Cosmic-ray-produced (cosmogenic) radionuclides in meteorites

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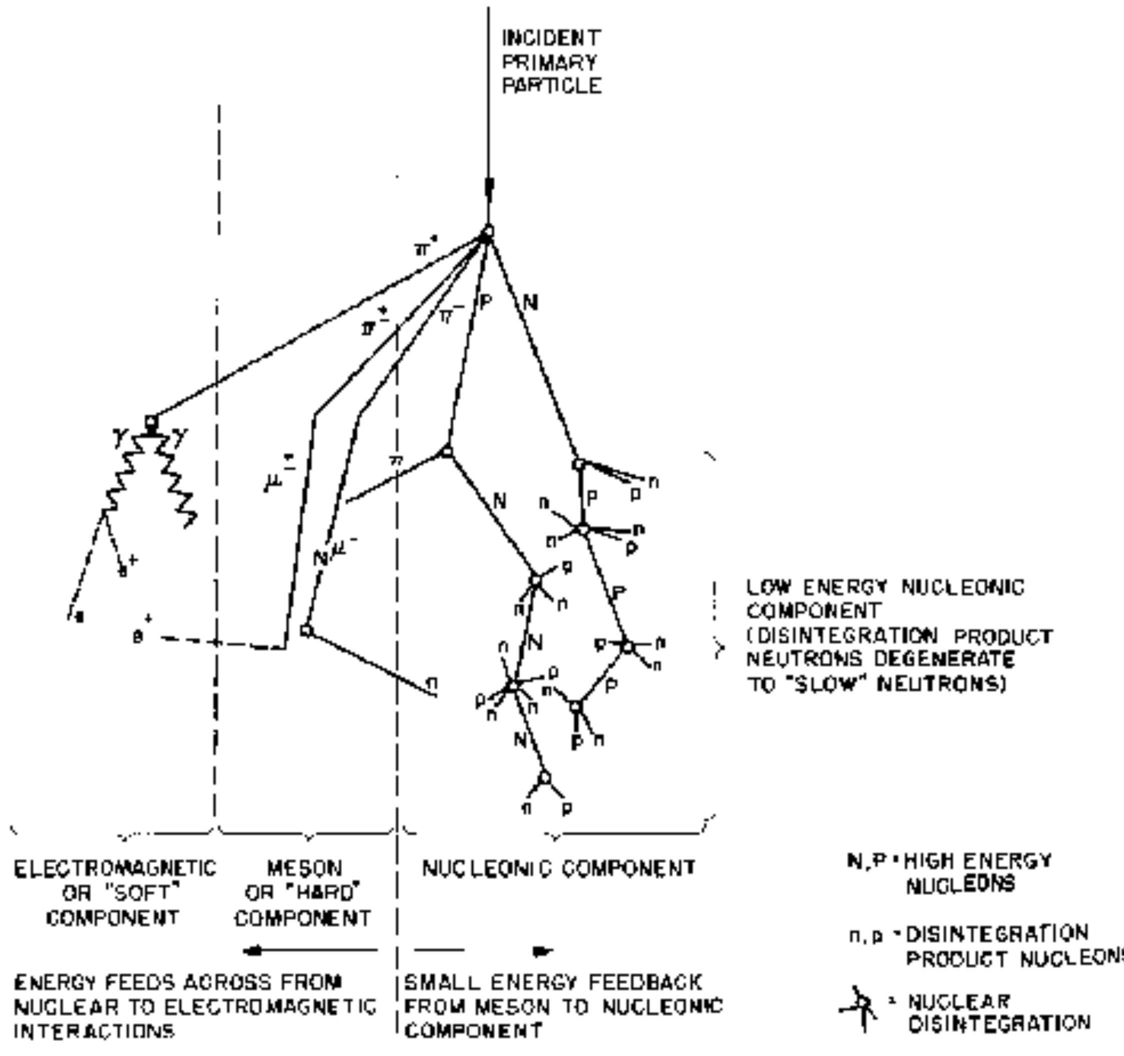
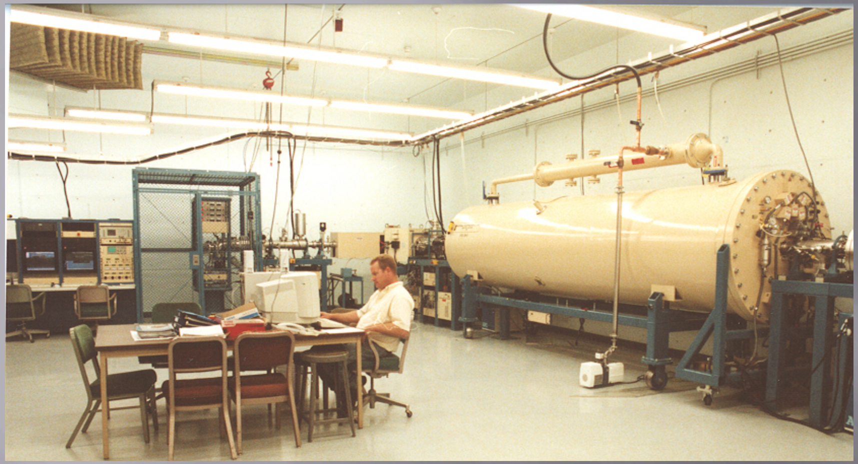
Cosmic rays form
a shower of particles
in the atmosphere,
some of which reach
the surface of the earth



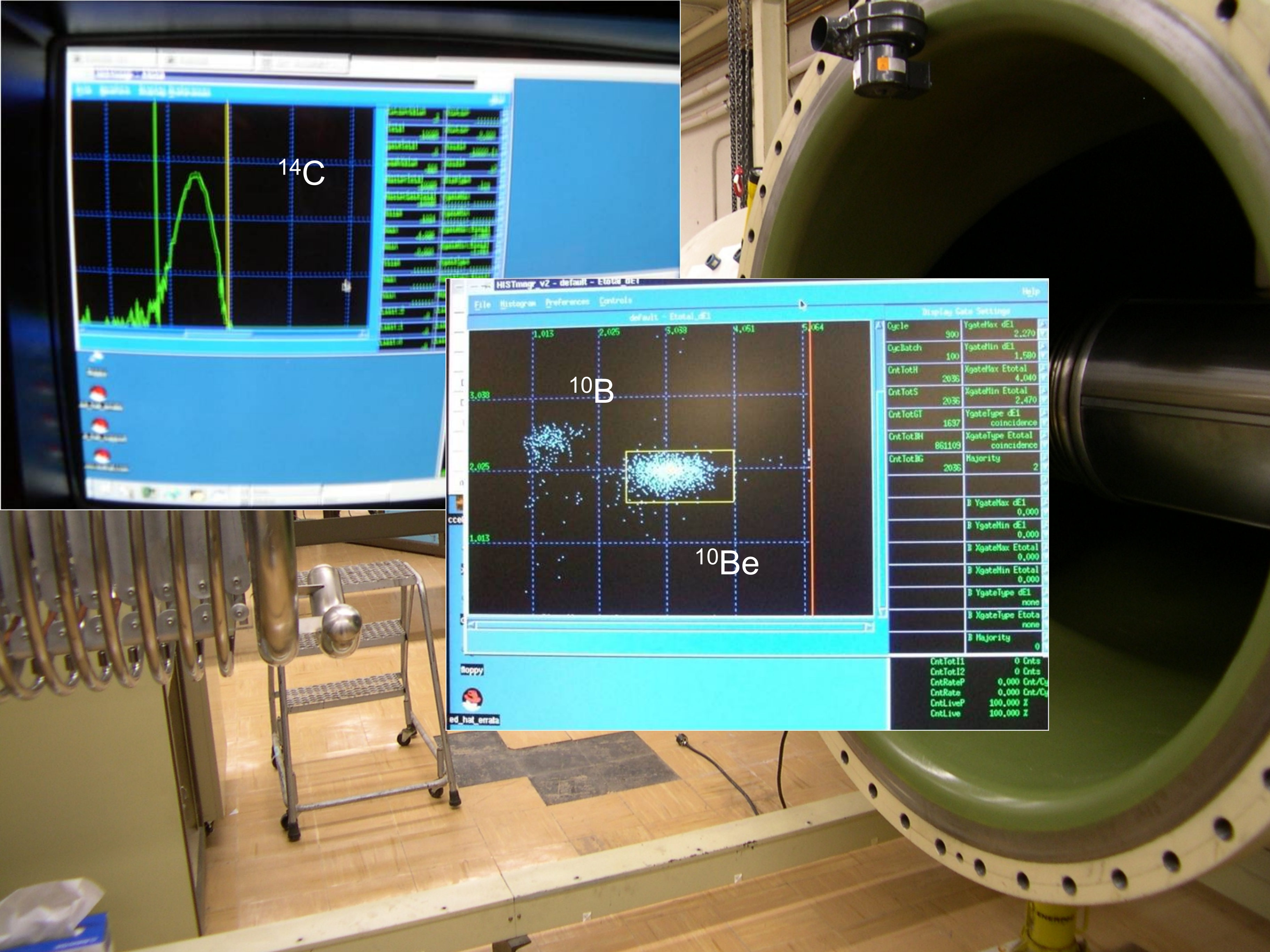
Schematic Diagram of Cosmic Ray Shower

The 3MV Pelletron at Arizona



High-energy mass spectrometry

Low-energy end showing ion source and accelerator.


14C
10B
10Be
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CntTotS 2036
CntTotGT 1697
CntTotBH 861109
CntTotBG 2036
YgateMax dE1 2.270
YgateMin dE1 1.580
XgateMax Etotal 4.040
XgateMin Etotal 2.470
YgateType dE1 coincidence
XgateType Etotal coincidence
Majority 2
B YgateMax dE1 0.000
B YgateMin dE1 0.000
B XgateMax Etotal 0.000
B XgateMin Etotal 0.000
B YgateType dE1 none
B Majority 0
CntTotI1 0 Cnts
CntTotI2 0 Cnts
CntLiveP 100.000 %
CntLive 100.000 %
floppy

“In situ” production

- In extraterrestrial samples:
  - Meteorites (exposure, terrestrial age)
  - Lunar samples (exposure)
- In terrestrial samples:
  - rock exposures (erosion, burial, exposure time)
  - Ice (accumulation, exposure time)

Production of a cosmogenic nuclide from cosmic ray interactions

$$P_j(R,d,M) = \sum_{i=1}^{N} c_i \frac{N_A}{A_i} \sum_{k=1}^{3} \int_0^{\infty} \sigma_{j,i,k}(E) \times J_k(E,R,d,M)\,dE$$

Production of any cosmogenic nuclide as a function of:
N_A = number of atoms of the target
σ (E) = excitation function
E = energy
R – radius of the object
d = depth in the object
M = mass of the object

Cosmogenic *in situ* production of ^{14}C and other radionuclides on the Earth

Some basic papers on this subject (www.sciencedirect.com):

Lal, D. 2007. Cosmic-ray interactions with minerals. Encyclopedia of Quaternary Science, pp. 419-436 (lot of math..)

Ivy-Ochs, S. and Kober, F. 2007. Exposure geochronology. Encyclopedia of Quaternary Science, pp. 436-445.

Granger, D.E. 2007. Landscape Evolution. Encyclopedia of Quaternary Science, pp. 445-452.

Very detailed:

Gosse and Phillips 2001. Quaternary Science Reviews 20: 1475-1560.

Background reading (now more or less supplanted by online calculators):

Stone, J.O. 2001. Air pressure and cosmogenic nuclide production. Journal of Geophysical Research 105: 23753-23759.

Extraterrestrial Production of Cosmogenic radionuclides

- Most are produced by high-energy nuclear reactions (spallation) in meteorites and planetary surfaces.
- Some nuclides produced by thermal and epithermal neutron reactions, e.g. ^{36}Cl, ^{41}Ca (^{14}C on the earth).
- Production from galactic cosmic rays (GCR), solar cosmic rays (SCR)
- May be some implantation by solar-energetic particles (SEP) and solar wind.

Russian bolide

- You Tube video
- With sound

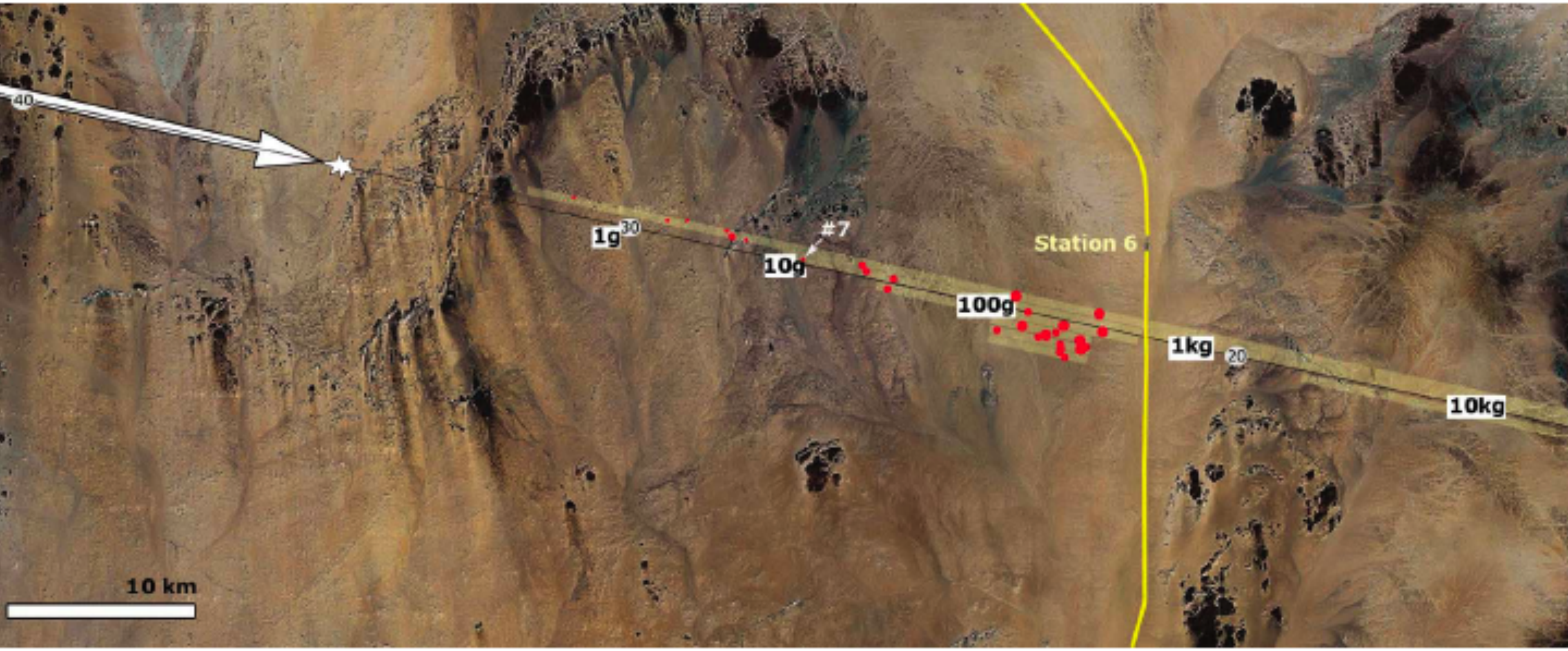
Shuttle photograph of Manicouagan Crater, Canada
Diameter = 60 miles, age = 210 million years old

Barringer (Meteor) Crater, Arizona – ~1km in diameter.
Age determined by cosmogenic nuclides ~50,000 years old

Debris impact on house 0.75km

Carancas, Peru – hypervelocity impact – September 15, 2007, 11:45 a.m. – 1-4 km/s – 1 kiloton blast – crater 23m in diameter – photos courtesy of Michael Farmer.

An observed fall



Almahata Sitta (Station 6), Sudan.

Picture courtesy Lucy McFadden


A collection team looking for meteorites in the Sudan


Types of Meteorites

Meteorites are classified by physical, chemical, isotopic, and mineralogical properties that are consistent with a common origin.

Stony Meteorites

Stony-Iron Meteorites

Iron Meteorites

Stony Meteorites

Carbonaceous chondrite

Chondrites – primitive meteorites that have undergone little change since their parent bodies originally formed and are characterized by the presence of chondrules. About 86% of meteorites that fall to Earth are of this type.

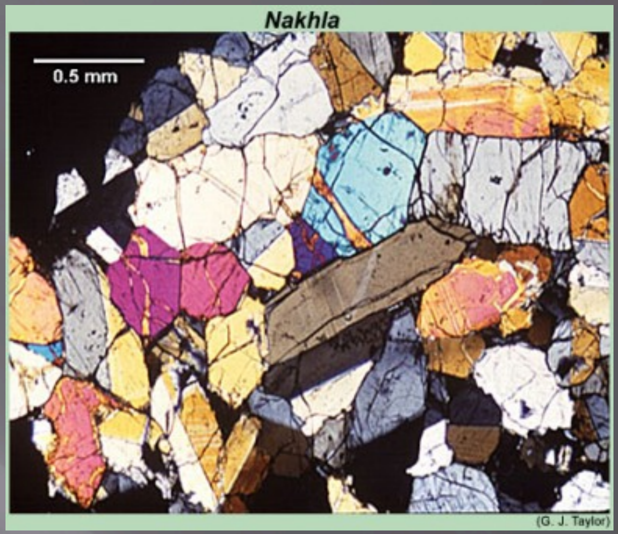
Achondrites - meteorites that have a complex origin involving asteroidal or planetary differentiation, including basalts. About 8% are of this type.

