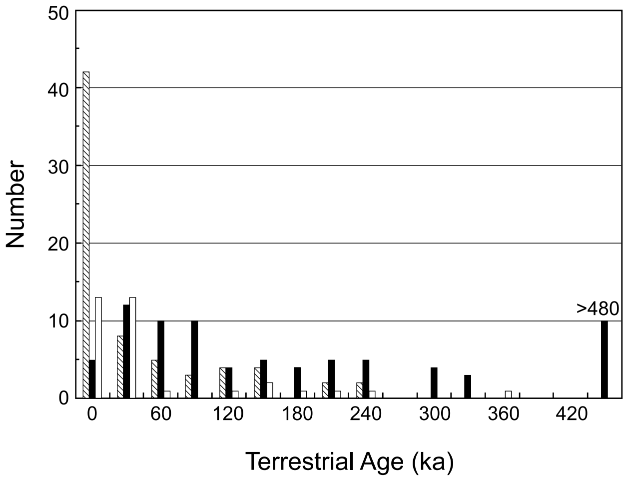

Fig. 5. Terrestrial age distributions of meteorites from the Yamato site — slanted bars (*Jull et al.,* 1993b, 1999a, unpublished data; *Nishiizumi et al.,* 1989a, 1999) — the Allan Hills main icefield (black) and Elephant Moraine (white) taken from *Nishiizumi et al.* (1999), *Michlovich et al.* (1995), *Jull et al.* (1998b), and A. J. T. Jull (unpublished data, 2003).

301,000 yr). Similarly, *Nishiizumi et al.* (1999) summarized the age distribution of Allan Hills Main and Near Western Icefield meteorites and determined that 49 of 107 samples were <70 ka.

Because of low storage temperatures, it makes sense that Antarctic meteorites can be stored for long periods of time in or on the ice. Interestingly, at Allan Hills, an H chondrite, Allan Hills 88019, and an L chondrite, Lewis Cliff 86360, were recovered, which have very long terrestrial ages in excess of 2 Ma (*Scherer et al.,* 1997; *Welten et al.,* 1997).

In Fig. 5, we show a summary of terrestrial ages determined by ^{14}C, ^{36}Cl, and ^{81}Kr for meteorites from Allan Hills, Elephant Moraine (*Welten et al.,* 1999b; *Jull et al.,* 1998b; and A. J. T. Jull et al., unpublished data, 2003), and also the Yamato site (*Jull et al.,* 1993b, 1999a, *Nishiizumi et al.* 1987). The age distribution of samples from the Allan Hills Far Western Icefield and ^{14}C ages from the Yamato site show a generally significantly younger population of meteorites. The Yamato site does show a large range of terrestrial ages, with four eucrites of terrestrial age >200 ka (*Miura et al.,* 1993).

Nishio and Annexstad (1980) developed a model involving long-range transport of meteorites, flowing along with the ice, to explain these long terrestrial ages. At the Allan Hills Far Western Icefield there are few meteorites with less than saturated ^{36}Cl (*Nishiizumi et al.,* 1989a), which would indicate short terrestrial ages consistent with the observation of significant levels of ^{14}C in most samples. In such cases, meteorites cannot have been transported any significant distance in the ice, and most likely fell at the location where they were recovered. Many Antarctic meteorites are clearly fragments of the same fall, which raises the question of "pairing." Two very large falls, one of an H5 chondrite at Lewis Cliffs and another of an LL5 chondrite at Queen Alexandra Range, are well documented in the U.S. Antarctic collection (*Zolensky,* 1998). *Lindstrom and Score* (1994) estimated a "pairing probability" for Antarctic meteorites, which they proposed might reduce the number of discrete falls by a factor of 2–6. If pairing is also taken into account, it may be possible to relate the distribution of meteorite terrestrial ages to ice flow patterns in the Allan Hills region.

