Irradiation Effects on the Lunar Surface: Regolith Mixing and Safety

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Neutron Fluence Effects

- Recognized very early (e. g., Daniels 1953) that the large thermal neutron capture cross section of ^{157}Gd ($\sigma_{thermal}$ = 2.6×10^5 barns) could be used to provide a measure of neutron fluences (the time-integrated exposure to the neutron flux) in the geologic record.
- Lingenfelter, Canfield, and Hess (LCH 1961 and revised 1972) calculated the lunar neutron albedo as a function of chemical composition, and especially of possible water content on the Moon.
- Analytical techniques (REE chemistry and mass spectrometry) developed in anticipation of the return of Apollo 11 samples (Eugster, Tera, Burnett, and Wasserburg, 1970)
  - Effects for Gd found in the Norton County achondrite
  - Followed by extensive work on Apollo samples

Summary of Observations

- Lunar soils have substantial neutron capture effects for Gd and Sm (and more recently for Cd) indicating extensive exposure to irradiation near the lunar surface
- All lunar soils show neutron capture effects, so that it is likely that in all locations the effects are due to a prior irradiation plus static irradiation in situ
- Materials with low fluences are associated with ejecta blankets of fresh deep craters
- Lunar highland samples show longer irradiation effects than mare samples
- Lunar breccias typically show larger effects than igneous rocks, indicating that the materials forming the breccias include a prior irradiation of their parent materials near the lunar surface
- Neutron fluences are a function of the chemistry of the samples, but corrections for chemistry permit comparison of neutron irradiation effects for samples in different geologic settings
- The neutron exposure effects indicate that resurfacing the lunar surface through impact ejecta includes significant contributions from depths below 10 m, where the materials are not subject to irradiation by secondary neutrons
- Studies of lunar deep drill cores indicate that the rapid emplacement of several meter-thick ejecta blankets is a typical occurrence
- Lunar gardening processes that can regularly deposit at least 2-3 meter-thick blankets of well-mixed materials, in a relatively short time

Auspicious Analytical Developments

- Fouad Tera developed, just prior to Apollo 11, ion exchange chemical separation techniques to meteorites and then applied to lunar samples
  - A new and critical development enabled by the Apollo Program
- Eugster et al. (1970) developed Gd mass spectrometry, using the Lunatic I thermal ionization mass spectrometer
  - Established that Gd ionizes more efficiently as GdO^+, at ~0.01%
  - Precision at 1 part in 10^4 (epsilon unit), for 0.5-1 μg Gd
- Both developments were applied also to Sm (for neutron capture effects, Russ et al.), and, after the end of the Apollo missions, to Sm-Nd dating (Lugmair; Papanastassiou et al.; DePaolo and Wasserburg, and many, many more)
  - Ionization efficiencies GdO^+ 0.01%; SmO^+ 0.1%; NdO^+ up to 40% for ng
  - A premier example of the influence of key analytical advances, due to the Apollo Program, on cosmochemistry and terrestrial geochemistry
  - Sm-Nd used for chronology and for identifying terrestrial mantle evolution (Sr and Nd isotope correlations), for which G. J. Wasserburg and C. J. Allègre shared the 1986 Crafoord Prize, of the Royal Swedish Academy of Sciences
  - Now a standard dating and isotope fingerprinting technique

Lunar Neutron Probe Experiment

D. S. Burnett and D. S. Woolum

- Example of early results on Apollo guiding the development of a new instrument
  - Rapid design construction and passage through strict testing, designed for human exploration
  - Neutron detection by nuclear track counting
    - ^{235}U neutron fission tracks
    - $^{10}B(n, \alpha)\,^{7}Li$, alpha tracks on cellulose triacetate
- Flown on Apollo 17; inserted in deep drill stem hole, after extraction of core

Lunar Neutron Probe Experiment

D. S. Burnett and D. S.Woolum

- Results
- Confirmed calculated secondary neutron spectrum by LCH (magnitude and shape)
- Agreement with LCH to 10%; uncertainty (in normalization of LCH 30%)
- Agreement with neutron profiles with depth, obtained using deep drill stem samples for Gd and Sm isotope neutron capture.