Chondrules

Chondrules are submillimeter-sized, rounded objects composed mainly of ferromagnesian silicates with accessory FeNi metal and minor sulfides. It is generally believed that chondrules formed in dusty regions of the solar nebula during localized, brief, repetitive heating events with peak temperatures of ~1800 to 2100 K (Krot et al., 2001).

Chondrules provide clues to the initial development of our planetary system.

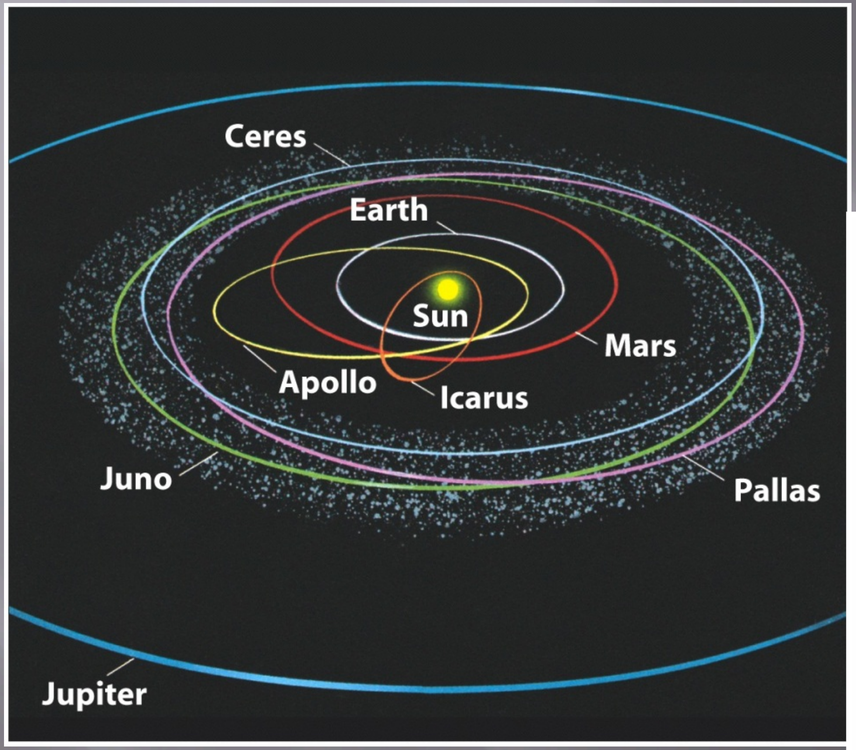
Achondrites



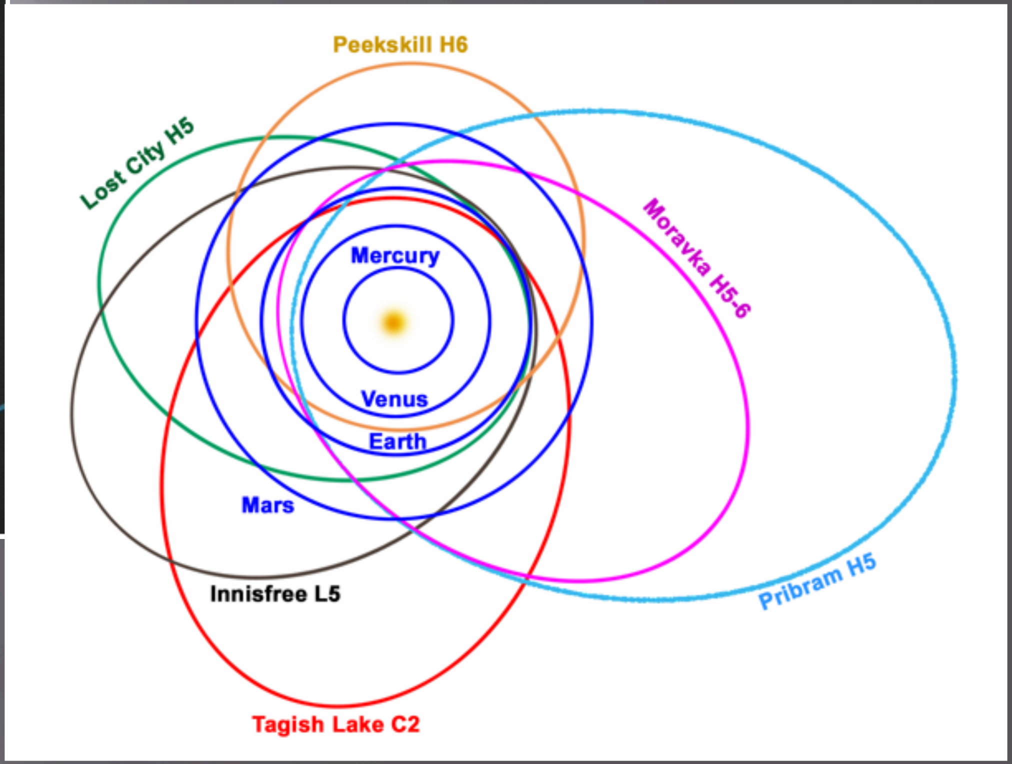
Achnondrites - meteorites that have a complex origin involving asteroidal or planetary differentiation – on a large object.

1) primitive achondrites
2) HED meteorites
3) lunar meteorites
4) Martian meteorites (SNC)
5) Angrite group
6) Aubrite group

Most meteorites are derived from parent bodies in the asteroid belt.



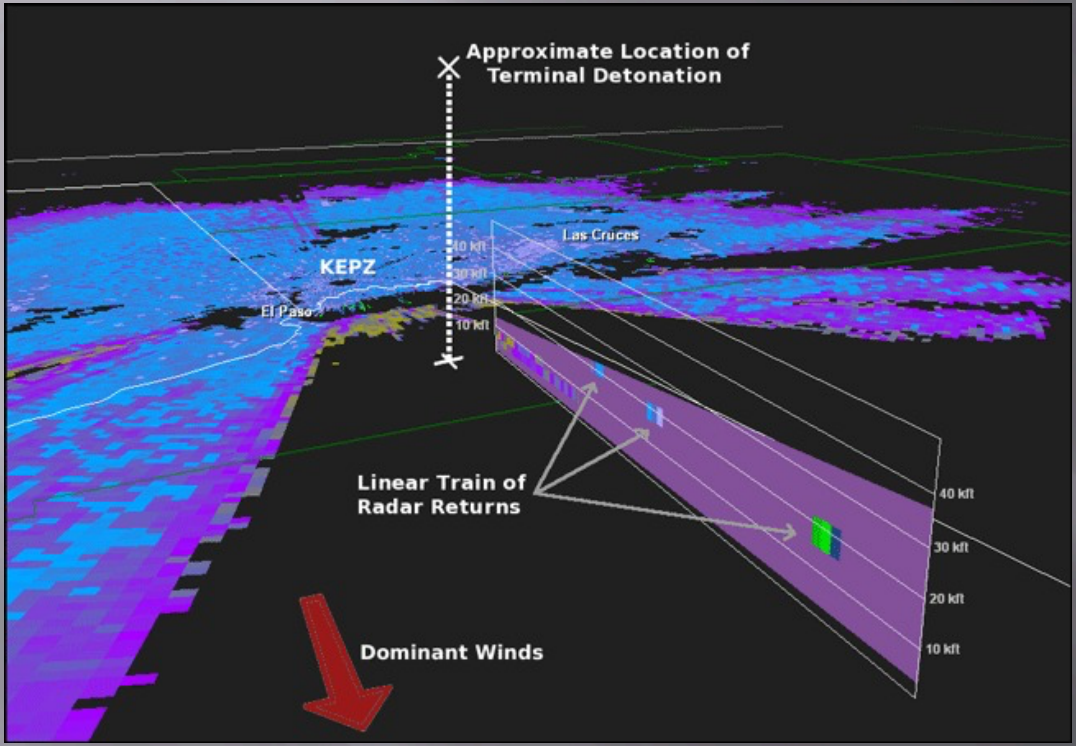
Orbits are only known for a few objects



An increasing number of meteorite falls have known orbits based on fireball observations

Pribram (Ceplecha, 1960)	1959-04-07	8pm	H5
Lost City (McCrosky et al., 1971)	1970-01-04	8pm	H5
Innisfree (Halliday et al., 1978)	1977-02-06	7pm	LL5-6
Peekskill (Brown et al., 1994)	1992-10-09	7pm	H6
Tagish Lake (Brown et al., 2000)	2000-01-18	8am	CI
Moravka (Borovicka et al., 2003)	2000-05-06	1pm	H5-6
Neuschwanstein (Spurny et al., 2002, 2004)	2002-04-06	10:20pm	EL6
Almahata Sitta (Jenniskens et al 2010)	2008-10-08	5:46am	Urei

Detection with Weather Radar



Small debris falling from the El Paso "superbolide" of October 09, 1997.

A perspective view of a cross section through composite radar data showing three radar returns from fine debris originating from the high-altitude superbolide detonation. This illustrates "type C" radar detection of dust-sized material. The three returns occur approximately 38 min after the detonation and constitute three points in three different radar sweeps where the radar beam intersects a linear chain of fine, slowly settling debris that have been transported toward the east by prevailing winds. The KEPZ NEXRAD radar is located at the center of the fan-shaped radar "noise."

Fries and Fries 2010.
Meteoritics and Planetary Science 45: 1476-1487

Table 1. Radionuclides of interest for terrestrial-age studies[1]

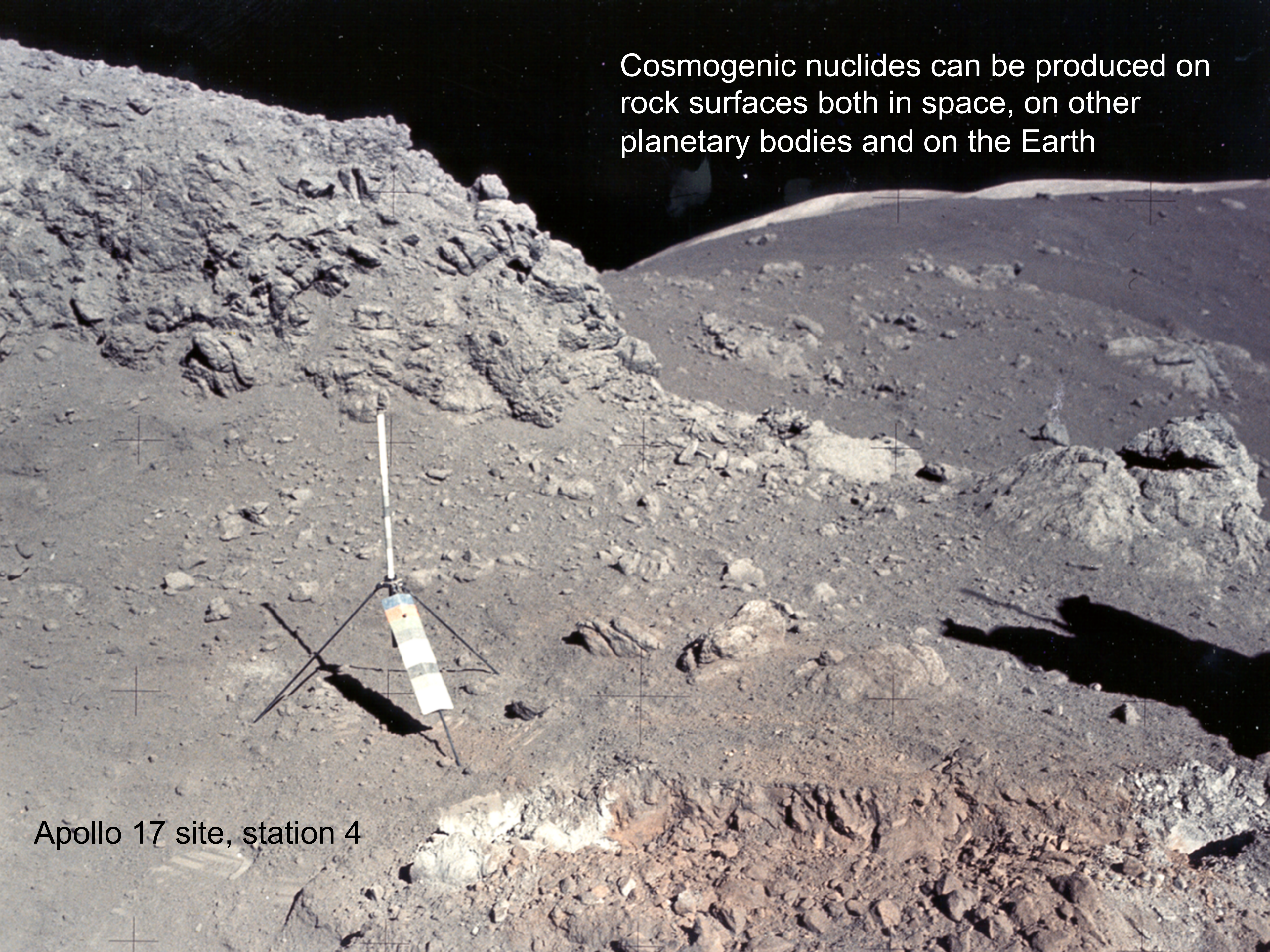
	Half-life	Phase	Saturated Activity (dpm/kg) L	H	References:
^{39}Ar	269 yr	metal	25	21	Begemann et al. (1969)
^{14}C	5.73k.y.	bulk	51	46	Jull et al. (1998b); Jull (2001)
^{41}Ca	100k.y.	metal	24		Herzog et al. (1997)
^{59}Ni	108k.y.[3]	metal	~350		Schnabel et al. (1999)
^{81}Kr	229k.y.	bulk	0.003-0.0045[2]		Freundel et al. (1986); Eugster (1988)
^{36}Cl	300k.y.	metal	22.8		Nishiizumi et al., (1989a); Herzog et al. (1997)
^{26}Al	700k.y.	bulk	60	56	Evans et al., (1982); Vogt et al. (1990)
^{60}Fe	1.49m.y.				Knie et al. (1999); Goel & Honda, (1965)
^{10}Be	1.37m.y.	bulk	22	20	Nishiizumi et al, (1989a, 1995)
^{53}Mn	3.7m.y.	metal	434		Nishiizumi et al., (1977, 1989a)

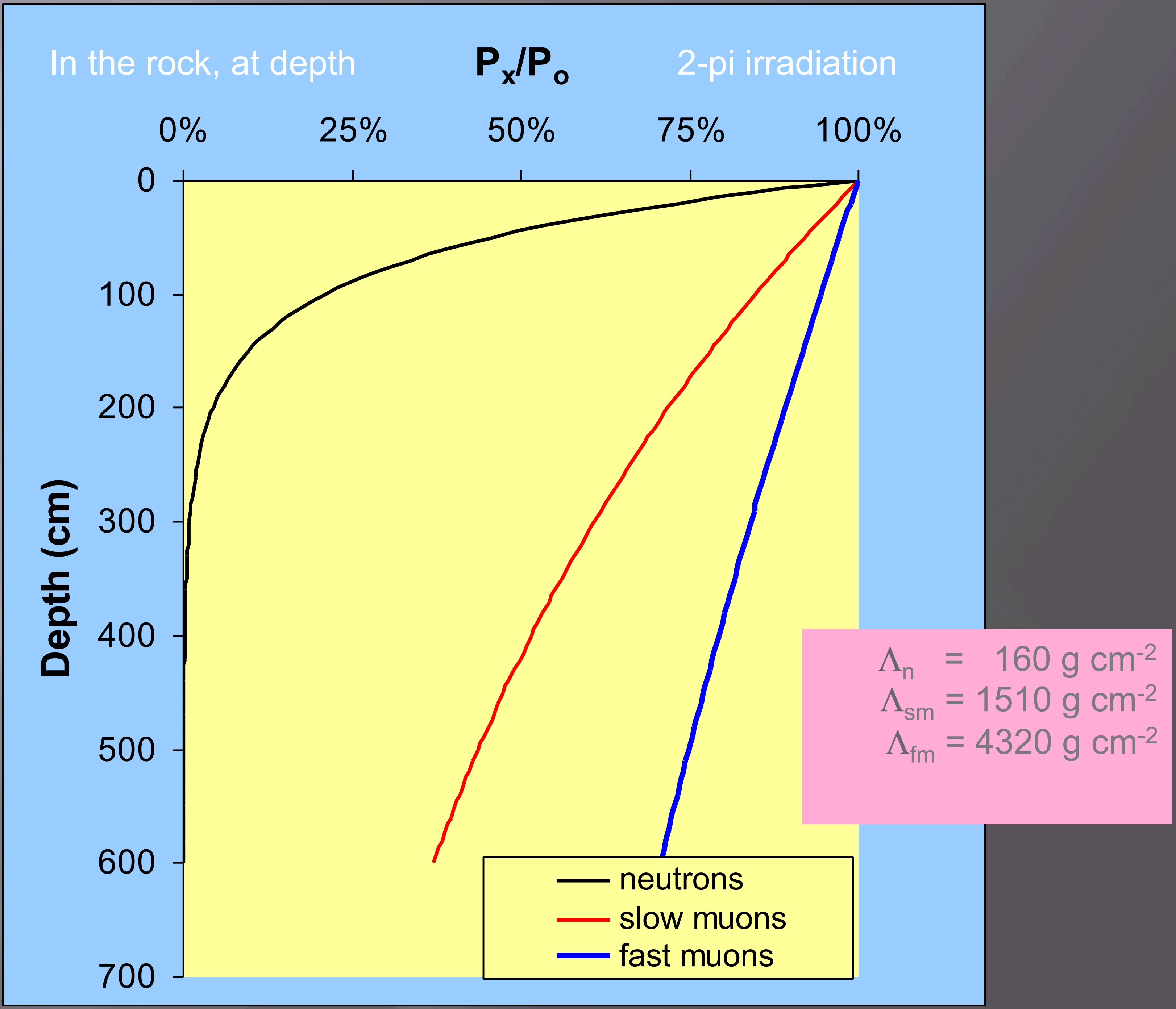
[1] adapted from Jull (2001)
[2] based on the average production rates for ^{81}Kr of 6-9 X 10^{-14} cm^3/g/m.y.(Eugster, 1988), depends on composition.
[3] *Ruhm et al. (1994)*_

For historical reasons, units given in dpm/kg. 1dpm = 60 Bq
50 dpm/kg = 0.3 Bq/g

We are mainly interested in the effects of high-energy galactic cosmic rays (>1 GeV).