5.2. Desert Meteorites

One of the first recognized areas for collections of meteorites from nonpolar regions was Roosevelt County, New Mexico (*Scott et al.,* 1986; *Zolensky et al.,* 1990). The deserts in Australia and the northern Sahara Desert in Africa have also become sources of a large number of meteorites (*Wlotzka et al.,* 1995; *Jull et al.,* 1995; *Bevan et al.,* 1998). Recent searches in Oman (*Hofmann et al.,* 2003), Libya (*Ghadi et al.,* 2003; *Schlüter et al.,* 2002), and other desert areas have been very productive. Smaller-scale searches have been undertaken at the dry lakes in the Mojave Desert, California (*Verish et al.,* 1999), and less-explored areas such as the remote deserts of southern Africa and South America may yield many more meteorites. Many meteorites are found in Northwest Africa and are often purchased from sources with unclear provenance of the material. These meteorites are labeled "Northwest Africa" meteorites.

The collection of meteorites from the Nullarbor Plain in Australia (*Bevan and Binns,* 1989a,b) and from Roosevelt County, New Mexico (*Sipiera et al.,* 1987; *Scott et al.,* 1986) has catalyzed other searches in many desert environments. Searches have been conducted in the Saharan and Saudi deserts, in North and South America, and in central Asian deserts. Where meteorites were found, many of these meteorites were heavily weathered, and thus the actual length of time they have resided on the desert floor or in surface sediments became of great interest. It would appear that achondrites can survive longer than chondrites, based on observations from Antarctica (see *Jull et al.,* 1998b). *Miura et al.* (1993) demonstrated the longevity of some Yamato eucrites. Another example is the long terrestrial ages observed for a martian and a lunar meteorite at Dhofar, Oman, of 340 and 500 Ma, respectively, by *Nishiizumi et al.* (2002).

It is interesting to note that differences in trace-element composition may not be due to differences in meteoritic composition of infall streams. *Al-Kathiri et al.* (2003) showed that uptake of trace elements from the local soil was an important source of changes in trace-element chemistry. This is the likely focus of future studies of contamination of meteorites from desert environments.

In recent years, large numbers of meteorites have been recovered from desert environments and these meteorites are becoming the major source (other than Antarctica) for meteorites. We expect that weathering occurs at different rates depending on sample chemistry and local climatic effects. Measurement of terrestrial ages of desert meteorites has been performed almost exclusively by ^{14}C, due to the problem of recovery of sufficient metal for ^{41}Ca and ^{36}Cl analysis (*Welten et al.,* 1999a).

5.2.1. The Sahara. The first terrestrial-age study of a group of meteorites from one region, outside the Antarctic, was conducted by *Jull et al.* (1990), who reported on the ^{14}C terrestrial ages of meteorites that had been recovered by a private collector near the town of Daraj, in the Hammadah al Hamra (stony desert) region of Libya. We measured the terrestrial ages of 13 meteorites, apparently from 12 discrete falls, which gave terrestrial ages between 3.5 and 35 ka. There also appeared to be a correlation between the storage of the meteorites and changing climatic conditions (*Jull et al.,* 1990). The potential of desert regions as storehouses for meteorites was slow to be recognized, but a workshop in Nördlingen, Germany, in 1994 showed much interest in the potential of these areas (*Schultz et al.,* 1995). Similarly, *Wlotzka et al.* (1995) reported on similar age distributions of 53 meteorites found in Acfer, Algeria. Two of the meteorites from Acfer were close to the limit of ^{14}C measurements, indicating ages of 35 to 42 ka. *Schlüter et al.* (2002) collected 869 meteorites of varying size from the central Sahara, south of Tripoli, from 6 g to 95 kg from Dar al Gani and the Hammadah al Hamra regions. *Welten et al.* (2004) reported on the terrestrial ages on 17 of these meteorites, which ranged from 0–30 ka, except for one that had a terrestrial age (based on ^{41}Ca) of 150 ± 40 ka.