Isotope pairs with large neutron capture cross sections for Apollo 11 soils

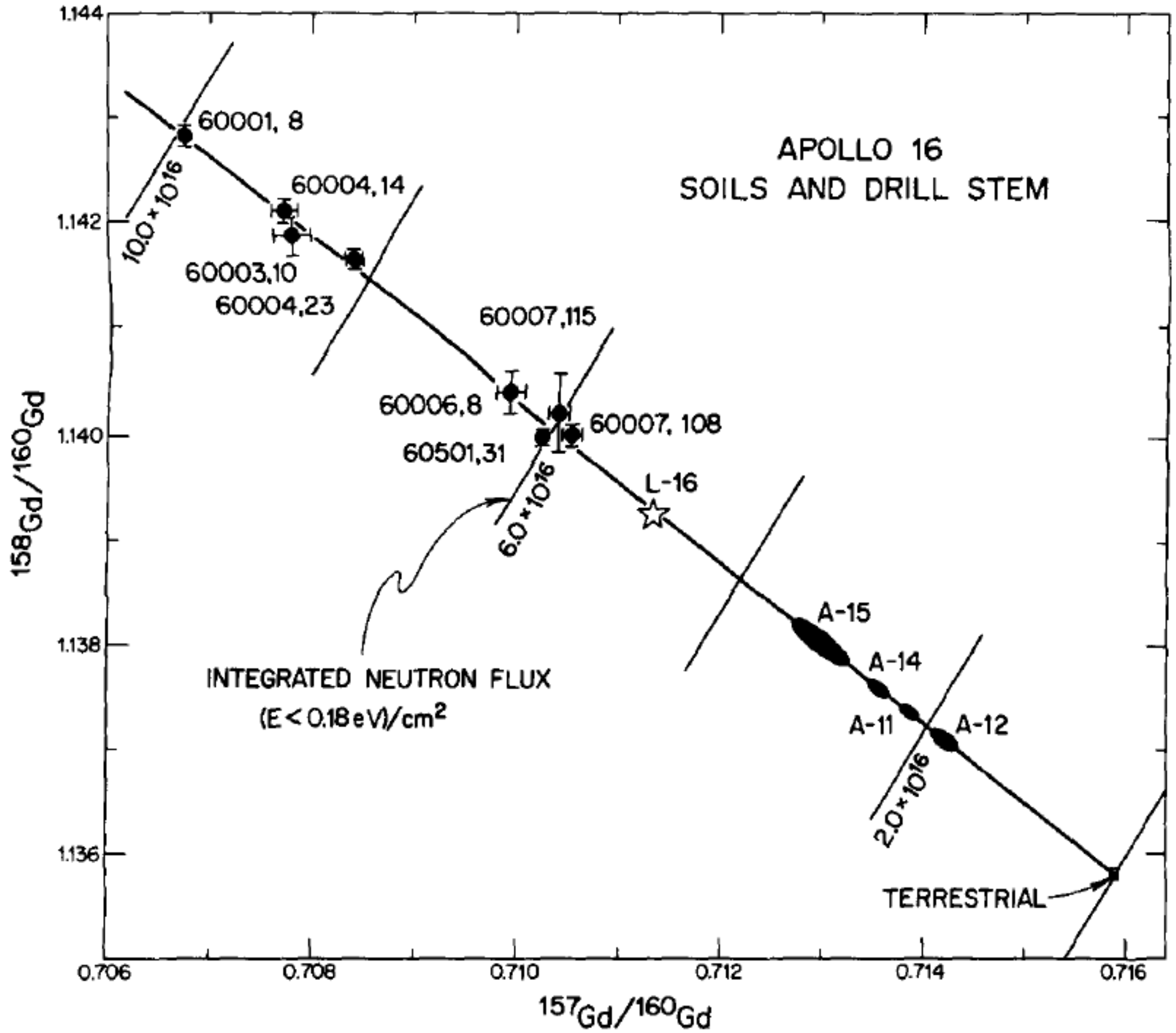
Reaction	f^a	$\sigma_{eff}{}^b$	$\sigma_{eff}(1 + f)^c$
		barns	
^{149}Sm (n, γ) ^{150}Sm	1.86	5.6×10^4	1.6×10^5
^{157}Gd (n, γ) ^{158}Gd	0.63	9.0×10^4	1.5×10^5
^{155}Gd (n, γ) ^{156}Gd	0.72	2.2×10^4	3.7×10^4
^{113}Cd (n, γ) ^{114}Cd	0.425	3.9×10^4	5.6×10^4
^{186}W (n, γ) ^{187}W (β^-) ^{187}Re	~3×10^3	6.0×10^2	1.8×10^6

[a]Ratio of isotope abundances.