For planetary bodies, like the Moon, solar effects Can also be important


Cosmogenic nuclides can be produced on rock surfaces both in space, on other planetary bodies and on the Earth
Apollo 17 site, station 4



In the rock, at depth
P_x/P_o
2-pi irradiation
0%
25%
50%
75%
100%
0
100
200
300
400
500
600
700
Depth (cm)
neutrons
slow muons
fast muons
Λ_n = 160 g cm^{-2}
Λ_{sm} = 1510 g cm^{-2}
Λ_{fm} = 4320 g cm^{-2}

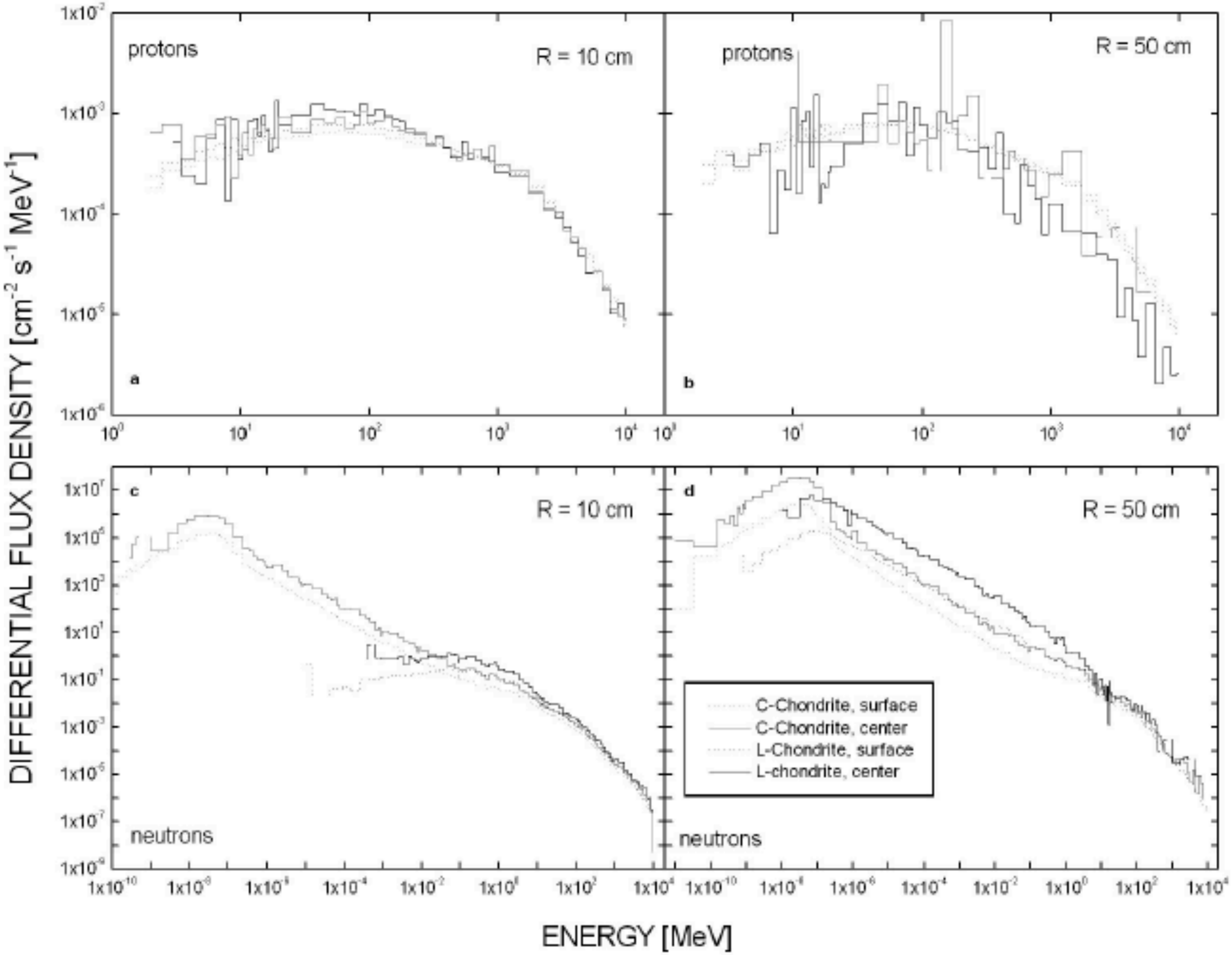


Fig. 2. Spectra of protons (primary + secondary) and secondary neutrons at the surface (dotted lines) and the center (solid lines) of 10 cm and 50 cm L and C chondrites. All data are normalized to an incident flux of primary galactic particles of 1 $cm^{-2}s^{-1}$.

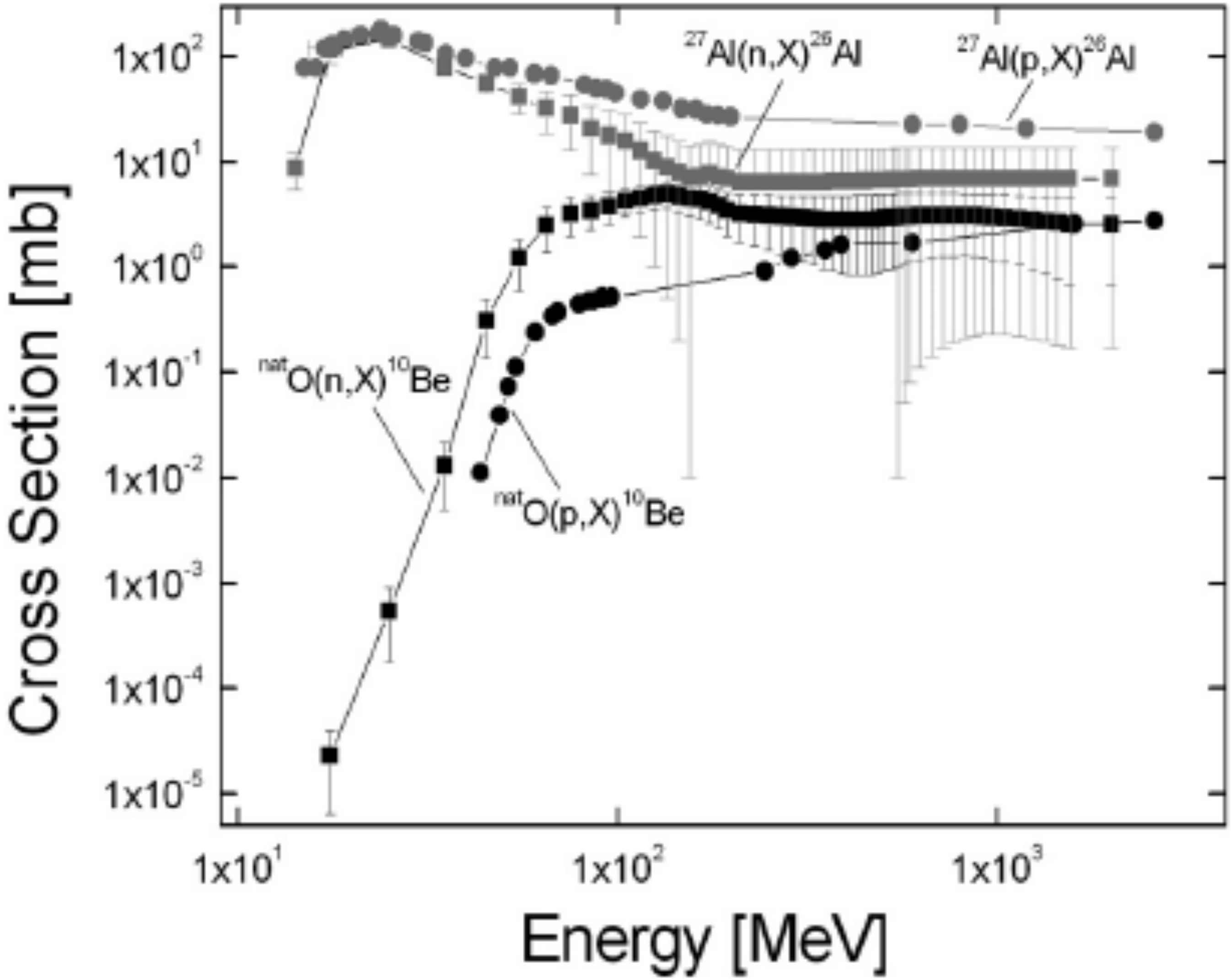


Fig. 1. Proton and neutron cross sections for the production of ^{10}Be from O and ^{26}Al from Al. The data demonstrate that the often used assumption of equal cross sections for proton and neutron induced reactions is generally not valid.

Leya & Masarik 2009, Meteoritics & Planetary Science 44:1061-1086

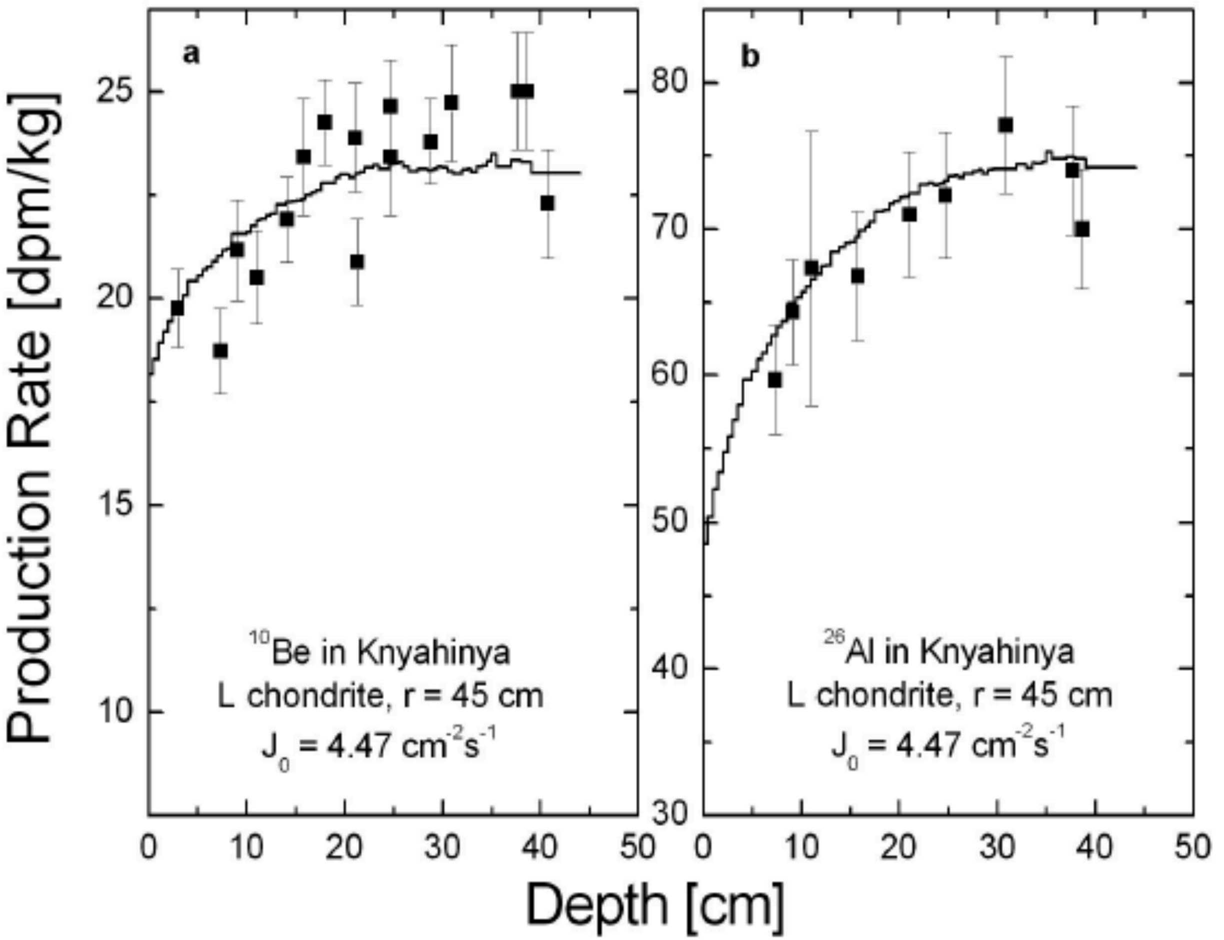
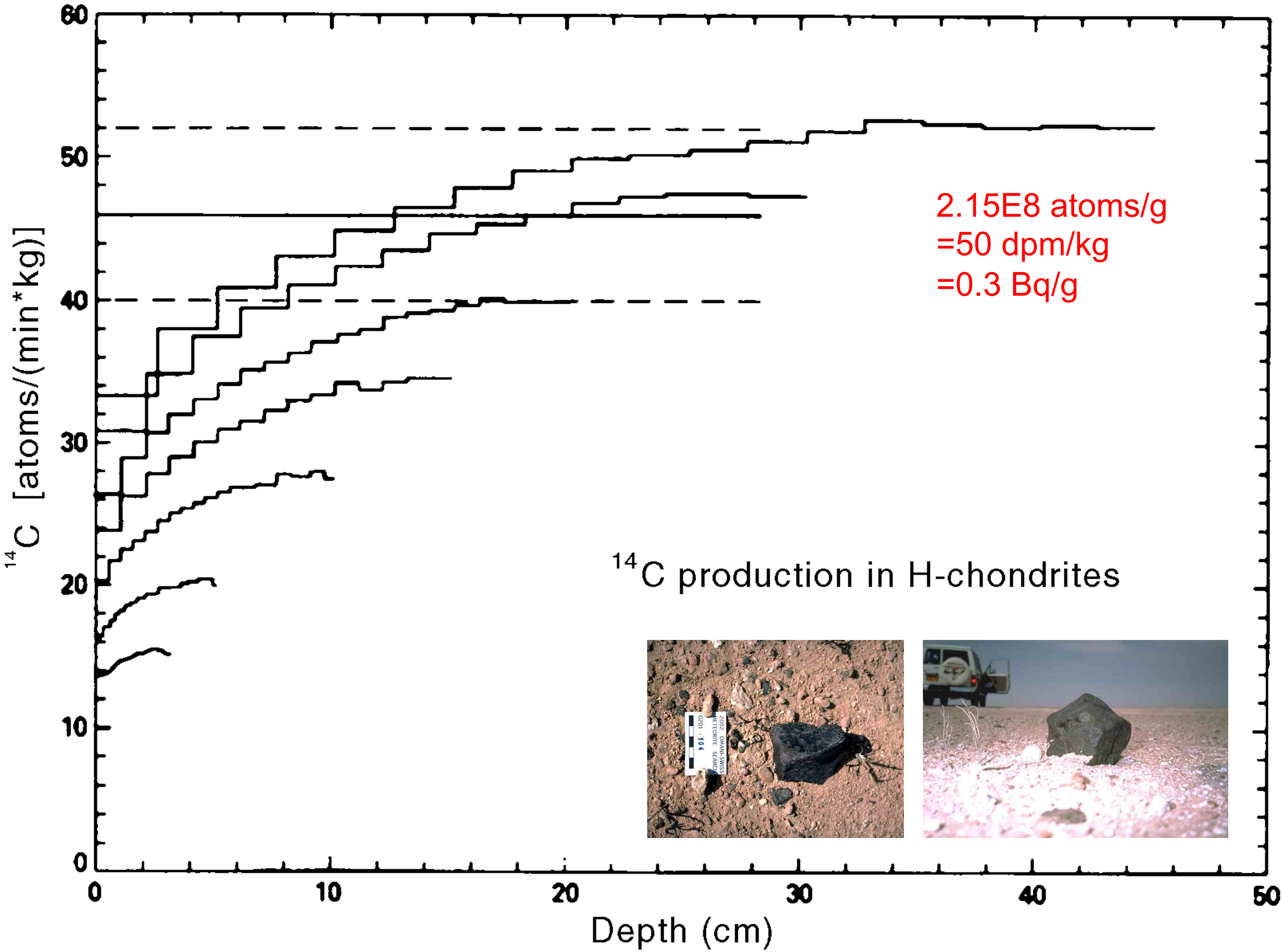
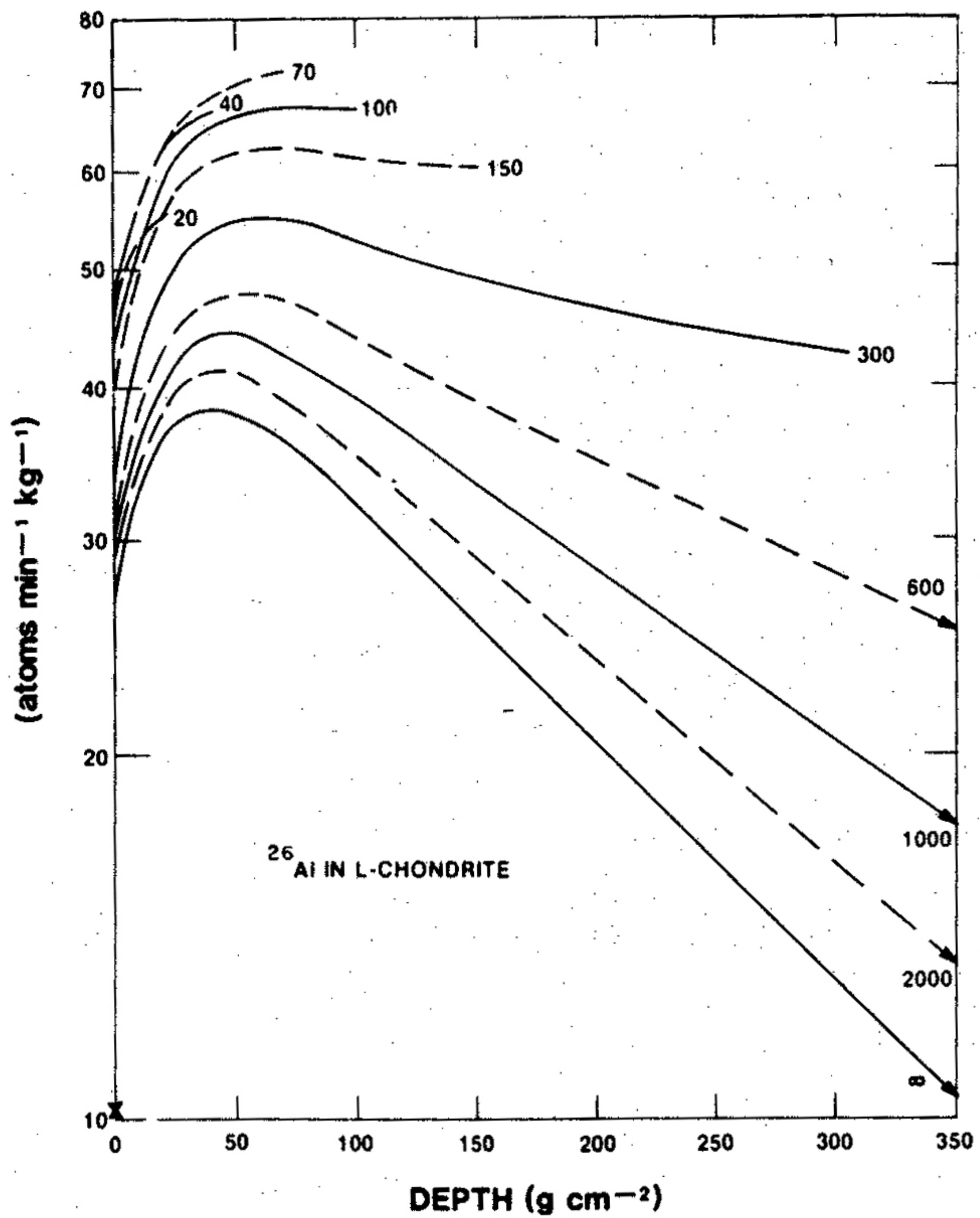