5.2.2. Roosevelt County, New Mexico. *Jull et al.* (1991) had also reported on the terrestrial ages of 17 meteorites from Roosevelt County, New Mexico. This study contradicted higher estimates of the meteorites' age, which had been based on age estimates of the cover sands at Roosevelt County. *Zolensky et al.* (1990) made a much higher estimate, based on recovery of meteorites at Roosevelt County, but they had used a thermoluminescence age of cover sands at the Roosevelt County sites as the estimate of the meteorites' age. Later studies on the age of the cover sands were more consistent with the terrestrial age of the meteorites (*Zolensky et al.,* 1992). The terrestrial ages of the meteorites ranged from 7 to >44 ka and there was a deficiency, with respect to the expected exponential dropoff with age, of meteorites of <20 ka terrestrial age. These results, together with newer measurements on a total of 32 Roosevelt County meteorites (A. J. T. Jull, unpublished data, 2004), are shown in Fig. 6. The deficiency of younger meteorites can be explained by the fact that the Roosevelt County meteorites are found in blowouts in the cover sands of late Quaternary age (Blackwater Draw formation) found in this region.

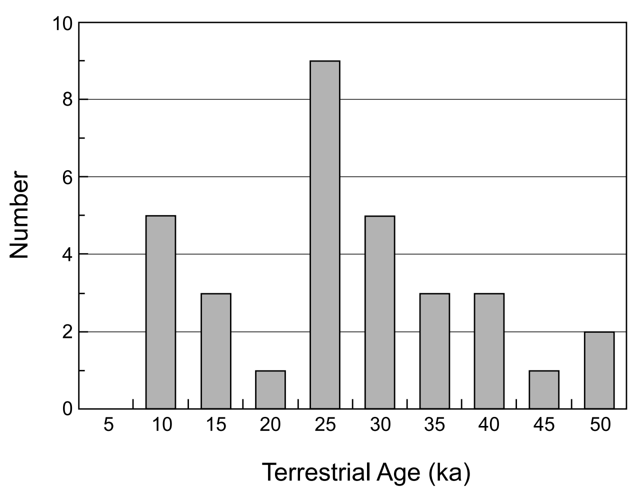

Fig. 6. Distribution of terrestrial ages from Roosevelt County meteorites (*Jull et al.,* 1991, and unpublished data). Note the peak at 20–25 ka, which may be due to pairing of several meteorites.

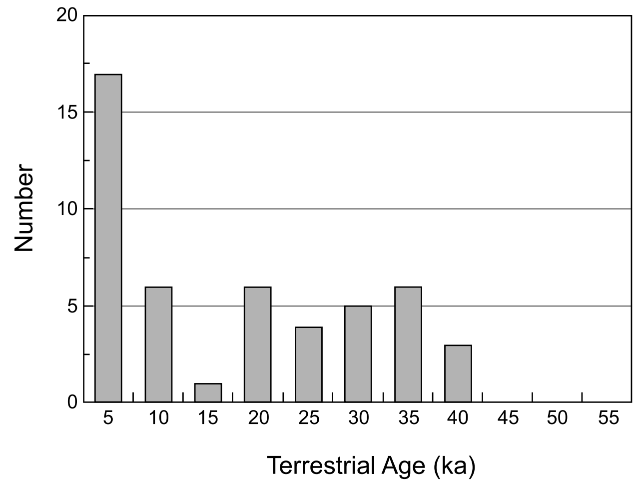

Fig. 7. Distribution of terrestrial ages from Western Australian meteorites (*Jull et al.,* 1995, 2001; *Bland et al.,* 2000).

5.2.3. Western Australia. *Jull et al.* (1995) presented results of terrestrial age determinations from 22 Western Australian meteorites, which showed that these meteorites could survive for up to 30 k.y. Further results were reported by *Bland et al.* (2000). *Jull et al.* (2001) also discussed $^{14}C/^{10}Be$ ages for some of these meteorites. In Fig. 7, the age distribution for the Western Australian meteorites shows an exponential dropoff of number of meteorites with increasing age. This indicates a mean residence time of perhaps 10 k.y. at this location. The difference in the age distribution with that of Roosevelt County (Fig. 6), where the meteorites were protected by late Quaternary cover sands, indicates a marked difference in storage conditions.