[b]value of the 1/v-dependent capture cross section at 0.0253 eV which gives the same total capture rate as the exact resonance capture cross section, when summed over the neutron energy flux spectrum.

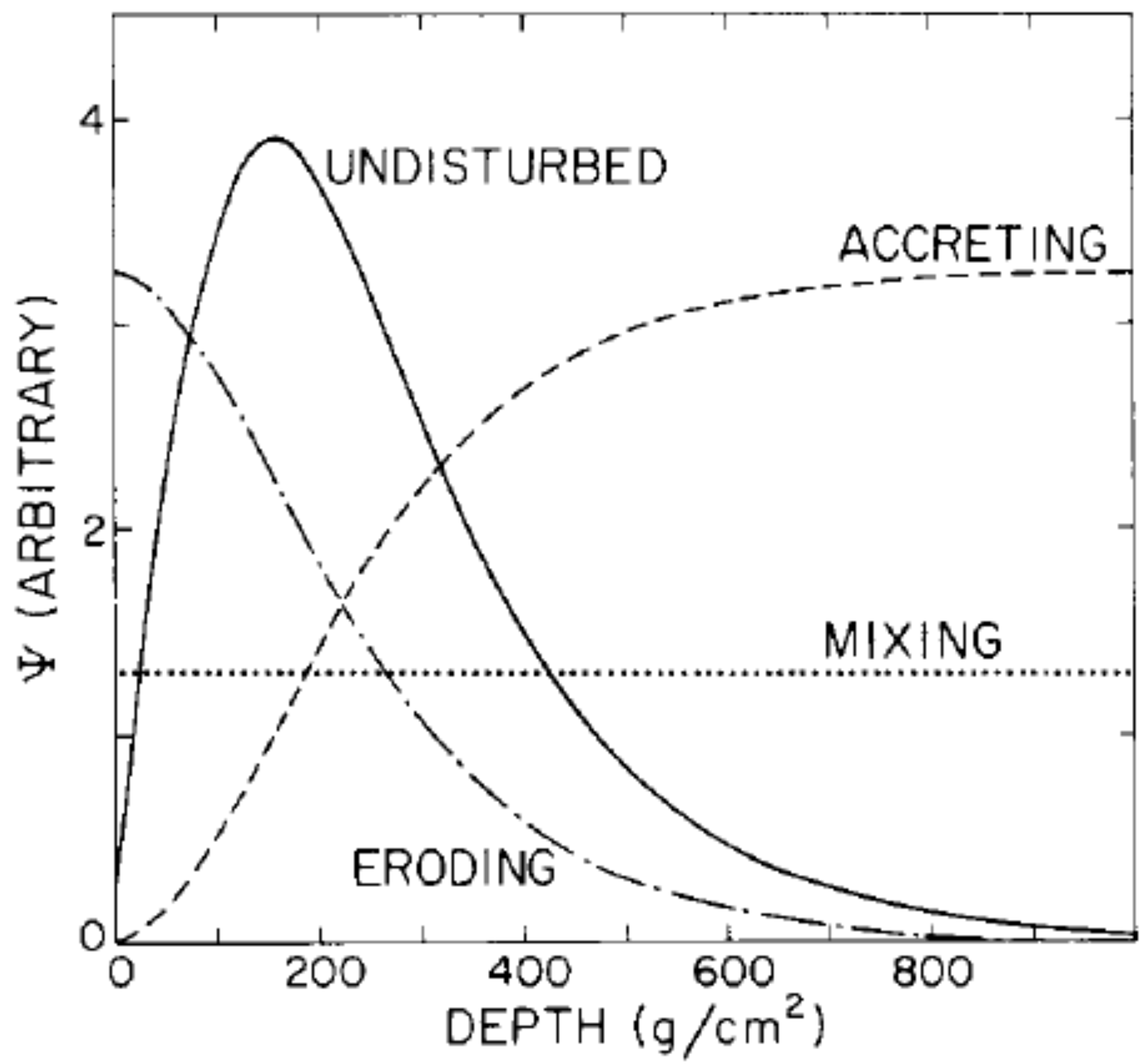
[c]Expected isotope effect when multiplied by neutron fluence.