Fig. 3. Depth profiles of ^{10}Be and ^{26}Al in Knyahinya. The experimental data (Graf et al. 1990b; Vogt 1988) are used to determine the integral number of GCR particles by fitting the modeled depth profiles to the measured data.



2.15E8 atoms/g
=50 dpm/kg
=0.3 Bq/g
14C production in H-chondrites
14C [atoms/(min*kg)]
Depth (cm)
0
10
20
30
40
50
60



From
Reedy et al (1995)

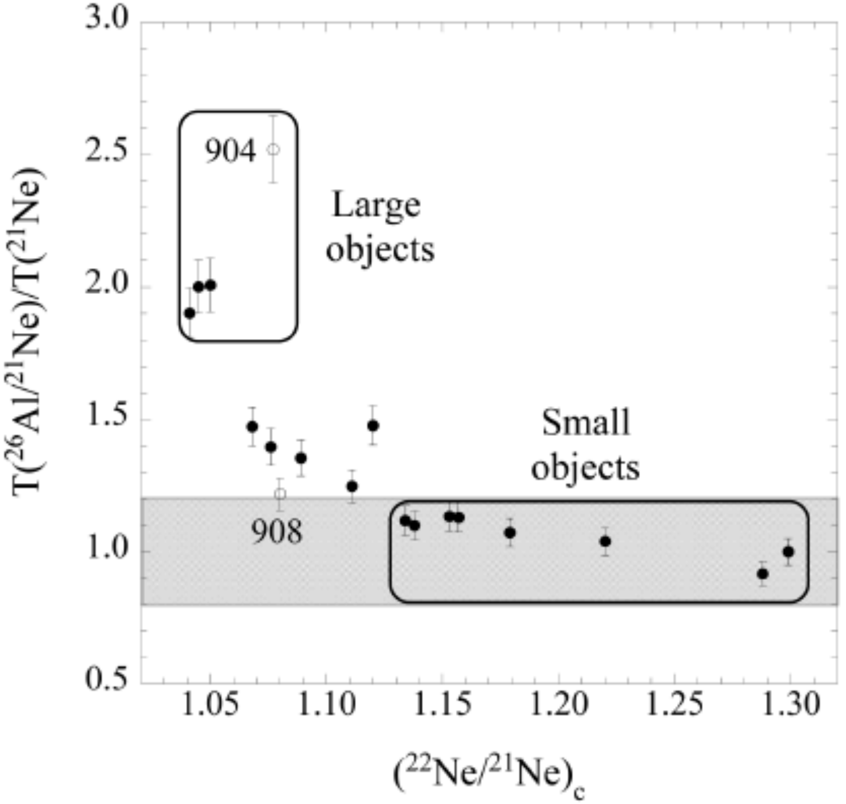


Fig. 10. Dependence of the T(^{26}Al/^{21}Ne)/T(^{21}Ne) exposure age ratio as a function of the ^{22}Ne/^{21}Ne ratio. For small objects (with ^{22}Ne/^{21}Ne ratios >1.13), the two ages show good agreement, while for large objects (with ^{22}Ne/^{21}Ne ratios <1.09 and significant contributions of neutron-capture ^{36}Cl and ^{41}Ca), the ^{26}Al/^{21}Ne age is 1.8–2.6 times higher than the ^{21}Ne age. These results confirm that the relation between the ^{21}Ne production rate and the ^{22}Ne/^{21}Ne ratio is not unambiguous.

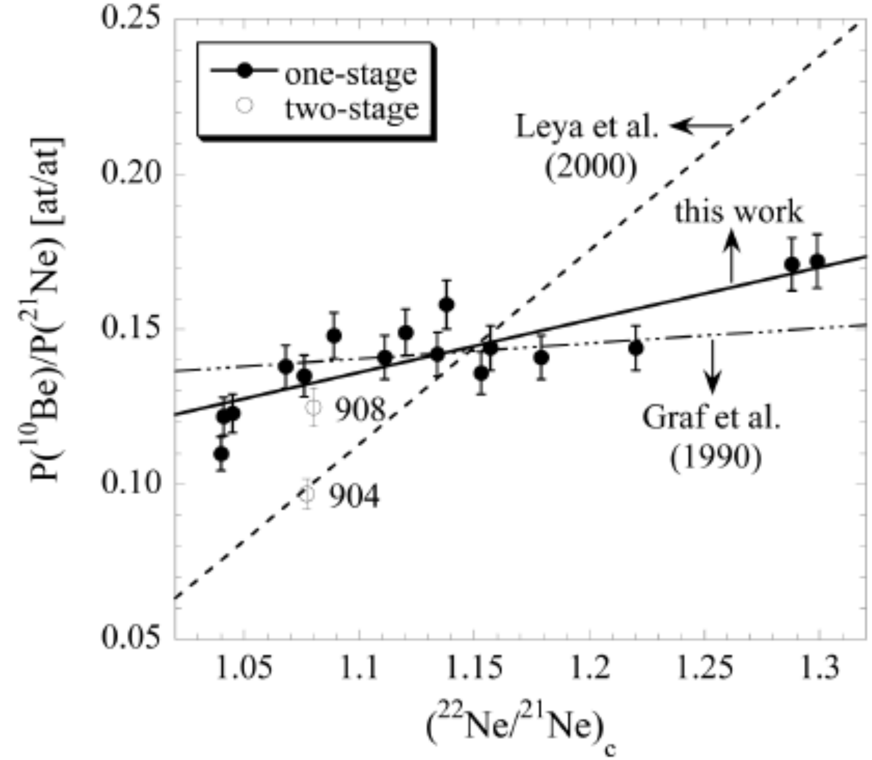
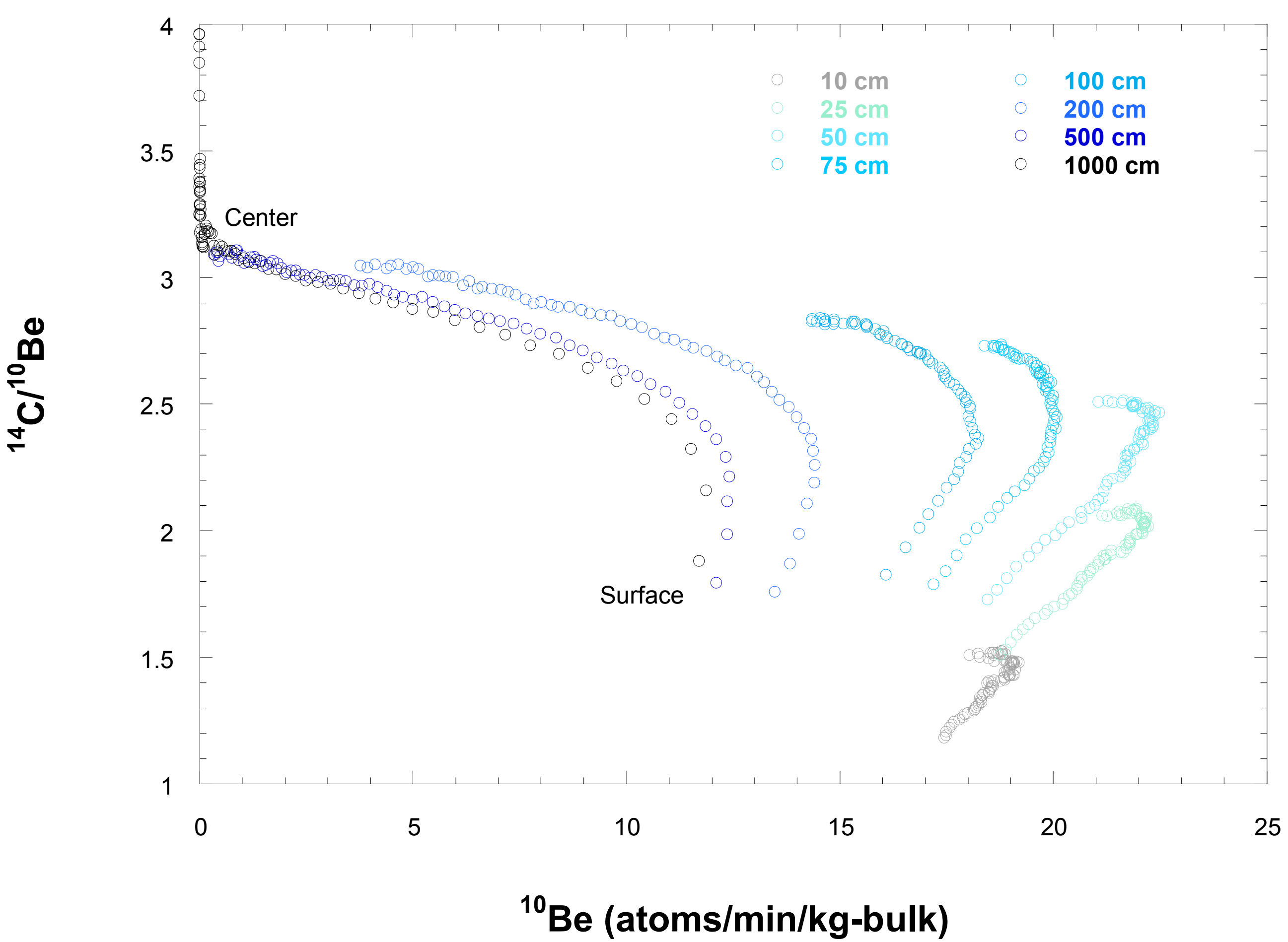


Fig. 11. The ^{10}Be/^{21}Ne production rate ratio as a function of the cosmogenic ^{22}Ne/^{21}Ne ratio. The production rate ratios are based on measured ^{10}Be, ^{26}Al, and ^{21}Ne concentrations in 18 DaG samples and T(^{10}Be/^{21}Ne) = T(^{26}Al/^{21}Ne) and P(^{26}Al)/P(^{21}Ne) is calculated using Equation 1. The solid line represents a linear fit through the solid symbols (this study), which represent samples with a simple exposure history. The dashed line represents the correlation derived by the physical model of Leya et al. (2000), the semi-dashed line the semi-empirical correlation of Graf et al. (1990).

Production dependence on size of the object

^{14}C and ^{10}Be vs. depth (model calculation)



Calculation

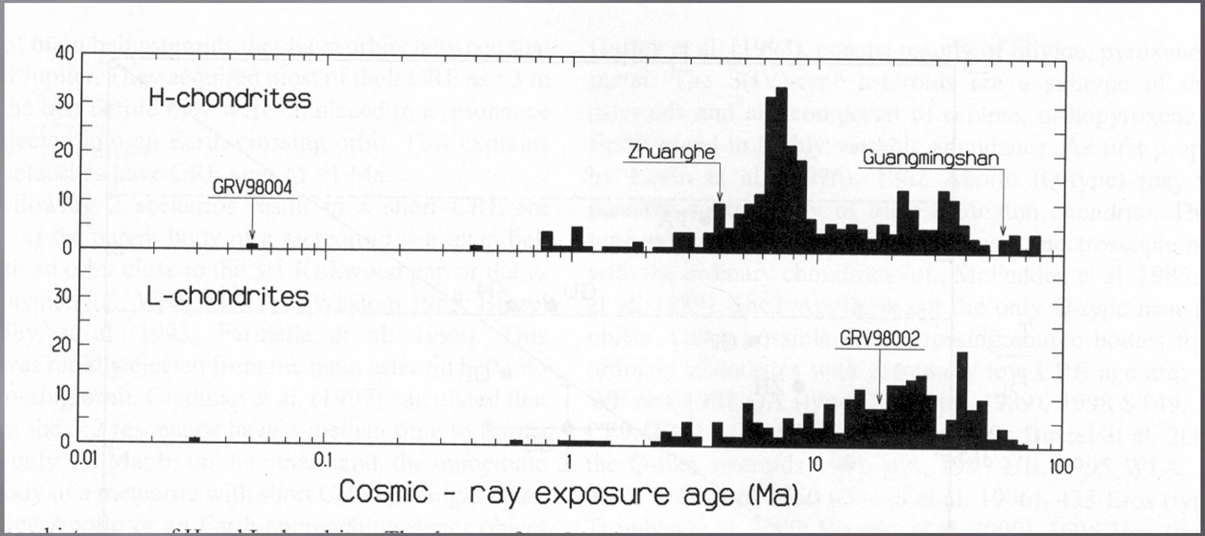
Terrestrial age based on ^{14}C only

$$T_{age} = -\frac{1}{\lambda_{14}} \ln\left(\frac{Am}{Asat}\right)$$

Terrestrial age based on ^{14}C and ^{10}Be

$$T_{age} = -\frac{1}{\lambda_{10} - \lambda_{14}} \ln\left(\frac{{}^{14}C_m / {}^{10}Be_m}{{}^{14}C_{sat} / {}^{10}Be_{sat}}\right)$$

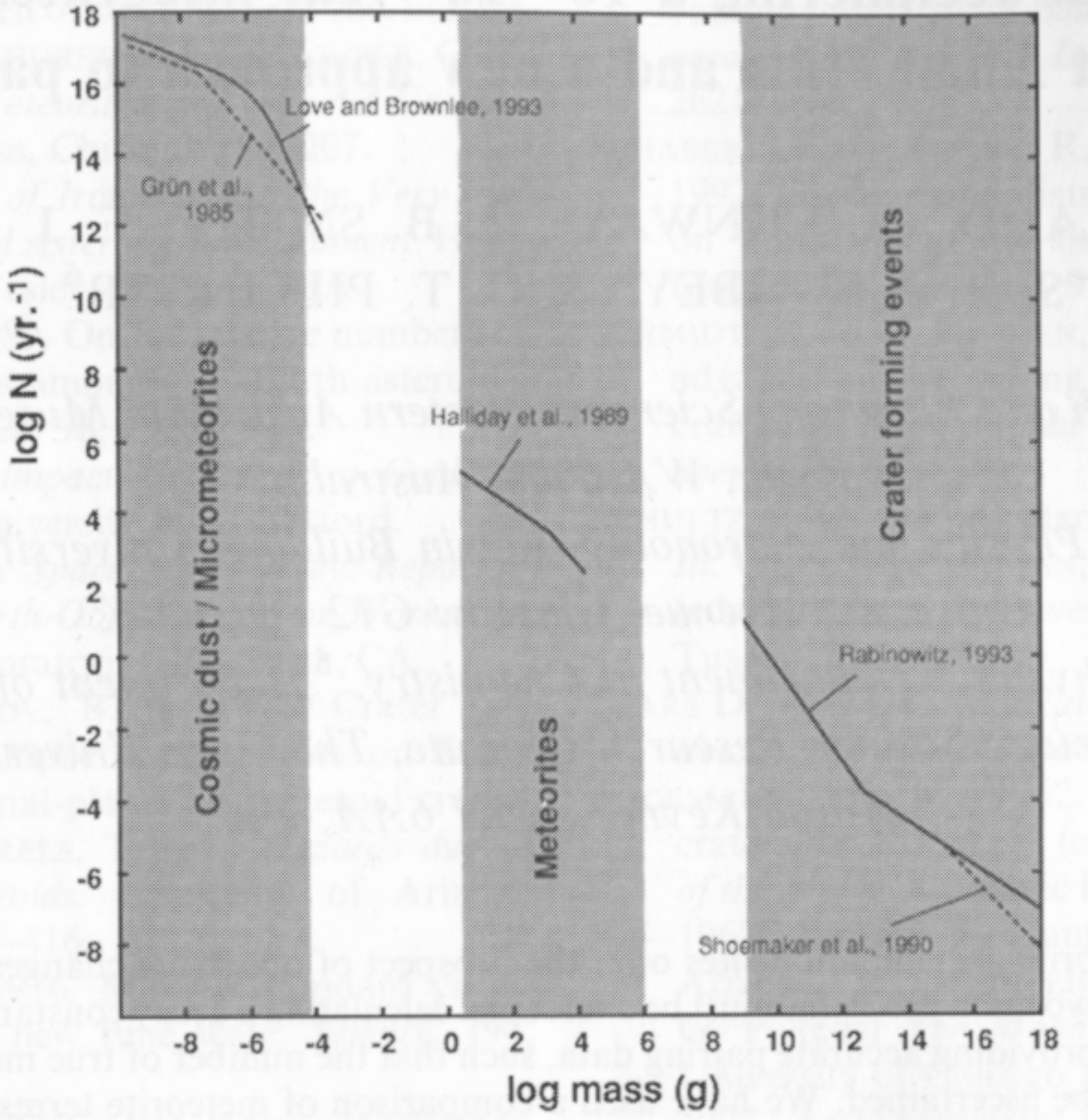
Build-up of stable nuclides can be used to determine exposure ages



From Lorenzetti et al. (2003), MAPS

Infall rate of meteoroids

Adapted from Bland (1998)



Infall rates

The observed infall rate (on the ground) can be described as a mass-dependent function (Halliday et al., 1989):

$$\log N(>M) = a \log M + b$$

	M<1030g	M>1030g
a	-0.49	-0.82
b	+2.41	+3.41

What does this mean?