5.2.4. The Arabian Peninsula. At the Nördlingen workshop, *Franchi et al.* (1995) discussed the potential of the Arabian peninsula for recovery of meteorites. At that time, only 24 meteorites were known from this region, mostly collected by geologists in the 1930s and 1950s. *Franchi et al.* (1995) had only measured about six ^{14}C ages on meteorites from Oman and Saudi Arabia. All these measurements were made on museum samples. By 2003, several different groups of collectors had recovered thousands of specimens from Oman alone (*Hofmann et al.,* 2003; *Gnos et al.,* 2003). *Gnos et al.* (2003) have found a large strewnfield at the Jiddat al Harasis, consisting of nearly 3000 individual stones ranging in size from 1 g to 54 kg. During three meteorite field search seasons in Oman by a Swiss-Omani team (2001–2003), more than 200 individual meteorites were recovered plus several strewnfields, including that at the Jiddat al Harasis. The measured ^{14}C terrestrial ages of Omani meteorites is in the range of 2.2 to >49 ka, with many between 10 and 40 ka. The older meteorites generally are more weathered. *Gnos et al.* (2003) also observed that meteorites from the same strewnfield may have different weathering grades depending on burial conditions and the size of the meteorite. These authors also studied the chemical analysis of some of the meteorites with mean compositions of H and L chondrites and found that enrichments of Sr and Ba are most prominent. These compositional changes increase with age and weathering grade.

Nishiizumi and Caffee (2001) and *Nishiizumi et al.* (2002) have used the nuclides ^{36}Cl and ^{41}Ca for estimates of the ages of achondrites. In particular, they found terrestrial ages of a lunar and martian meteorite from Dhofar, Oman, to be 500 and 350 ka respectively. Such terrestrial ages had previously only been observed for a few achondrites in Antarctica (*Miura et al.,* 1993).

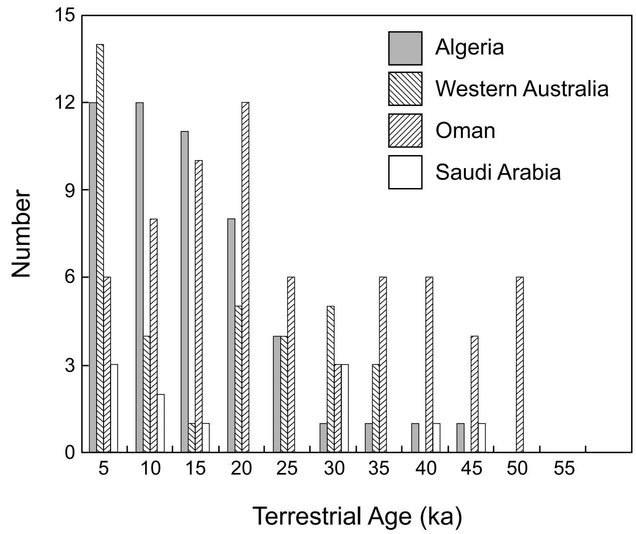

Fig. 8. Comparison of the terrestrial ages of meteorites recovered from arid regions of Algeria, Western Australia, Oman, and Saudi Arabia (*Wlotzka et al.,* 1995; *Bevan et al.,* 1998; *Bland et al.,* 2000; *Jull et al.,* 1990, 1995, 2001; *Stelzner et al.,* 1999; *Hofmann et al.,* 2003).

5.3. Trends in Terrestrial Ages

For the Nullarbor Plain, Western Australia, we observe (see Fig. 7) an approximately exponential dropoff of number of meteorites with increasing terrestrial age (*Bland et al.,* 2000; *Bevan et al.,* 1998; *Jull et al.,* 1995). *Jull et al.* (1990, 1995, 1999b), *Knauer et al.* (1995), *Neupert et al.* (1997), and *Wlotzka et al.* (1995) have reported on terrestrial ages of meteorites from the Sahara in Libya and Algeria, which show similar trends. Different climatic regimes and local geology can affect the distribution of terrestrial ages of meteorites from areas such as the Sahara and Roosevelt County, as weathering occurs at different rates depending on sample chemistry and local climatic effects.