From Table 3, LCH (1972).

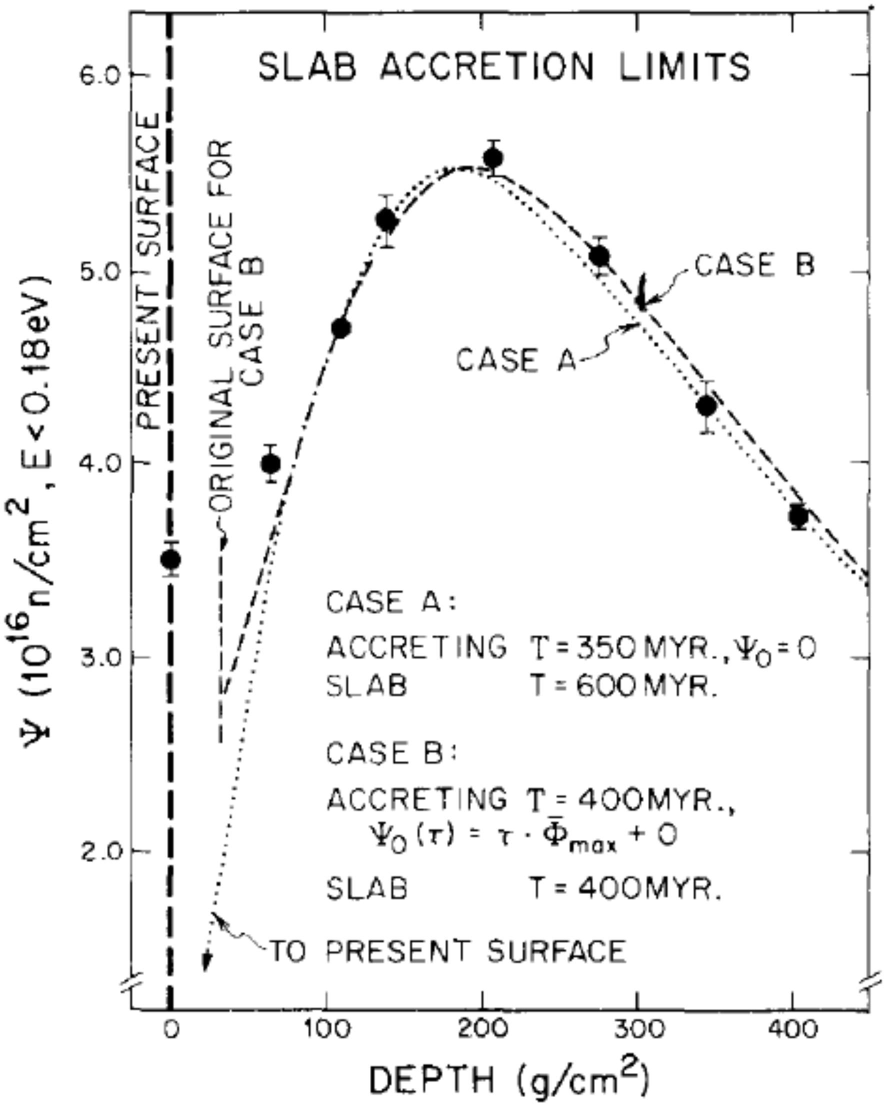


Isotope effects for Gd up to 200 ± 1 εu (parts in 10^4)