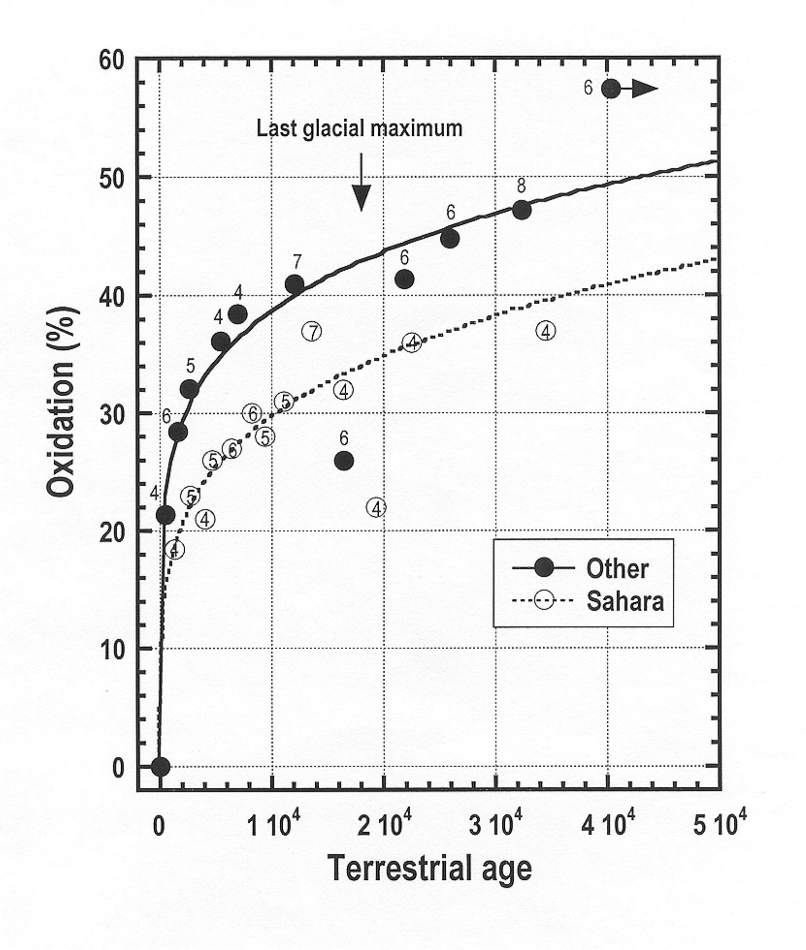
~1 (actually 0.83) event (M>10g) per km^2 per 10^4 yr.

~40,000 tons/yr over the entire Earth

(Halliday et al., 1989, 2000)

Weathering of meteorites:

Correlation between oxidation and Terrestrial age for Roosevelt County and Sahara desert meteorites



Bland et al 1996, 1998, 2000

Estimates based on meteorite weathering and recovery

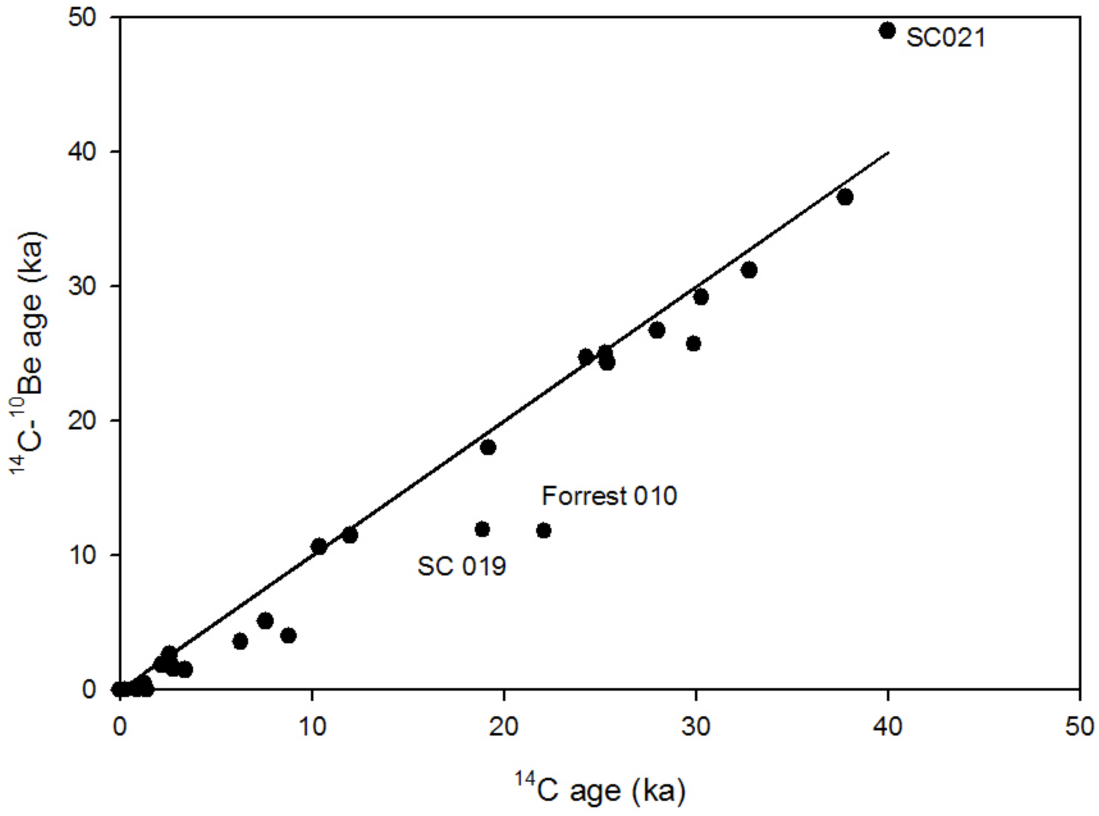
- Bland et al. (1996, 2000) estimated an infall rate of:

36-116 event (M>10g) per $10^6 km^2$ per yr.

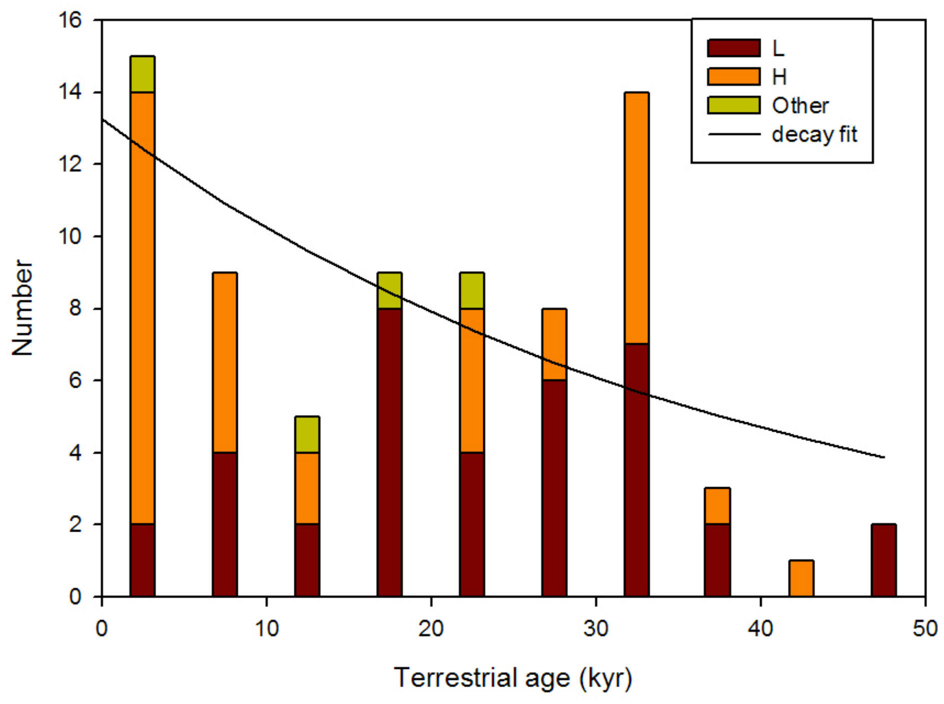
i.e. 0.36 to 1.16 events per $1 km^2$ per 10^4 yr.

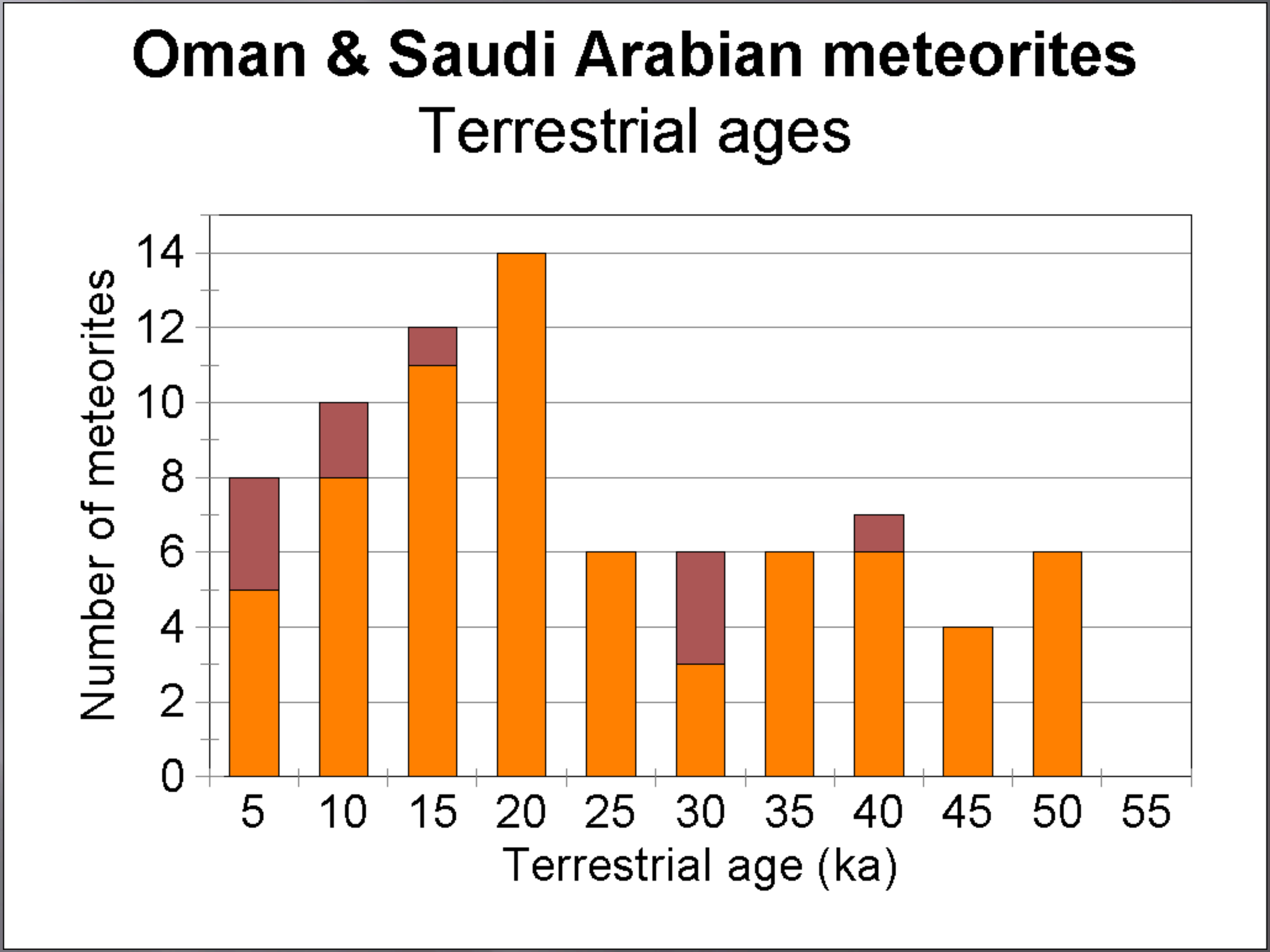
Based on meteorite weathering rates.

Terrestrial age measurement: An example from Western Australia



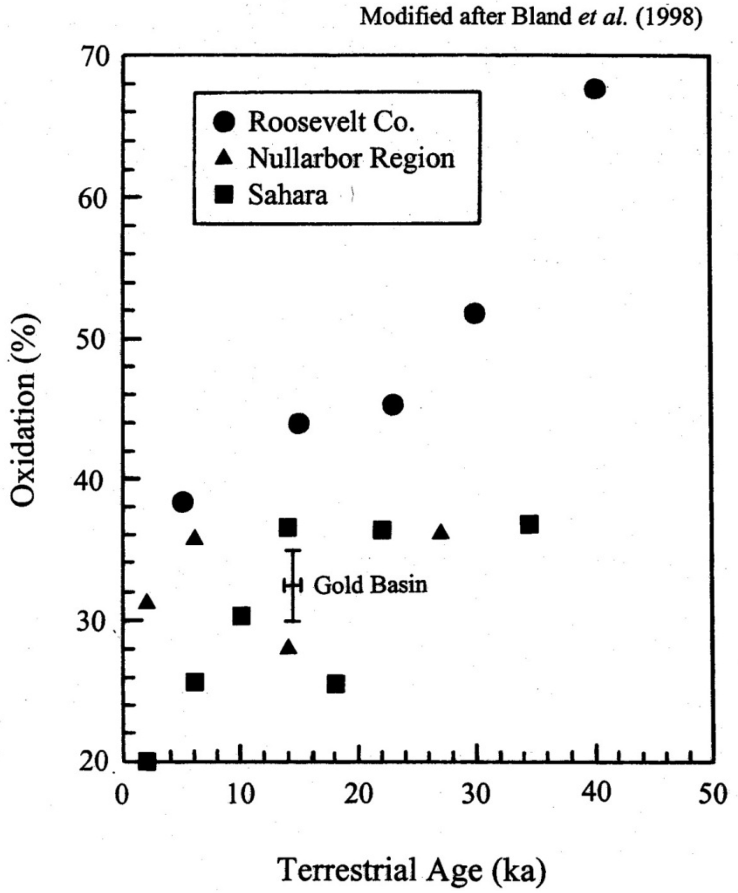
Terrestrial age distribution: by class



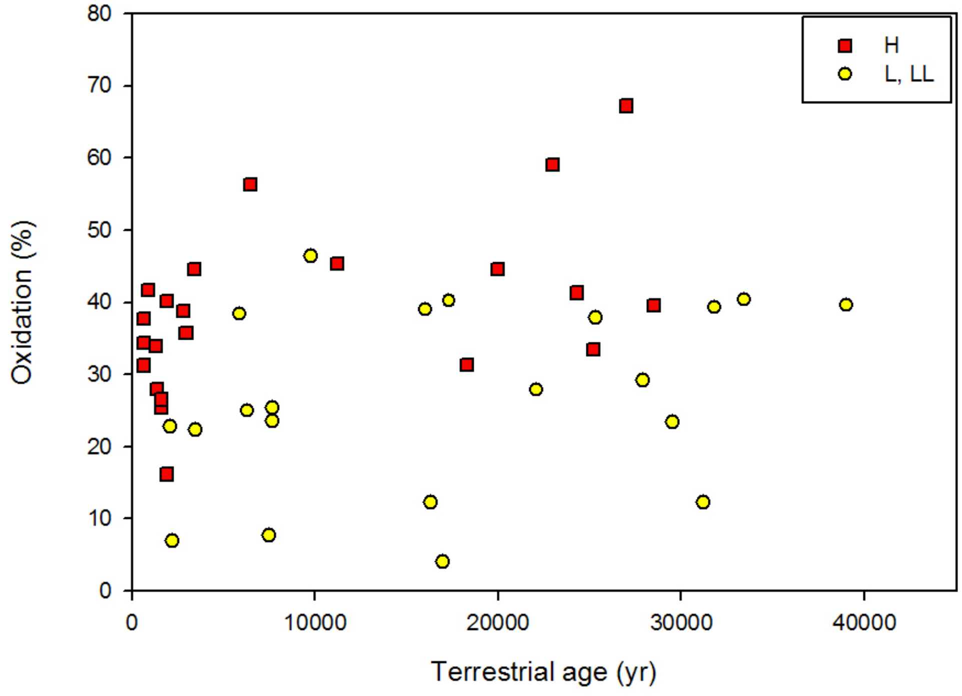


Oman & Saudi Arabian meteorites
Terrestrial ages
Number of meteorites
0
2
4
6
8
10
12
14
5
10
15
20
25
30
35
40
45
50
55
Terrestrial age (ka)

Oxidation vs. terrestrial age



Bland et al.