Figure 8 summarizes ^{14}C terrestrial ages observed for meteorites from Algeria, the Nullarbor Plain, New Mexico, and Libya. In general, the Nullarbor and Sahara meteorites show an approximately exponential decrease of number of finds with terrestrial age to at least 30 ka. Since weathering gradually destroys meteorites, we expect that the resulting distribution should show some exponential dependence on age. As an example, consider a collection where meteorites fell continuously directly on the collection area. The meteorites then should eventually disintegrate and reach a steady state where the disintegration rate will match the infall rate. Therefore, the number will decrease with increasing age, and so there should be more young meteorites than older ones. This is similar to a simple first-order model of meteorite accumulation (*Freundel et al.,* 1986; *Jull et al.,* 1993a). However, as *Bland et al.* (1996, 1998, 2000) have shown, weathering of meteorites is a complex process, where an initial rapid weathering phase is followed by slower, longer-term effects. We can show an example of the case of the Western Australian meteorites. Here, few meteorites beyond the range of ^{14}C are observed and this profile shows the simple decay model for meteorite ages. In a new approach to the question of meteorite survival and weathering, *Bland et al.* (1996, 1998, 2000) compared the terrestrial ages of many meteorites with the degrees of weathering, measured by Mössbauer spectroscopy, and they further showed that meteorites of different composition weather at different rates, a fact known qualitatively to many meteoriticists, but difficult to quantify. *Bland et al.* (1998) noted that the degree of oxidation observed for Antarctic finds was 25–30% lower than for desert meteorites, which they presumed was due to the low storage temperatures. The burial of the meteorites in the ice during transport also likely protects the meteorites from weathering. As a result, correlations between degree of oxidation and weathering and terrestrial age are much weaker for Antarctic meteorites than for those from other locations.

However, the situation was much clearer for desert meteorites. *Bland et al.* (1996) showed that H chondrites, which contain more metallic iron, weather at faster rates than L chondrites. We can also conclude that achondrites, since they contain no iron metal, ought to survive the longest, which is in agreement with the observations of *Nishiizumi et al.* (2002) and *Miura et al.* (1993).

5.4. Martian and Lunar Meteorites

Meteorites from the Moon and Mars are of particular interest to many meteoriticists. A total of about 32 meteorites from Mars (representing 24 discrete falls) and 29 from

TABLE 2. Terrestrial and ejection ages of lunar meteorites.

Meteorite	Ejection Depth (g/cm^2)	Ejection Age (m.y.)	Transit Time (m.y.)	Terrestrial Age (ka)	Reference
ALHA 81005	150–180	0.04 ± 0.02	<0.05	18 ± 1	*Nishiizumi et al.* (1991a); *Jull and Donahue* (1992)
Asuka 881757	>1000	0.9 ± 0.1	0.9 ± 0.1	<50	*Nishiizumi et al.* (1992a)
Calcalong Creek	>1000	3 ± 1	3 ± 1	<30	*Nishiizumi et al.* (1992a)
Dar al Gani 262	75–90	0.16 ± 0.01	0.08 ± 0.01	80 ± 10	*Nishiizumi et al.* (1998)
Dar al Gani 400	>1100	0.24 ± 0.02	0.22 ± 0.02	17.3 ± 1.4	*Nishiizumi* (2003)
Dhofar 025	>1000	13–20	13–20	~500	*Nishiizumi et al.* (2002)
Dhofar 026	~1400	0.003	0.003		*Nishiizumi et al.* (2002)
Dhofar 081	200–230	0.04 ± 0.02	<0.01	40 ± 20	*Nishiizumi et al.* (2002)
Dhofar 280, 281	200–230	0.04 ± 0.02	<0.01	40 ± 20	*Nishiizumi et al.* (2004)
Dhofar 489	1100	—	6 ± 2	—	*Nishiizumi et al.* (2004)
EET 87521, 96008	540–600	0.08 ± 0.04	<0.01	80 ± 30	*Nishiizumi et al.* (1999)
MAC 88104, 88105	360–400	0.28 ± 0.02	0.04–0.05	230 ± 20	*Nishiizumi et al.* (1991a)
NWA 482	240	0.29	0.27	8.6 ± 1.3	*Nishiizumi and Caffee* (2001); *Daubar et al.* (2002)
NWA 773	800–1000	—	1-30	17 ± 1	*Nishiizumi et al.* (2004)
NWA 032	>1100	0.047 ± 0.010	0.042 ± 0.005	<10	*Nishiizumi and Caffee* (2001)
QUE 93069/94269	65–80	0.16 ± 0.02	0.15 ± 0.02	10 ± 2	*Nishiizumi et al.* (1996)
QUE 94281	270–320	0.05 ± 0.03	<0.05	23.5 ± 1.8	*Nishiizumi and Caffee,* (1996); A. J. T. Jull, unpublished data, 1996
Sayh al Uhaymir 169	>1000	<0.85	<0.85	9.7 ± 1.3	*Gnos et al.* (2004)
Y 791197	4–8	<0.1	<0.1	30–90	*Nishiizumi et al.* (1991a)
Y 793169	500	1.1 ± 0.2	1.1 ± 0.2	<50	*Nishiizumi et al.* (1992a); *Thalmann et al.* (1996)
Y 793274, 981031	140–180	0.032 ± 0.003	<0.01	20–35	*Nishiizumi et al.* (1991c, 2004); *Eugster et al.* (1992)
Y 793885	~90	—	—	>36	*Jull et al.* (2004b); *Nishiizumi et al.* (2004)
Y 82192, 82193, 86032	>1000	11	11	80	*Nishiizumi et al.* (1988); *Eugster* (1988b)