Russ, 1973
EPSL

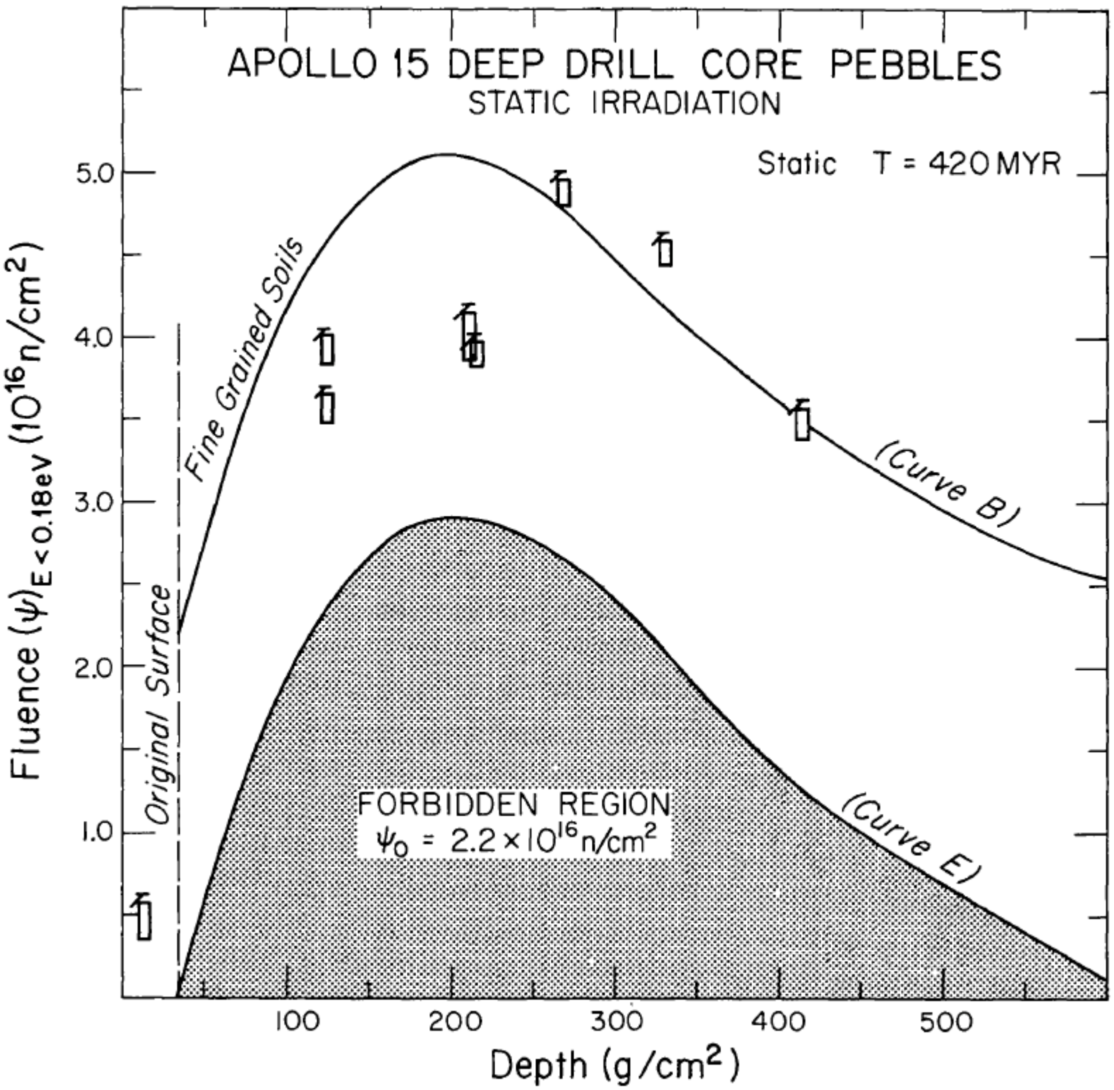


UNDISTURBED
ACCRETING
MIXING
ERODING
Ψ (ARBITRARY)
0
2
4
0
200
400
600
800
DEPTH (g/cm²)