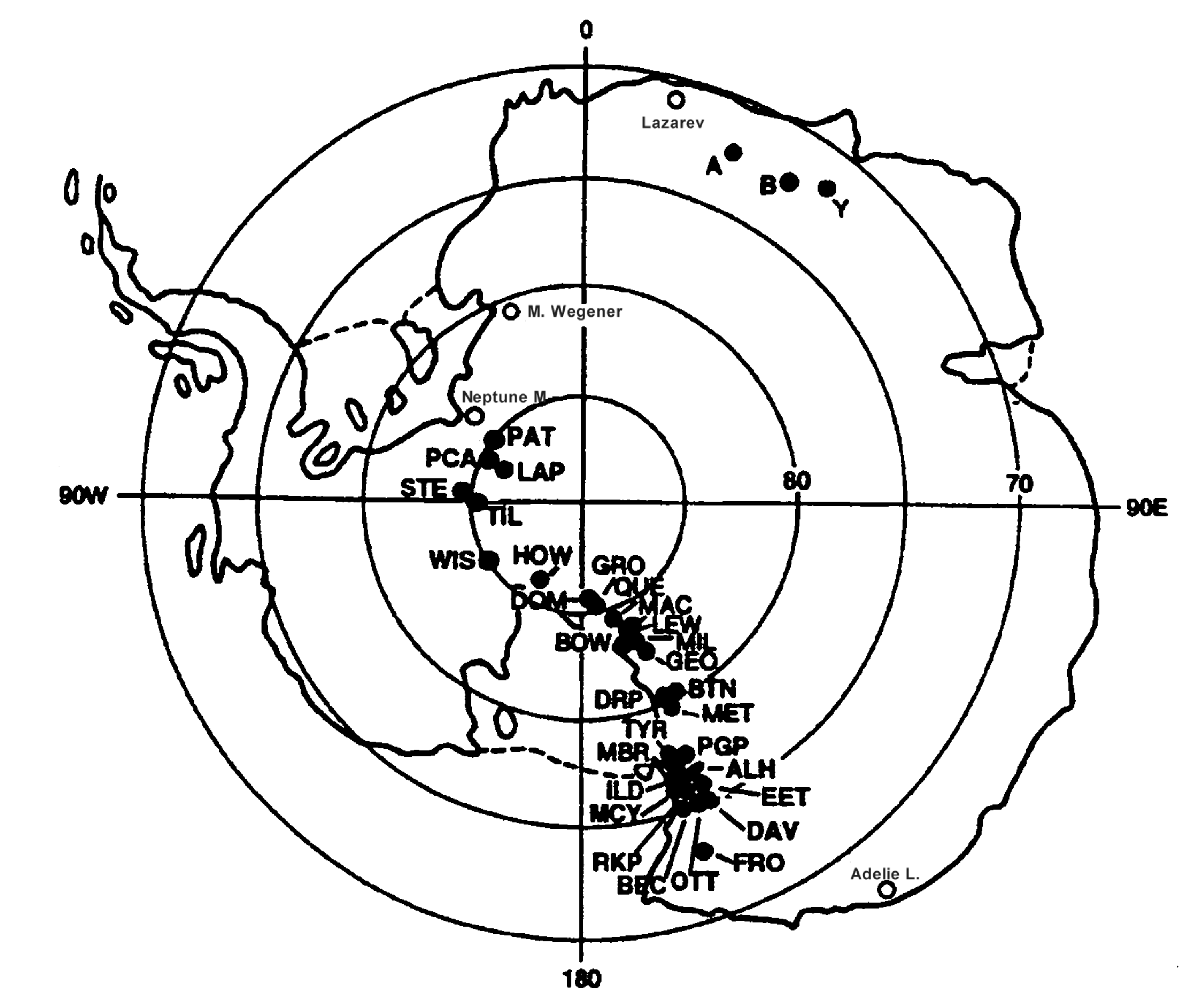
Jull et al. 2010 – WA only

Should we worry about weathering of desert meteorites?

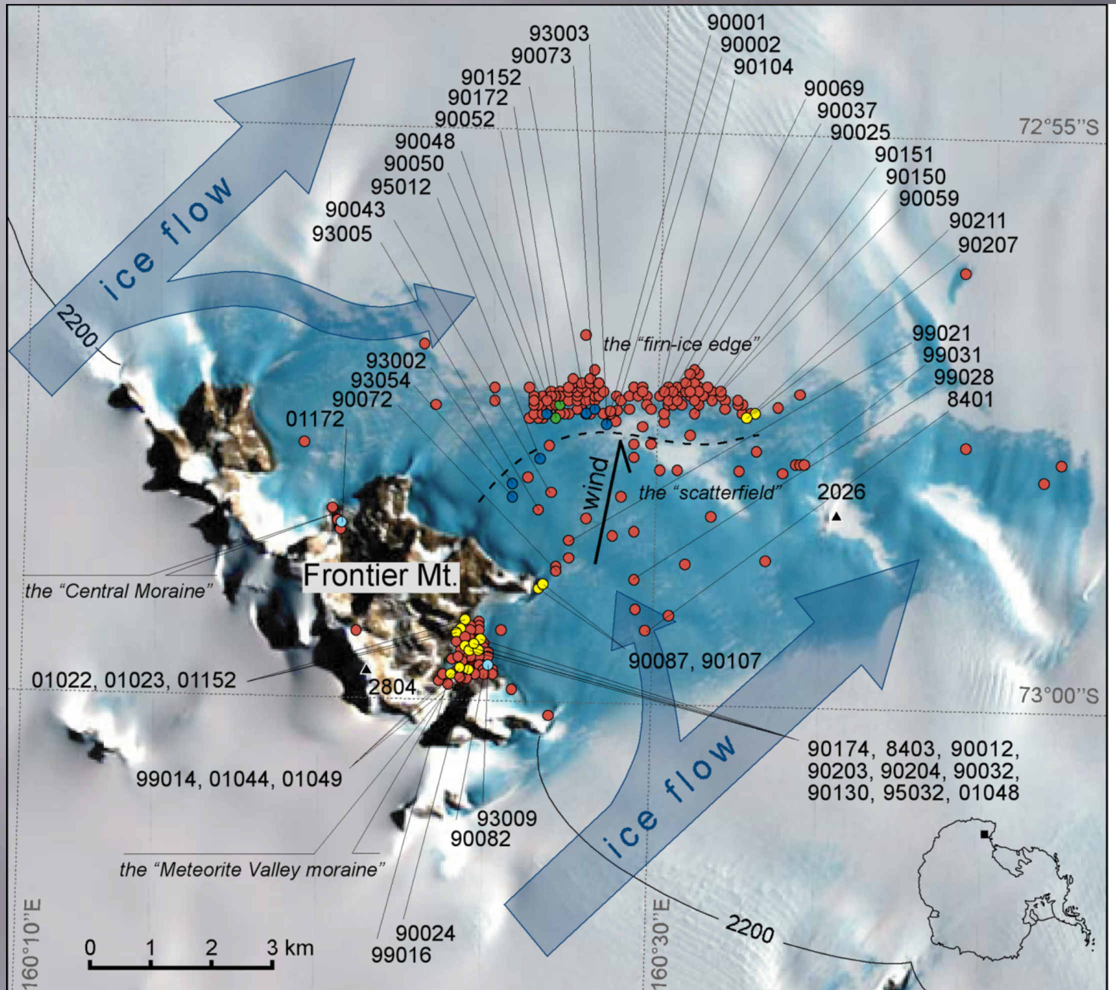
- Meteorites residing in desert environments undergo weathering
- Increasing evidence of weathering changing chemistry…
- Al-Kathiri et al. (2005) showed Sr added from soil to meteorites.
- Zurfluh et al. (2012) show further effects.

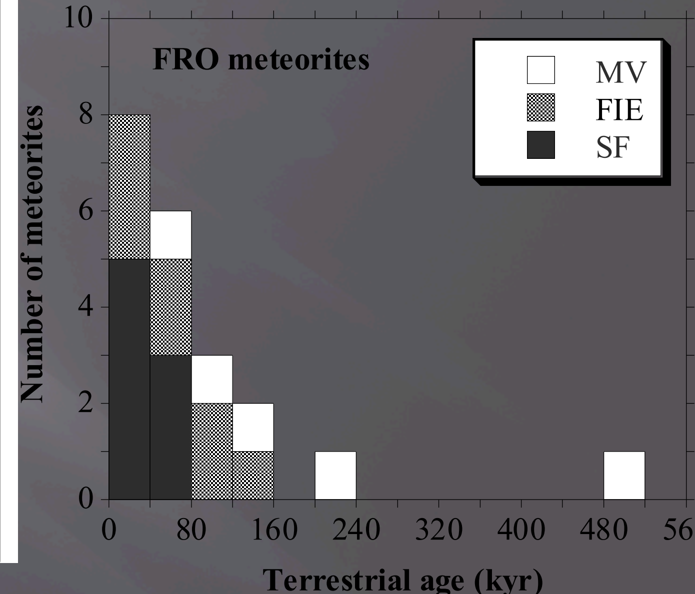
Hoba meteorite

Largest known find. Ni-rich ataxite.
One estimate ca. 80-110ka terr. Age (?)


0
Lazarev
A
B
Y
M. Wegener
Neptune M.
PAT
PCA
LAP
STE
TIL
90W
80
70
90E
WIS
HOW
GRO
QUE
DOM
MAC
LEW
BOW
MIL
GEO
BTN
DRP
MET
TYR
MBR
PGP
ALH
ILD
EET
MCY
DAV
RKP
FRO
BEC
OTT
Adelie L.
180

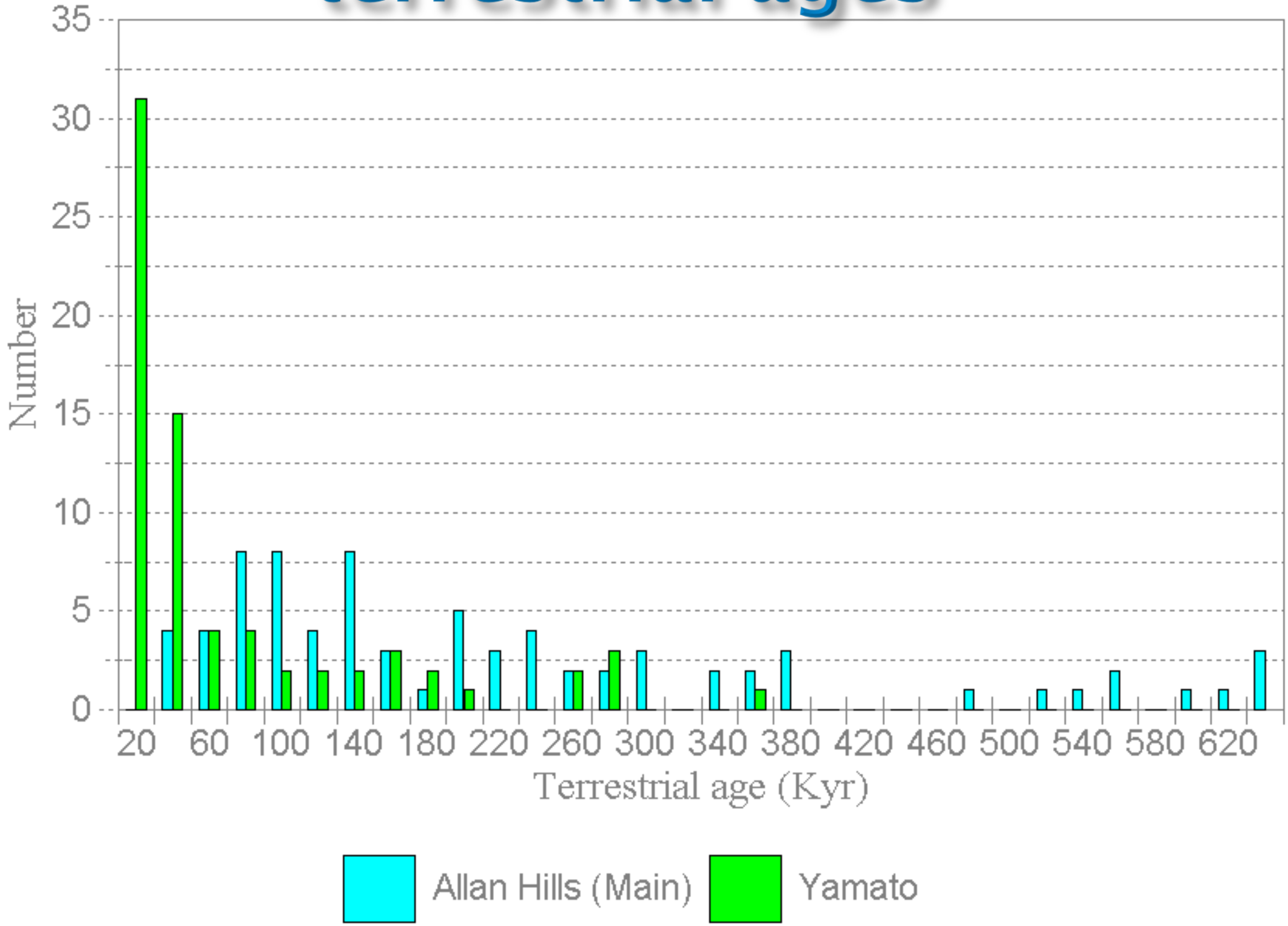
FRONTIER MTNS
Welten et al. 2006





- Schematic map of the Frontier Mountain blue ice field showing the geographic distribution of the FRO 90174 shower (yellow dots), the FRO 90001 pairing group (blue dots) and the 500-kyr FRO 93009/01172 pair (cyan dots) relative to other FRO meteorites (red dots) studied in this work. Meteorites studied by Welten et al. (1999, 2001) are labeled in black.
- MV=Meteorite Valley, FIE=Firn Ice Edge, S=Scatter Field

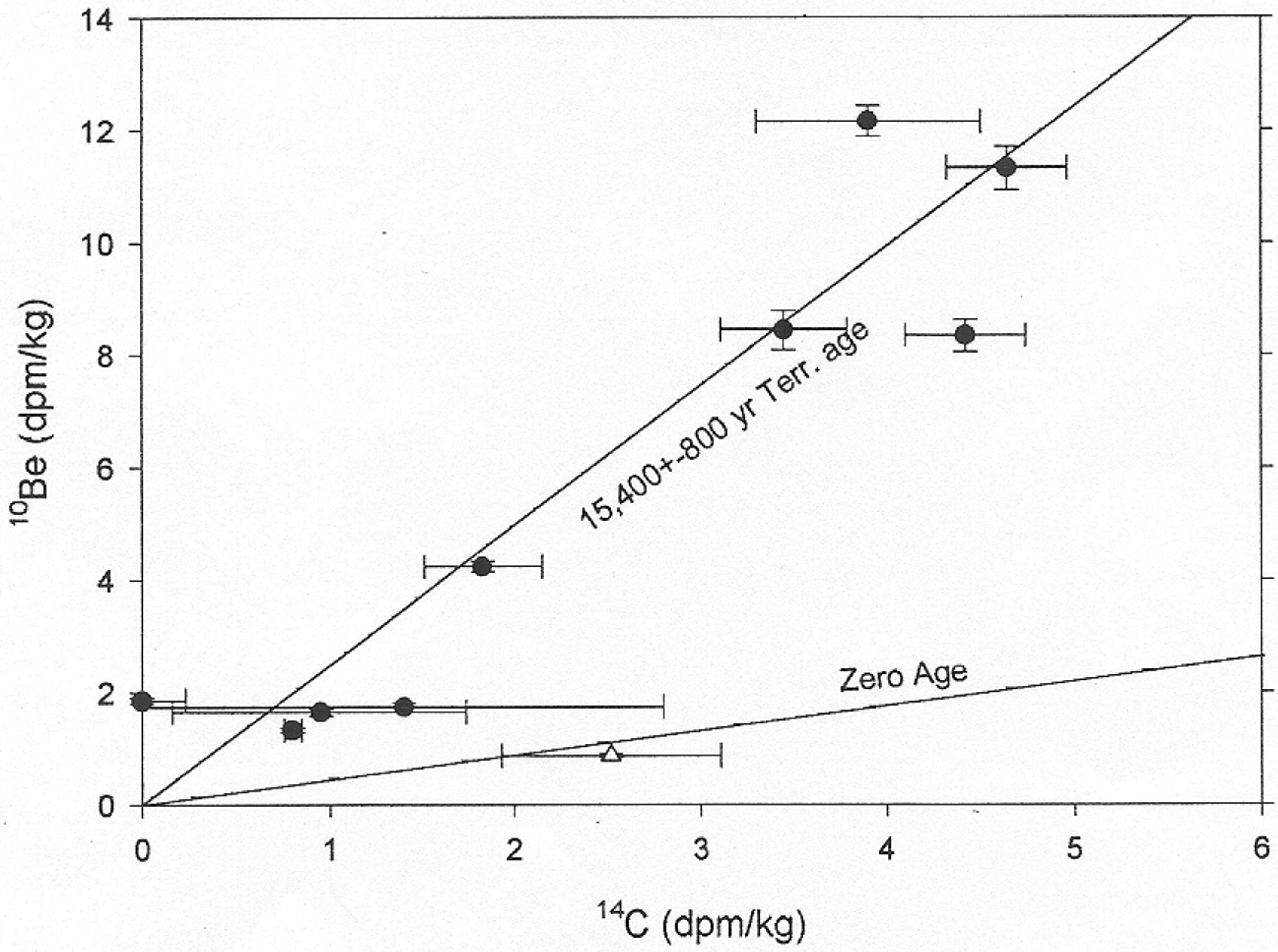
Antarctica: Much longer terrestrial ages