the Moon were known as of 2003 (*Cassidy,* 2003; *Gnos et al.,* 2004). It is interesting to note that the first lunar meteorite to be identified, ALHA 81005, was only found in 1981. Martian meteorites were not proposed to be a group, having previously been classified as shergottites, nakhlites, and chassignites, until the observation that they formed a discrete grouping in O-isotopic composition (*Clayton and Mayeda,* 1983) and also contained "trapped" gas similar to Mars atmospheric composition (*Bogard and Johnson,* 1983). The terrestrial age and the transit time (the cosmic-ray exposure age of a meteorite in free space) tells us much about its history. By calculating the sum of the terrestrial age and transit time, we can reconstruct the ejection times for meteorites that land on Earth and have an origin on Mars or the Moon. Hence, we can identify meteorites possibly related to the same impact event or common source areas. In Table 2, we give the ejection age, transit time, and terrestrial age for lunar meteorites. Similarly, martian (or SNC) meteorites are shown in Table 3; we can similarly observe that many shergottites have shorter exposure ages than nakhlites. For a detailed discussion of the ejection times of lunar and martian meteorites, the reader is referred to *Zolensky et al.* (2006).

5.5. Dating of Meteorite Craters Using *In Situ*-produced Cosmogenic Radionuclides

In the last 15 years, methods of *in situ* terrestrial cosmogenic nuclide (TCN) dating have developed (see *Tuniz et al.,* 1998). In these methods, the buildup of cosmogenic nuclides at a low level due to cosmic-ray interactions with material at Earth's surface can be used. This method can then be used to estimate the terrestrial age of a very large meteorite that caused an impact crater, by dating the crater itself. *Shoemaker et al.* (1990) considered these methods for the dating of some Australian meteor craters, and obtained estimates of the ages of Wolfe Creek (~300 ka), Boxhole (~30 ka), and Dalgaranga (apparent age ~270 ka) craters. However, the best example is the application to Meteor Crater, Arizona. *Nishiizumi et al.* (1991b) obtained an exposure age of 49.2 ± 1.7 ka reported on this new dating method using ^{10}Be-^{26}Al surface exposure dating, and *Phillips et al.* (1991) reported a similar value, using ^{36}Cl, of 49.7 ± 0.9 ka. Both of these results suggest that the impact age of Meteor Crater, and therefore the Cañon Diablo, Arizona, iron meteorite, is ~50 ka. Intriguingly, *Schnabel*

TABLE 3. Terrestrial and exposure ages of martian meteorites.