Newer methods

- ^{14}C-^{10}Be dating — Kring et al 2001
  Jull et al 1999, 2004, 2006
- ^{36}Cl-^{10}Be dating — Welten et al. 2002, 2004
- ^{36}Cl-^{41}Ca dating — Nishiizumi & Caffee, 1998
- ^{129}I exposure age dating …working on it

Gold Basin Meteorites



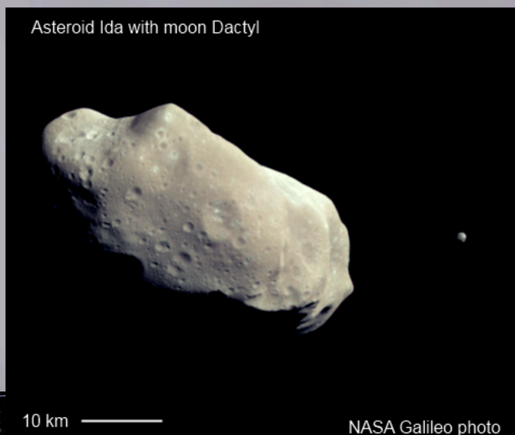
^{129}I Exposure ages

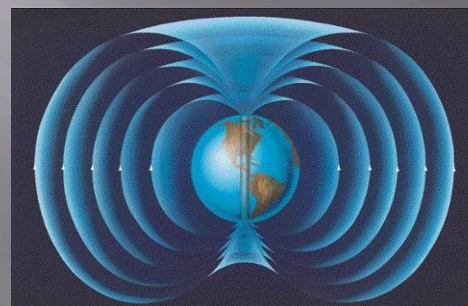
Sample ID	^{129}I *(10-4 dpm/kg)*	^{129}I Production *(10-4 dpm/kg)*	Exposure Age
Knyahinya [ref 6]			
Te 0.53ppm			
Ba 6.26ppm	2.72	3.30±0.25	39.4 Ma
QaM 001	4.2±0.4 X 10^5 at/g		
Te 0.5ppm			
Ba 6.0ppm	0.38±0.04	4.07	2.8Ma
Shisr 033	1.2±0.1 X 10^6 at/g		
Te			
Ba	1.0±0.1	3.3	8.4Ma

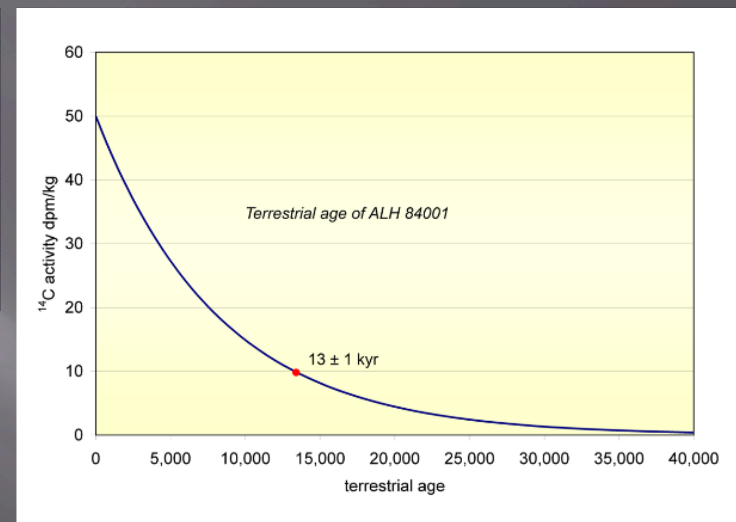
1) Dating the crater may tell us the terrestrial age of a meteorite

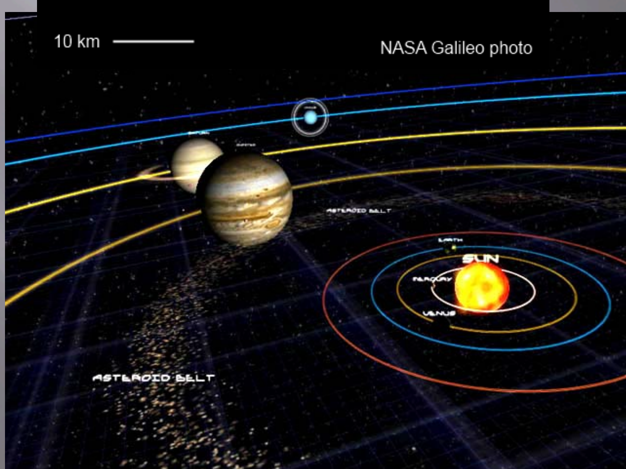
A terrestrial age is the length of time that a meteorite has spent on the surface of the earth. One way is to date the formation of a crater.

What if there is no crater? Terrestrial age of the meteorite Alan Hills (ALH 84001)



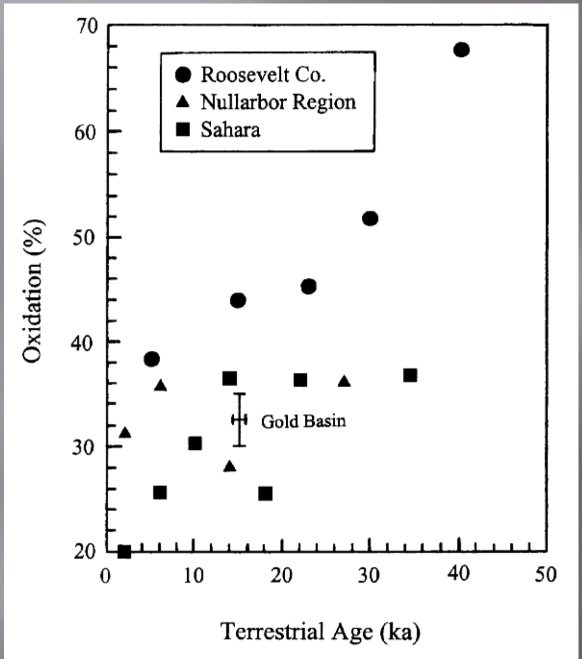






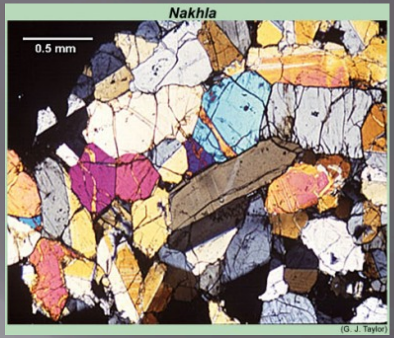
When a meteorite is in space a lot of ^{14}C is made in the rock by spallation on oxygen (50% of silicate minerals) because the cosmic ray intensity is relatively high (compared to the earth's surface). When the meteorite falls to Earth this ^{14}C begins to decay. By measuring the amount of ^{14}C in the rock we can determine its age.

2) Meteorites as paleoclimate indicators



2) using the terrestrial ages of meteorites and the degree to which they are oxidized you can say something about the climate at the fall site, since it fell to Earth.

3) What can AMS radiocarbon tell us about life on Mars?



Achnondrites - meteorites that have a complex origin involving asteroidal or planetary differentiation.

1) primitive achondrites
2) HED meteorites
3) lunar meteorites
4) Martian meteorites (SNC)
5) Angrite group
6) Aubrite group

3) Martian meteorites? How do you know that, and where can you find them?

Where can we find them?

Alan Hills 84001

How can you tell they are from Mars? This conclusion is based on noble gas and nitrogen isotopic ratios similar to those observed by the Viking Mars lander. *Where do you find them?* Antarctica.

Martian and Lunar meteorites

- Ejection depth, Ejection age
- Transition time
- Terrestrial age

⇒ Four or more cosmogenic nuclides

Nuclide	Half-life (yr)
^{10}Be	1.5×10^6
^{26}Al	7.05×10^5
^{36}Cl	3.01×10^5
^{41}Ca	1.04×10^5
^{14}C	5,730
Noble gases	

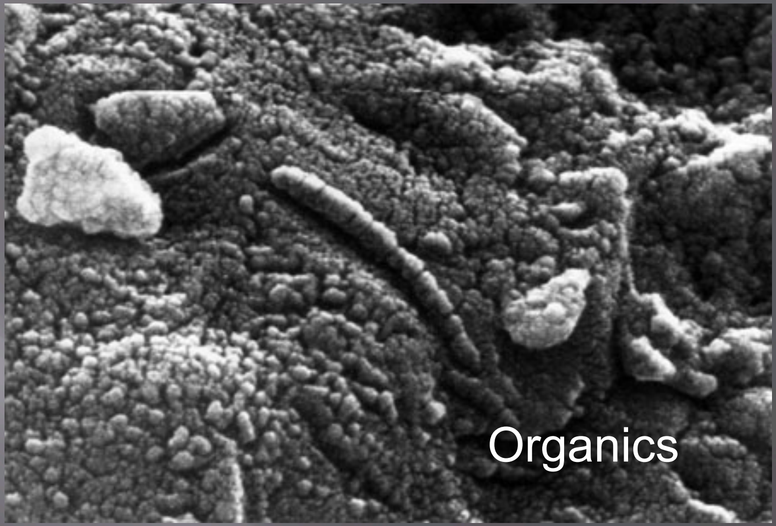
Ejection age and terrestrial age of Martian meteorites

Name	Ejection Age (Myr)	Terrestrial Age (kyr)
EET 79001	0.6 ± 0.1	12 ± 2
SaU 005/008/051	1.0 ± 0.2	11 ± 1
DaG 476/489/670/735	1.1 ± 0.1	60 ± 20
Shergotty	2.7 ± 0.4	0.134
Zagami	2.8 ± 0.4	0.037
QUE 94201	3.0 ± 0.5	250 ± 50
Los Angeles	3.0 ± 0.3	<20
ALH 77005	3.3 ± 0.6	210 ± 80
LEW 88516	3.6 ± 0.5	21 ± 2
Y-793605	5.4 ± 0.3	35 ± 35
Governador Valadares	9 ± 2	< 0.5
Nakhla	11 ± 2	0.088
Lafayette	11 ± 2	2.9 ± 1.0
Chassigny	12 ± 2	0.184
ALH 84001	16 ± 2	13 ± 2
Dhofar 019	20 ± 2	250-300

Life on Mars?

You can use ^{14}C as an isotopic tracer to investigate the origin of organic carbon in Martian meteorites.

The Martian meteorite ALH84001 has a lot of organic carbon in it, as well as carbonate minerals. It has been speculated that this carbon is from Mars.



Carbon isotopes in ALH 84001

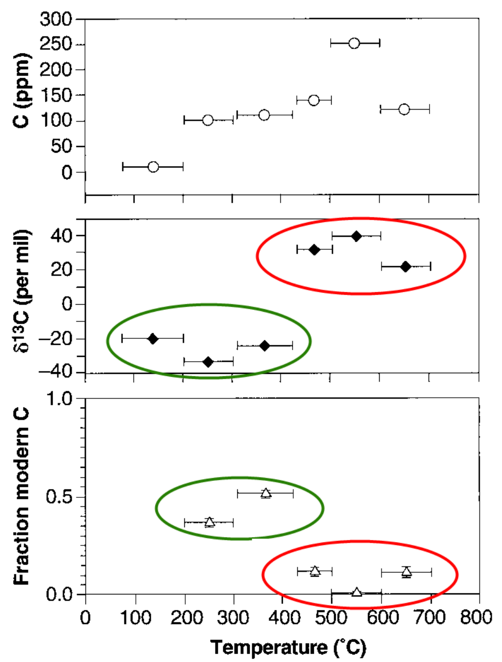


Fig. 2. Combustion experiments on ALH84001 (>250 μm) (E50): total carbon released per temperature step, $\delta^{13}C$, and fraction of modern ^{14}C.

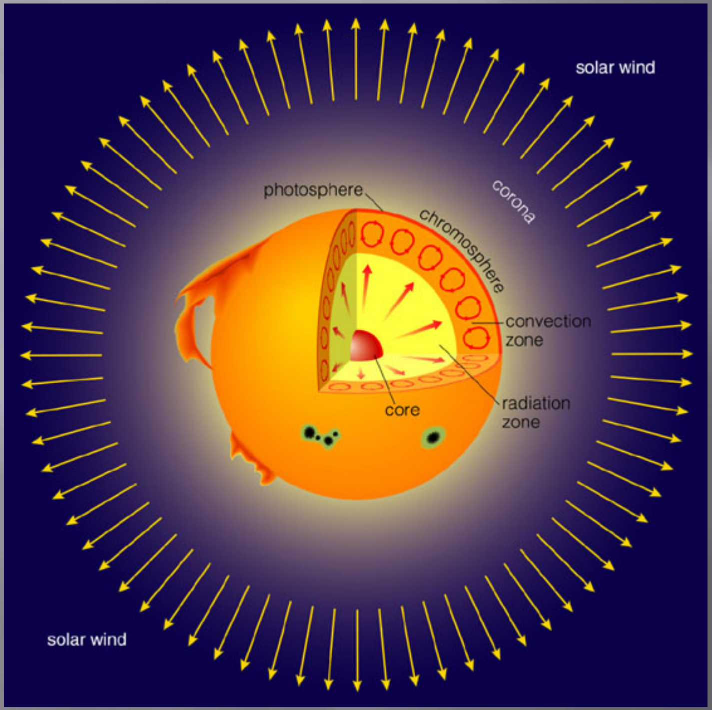
Jull et al. (1998) measured carbon isotopes from the meteorite ALH 84001 using stepped combustion and found a clear division between terrestrial and extraterrestrial carbon.

Table 2. Results of stepped-combustion experiments on martian meteorite ALH84001.

Experiment	Temperature range (°C)	C (μg)	C (ppm)	$\delta^{13}C$ (per ml)	Fraction modern ^{14}C	^{14}C age (ka BP)
0.268 g of powder, size >250 μm						
50A	75–200	8	30	−19.32 ± 0.06		
50B	200–300	27	101	−32.89 ± 0.01	0.372 ± 0.023	8.0 ± 0.5
50C	300–430	30	112	−23.43 ± 0.01	0.524 ± 0.019	5.2 ± 0.3
50D	430–500	38	142	+32.25 ± 0.01	0.127 ± 0.021	16.6 ± 1.3
50E	500–600	68	254	+39.96 ± 0.03	<0.027	>28.9
50F	600–700	33	123	+22.48 ± 0.05	0.125 ± 0.028	16.7 ± 1.8
0.297 g of powder after treatment with 85% phosphoric acid						
52A	76–200	7	24	−31.9 ± 0.1	0.398 ± 0.056	7.4 ± 1.1
52B	200–300	13	40	−25.2 ± 0.1	0.226 ± 0.061	11.9 ± 2.2
52C	300–400	33	111	−26.07 ± 0.01	0.245 ± 0.025	11.3 ± 0.8
52D	400–500	15	47	−14.7 ± 0.1	<0.106	>18.0
52E	500–600	~3	13	−8.1 ± 0.1	—	
52F	600–700	~4	<3	—	—	

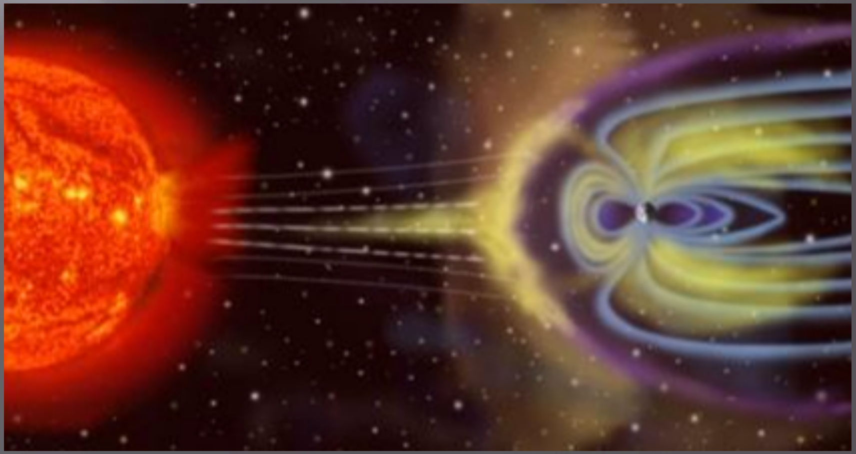
Green ellipses (organics) are terrestrial and red ellipses (from carbonates) are Martian.

What can radiocarbon tell us about the composition of the solar wind?



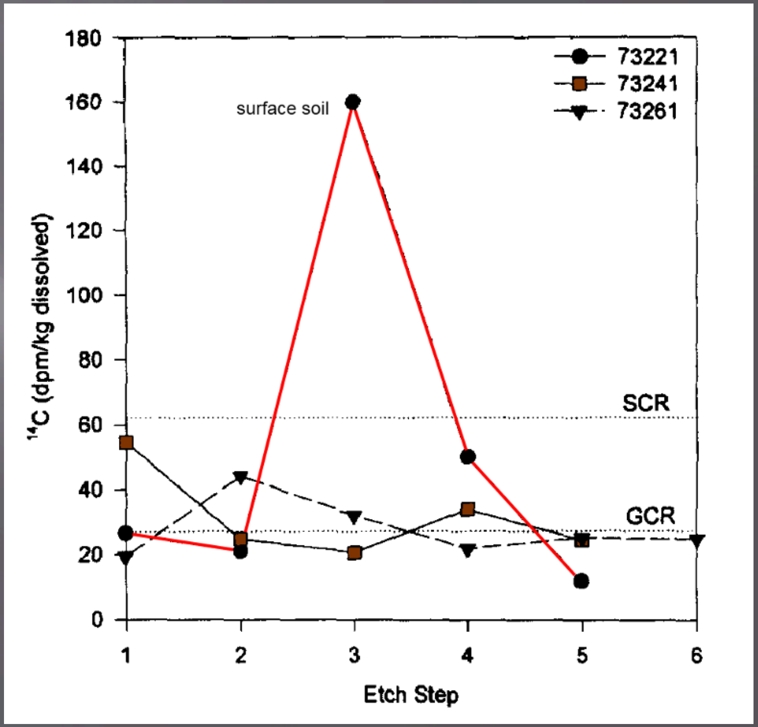
The solar wind is a stream of charged particles ejected from the upper atmosphere of the Sun.

The solar wind creates the heliosphere, a vast bubble in the interstellar medium that surrounds the solar system.

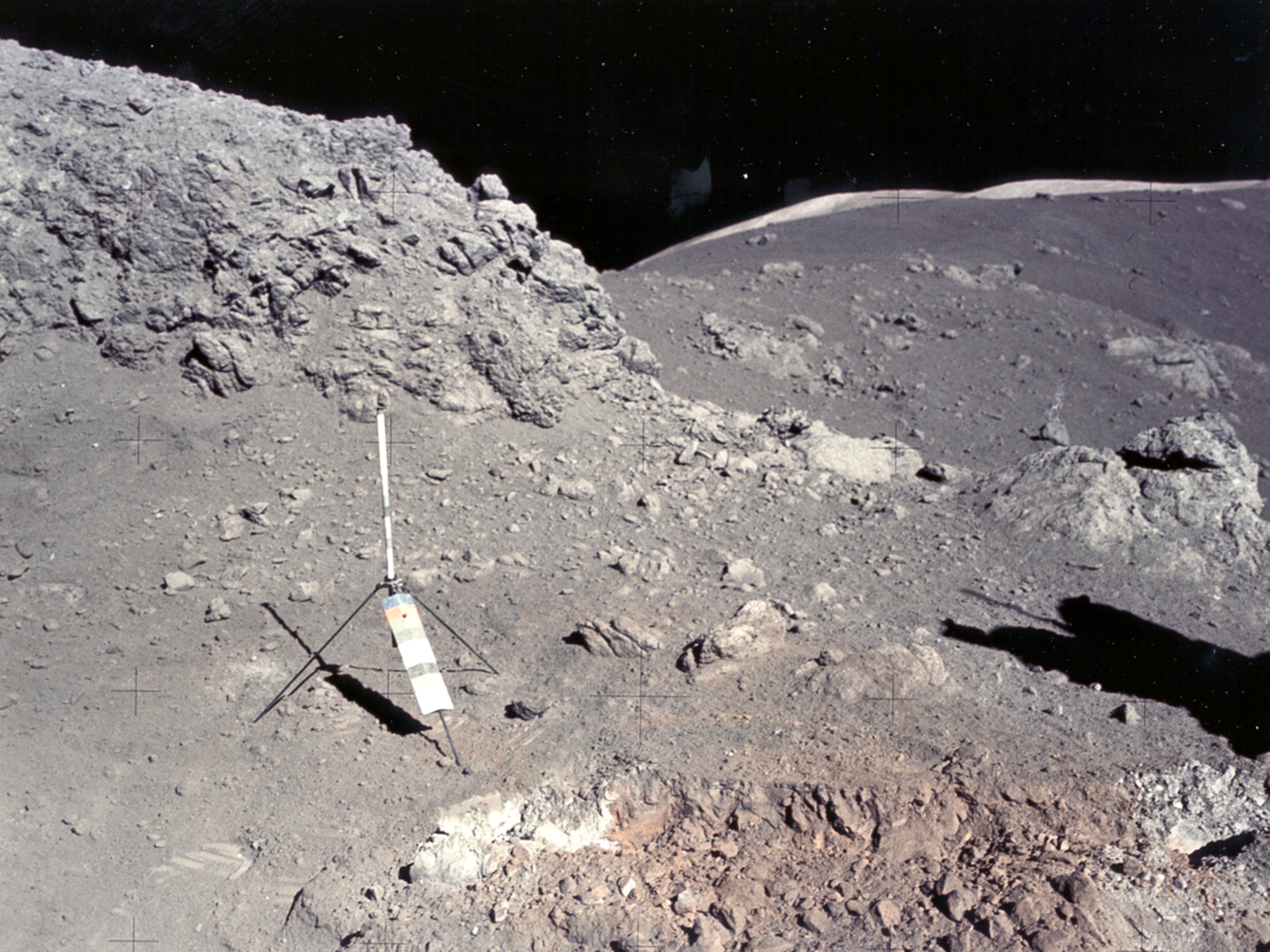


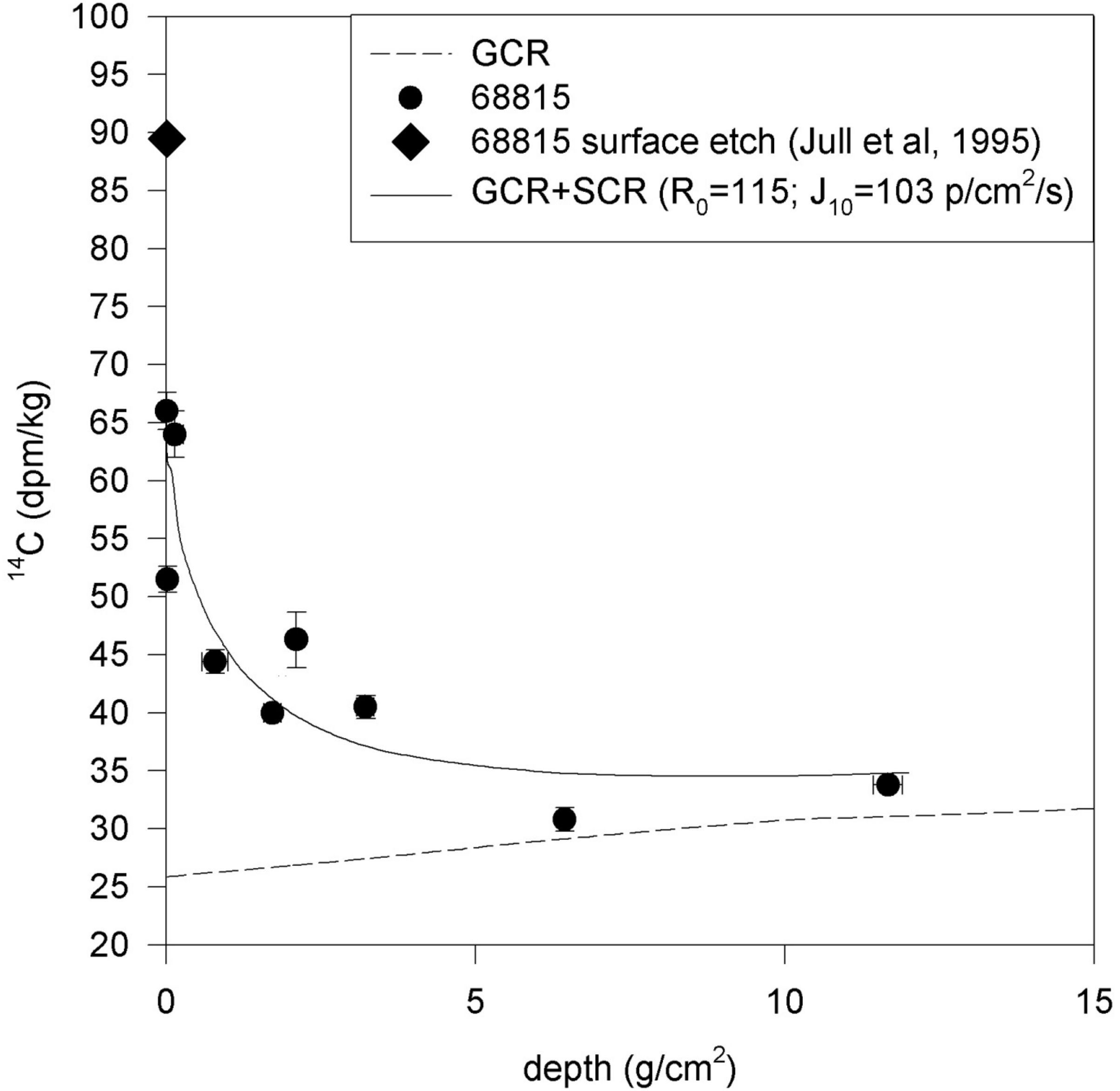
Does the solar wind contain ^{14}C?

The moon



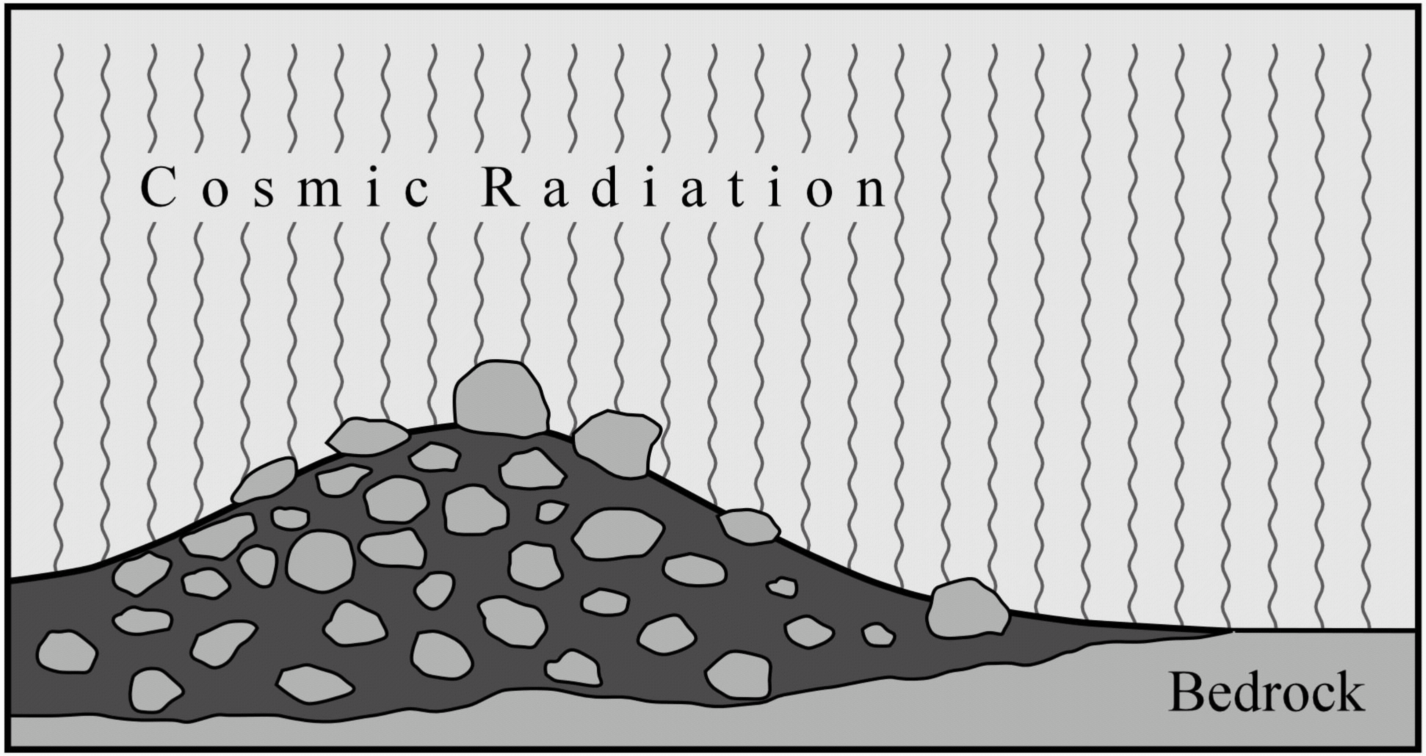
Jull et al. 1995

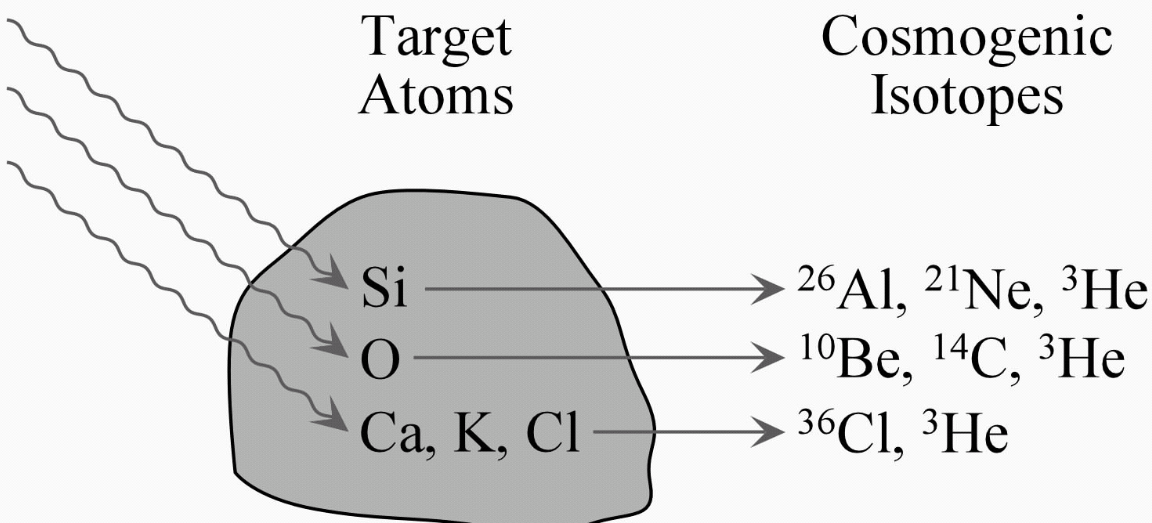



GCR
68815
68815 surface etch (Jull et al, 1995)
GCR+SCR (R0=115; J10=103 p/cm2/s)
14C (dpm/kg)
depth (g/cm2)
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
0
5
10
15

In situ production on the Earth: "daughter" isotopes

- ^{14}C, ^{10}Be, ^{26}Al, ^{36}Cl (radioactive)
- ^{3}He, ^{21}Ne (stable)
- Cosmic ray interactions with matter at the surface of the earth produces stable and radioactive isotopes.
- Produced directly in surface rocks and other material, not in the atmosphere.
- Important new way to verify geological and paleoclimatic events.


Cosmic Radiation
Bedrock


Target Atoms
Cosmogenic Isotopes
Si
O
Ca, K, Cl
^{26}Al, ^{21}Ne, ^{3}He
^{10}Be, ^{14}C, ^{3}He
^{36}Cl, ^{3}He

Production rates

- At sea level, high latitude:
  - ^{10}Be ~4.6 atoms/g/yr
  - ^{14}C ~16 atoms/g/yr
  - ^{26}Al ~31 atoms/g/yr
  - ^{36}Cl variable, several production mechanisms
  - ^{3}He ~110 atoms/g/yr
  - 21Ne ~45 atoms/g/yr

  - At altitude, higher production
  - At higher latitude (>40°N), higher production

$$N = \frac{P}{\lambda}\left(1 - e^{-\lambda t}\right)$$

P=production rate (atoms/g/yr)
N=number of atoms
Λ=decay constant (yr^{-1})
ε = erosion rate (cm/yr)
Λ = depth dependence of Nuclide (~150g/cm^2)

Including erosion, equation expands to…

$$N = \frac{P}{\lambda + \frac{\rho\varepsilon}{\Lambda}}\left(1 - e^{-\left(\lambda + \frac{\rho\varepsilon}{\Lambda}\right)t}\right)$$

Conclusions

Radionuclides are a valuable way to understand the terrestrial residence time ("terrestrial age") and exposure ages of meteorites.

These methods have also been successfully applied to terrestrial rocks.