Meteorite	Classification	Ejection Age (Ma)	Terrestrial Age (ka)	Reference
ALH 77005	Shergottite	3.32 ± 0.55	190 ± 70	*Eugster et al.* (1997); *Nishiizumi et al.* (1994)
ALH 84001	Orthopyroxenite (unique)	14.4 ± 0.7	13 ± 1	*Eugster et al.* (1997)
Chassigny	Dunite	12 ± 4	Fall	*Eugster et al.* (1997)
Dar al Gani cluster	Shergottite	1.05 ± 0.1	60 ± 20	*Nishiizumi et al.* (2001)
Dhofar 019	Shergottite	18.7 ± 4.3	340 ± 40	*Nishiizumi et al.* (2002)
EET 79001	Shergottite	0.65 ± 0.20	12 ± 1	*Eugster et al.* (1997); *Jull and Donahue* (1988)
Governador Valadares	Nakhlite	10.1 ± 2.2	Fall	*Eugster et al.* (1997)
Lafayette	Nakhlite	11.4 ± 2.1	2.9 ± 1.0	*Eugster et al.* (1997); *Jull et al.* (1999c)
LEW 88516	Shergottite	4.1 ± 0.6	21.5 ± 1.5	*Eugster et al.* (1997); *Jull et al.* (1994); *Nishiizumi et al.* (1992b)
Los Angeles	Shergottite	3.0 ± 0.4	9.9 ± 1.3	*Nishiizumi et al.* (2000); A. J. T. Jull, unpublished data, 2004
Nakhla	Nakhlite	11.6 ± 1.8	Fall	*Eugster et al.* (1997)
NWA 1068/1110	Shergottite	2.2-3	>40	*Nishiizumi et al.* (2004)
NWA 1195	Shergottite	1.1 ± 0.2	>37	*Nishiizumi et al.* (2004)
NWA 1460	Shergottite	2.2-3	—	*Nishiizumi et al.* (2004)
NWA 480	Shergottite	2.4 ± 0.2	—	*Marty et al.* (2001)
NWA 817	Nakhlite	9.7 ± 1.1	—	*Marty et al.* (2001)
NWA 998	Nakhlite	—	6 ± 1	*Nishiizumi et al.* (2004)
QUE 94201	Shergottite	2.6 ± 0.5	290 ± 50	*Eugster et al.* (1997); *Kring et al.* (2003)
Sayh al Uhaymir cluster	Shergottite	1.5 ± 0.3	—	*Nishiizumi et al.* (2001)
Shergotty	Shergottite	2.71 ± 0.45	Fall	*Eugster et al.* (1997)
Y 793604	Shergottite	4.4 ± 1.0	—	*Eugster and Polnau* (1997)
Y 980459	Shergottite	1.1 ± 0.2	—	*Nishiizumi and Hillegonds* (2004)
Y 000593, 000749, 000802	Nakhlite	12.1 ± 0.7	55 ± 20	*Okazaki et al.* (2003); *Jull et al.* (2004b); *Nishiizumi and Hillegonds* (2004)
Zagami	Shergottite	2.81 ± 0.18	Fall	*Eugster et al.* (1996)

et al. (1999b) obtained an approximate age based on ^{41}Ca/^{36}Cl on Cañon Diablo meteorite fragments of 82 ± 20 ka and concluded, when considering the other data, that the crater must be <75 ka.

6. CONCLUSIONS

To determine the terrestrial ages of meteorites, the levels of radionuclides produced by exposure to cosmic radiation in space must be measured. If we compare these levels to the expected activity of a recently fallen meteorite, we can then determine the terrestrial age. From measurements of ^{14}C and ^{36}Cl, we can show that the residence time of most desert meteorites is <50 k.y. Longer residence times are observed for some chondrites and achondrites in Antarctica determined by ^{36}Cl and ^{81}Kr studies. Some meteorites can survive for a very long time in desert environments, with a few achondrites surviving for hundreds of thousands of years (*Nishiizumi et al.,* 2002). There are also some large iron meteorites with a terrestrial age of up to 2.7 Ma (*Aylmer et al.,* 1988; *Chang and Wänke,* 1969), as well as a few Antarctic chondrites that have survived for 2 m.y. (*Scherer et al.,* 1997; *Welten et al.,* 1997). As a result of studies of the terrestrial ages and weathering of meteorites, we conclude that the infall rates agree with those discussed by *Halliday* (2001), and that there is still much to learn about the weathering processes that affect meteorites.

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