Apollo 15 deep drill stem soil samples

Russ, Burnett and Wasserburg, 1972 *EPSL*

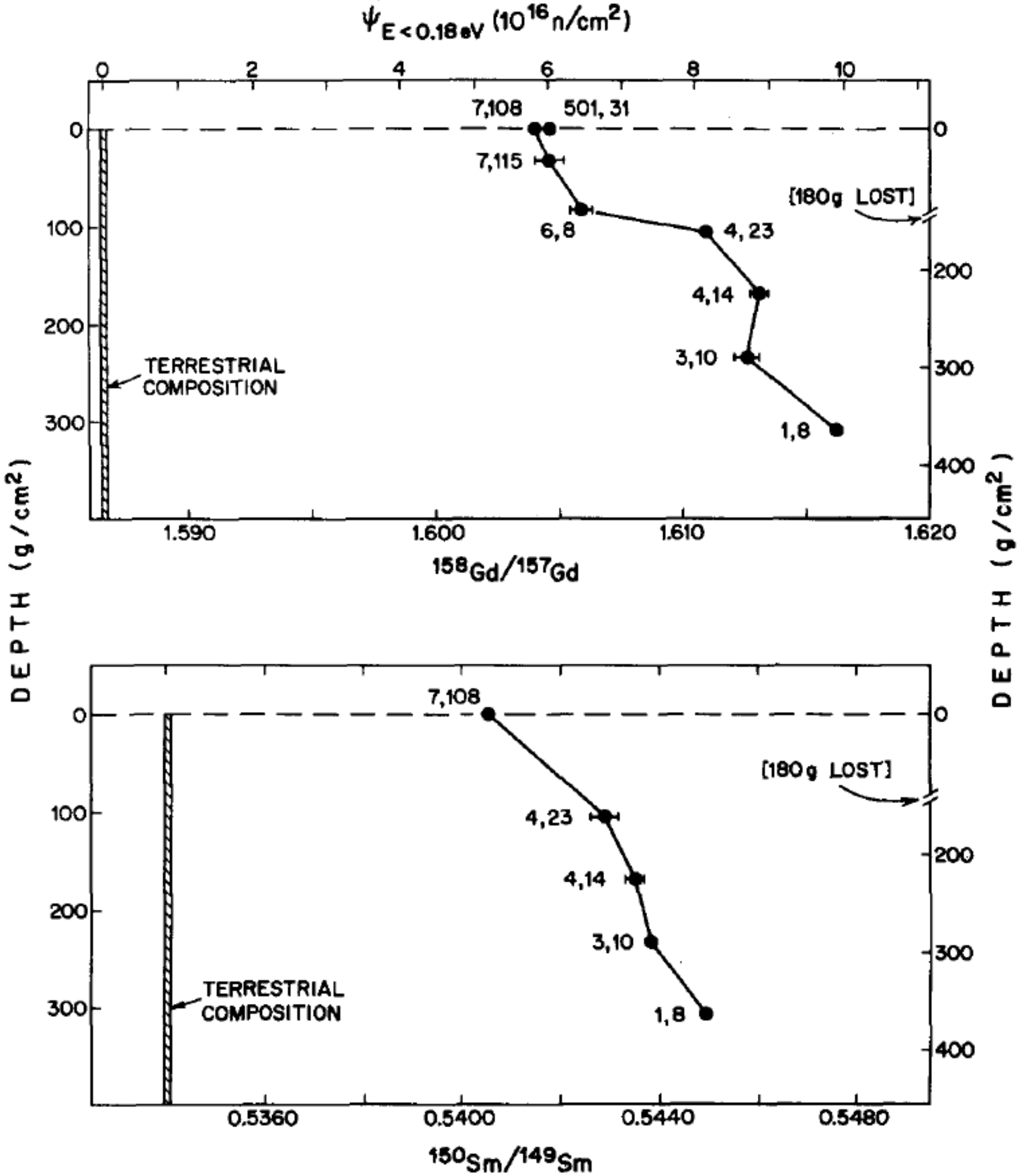


The solid line fit represents a model of rapid accumulation of previously irradiated material followed by 420 My of undisturbed irradiation (as a lower limit). Upper limit of total irradiation is 750 My.

Fragments on curve B are soil breccias and indicate pre-irradiation as soil fine grains

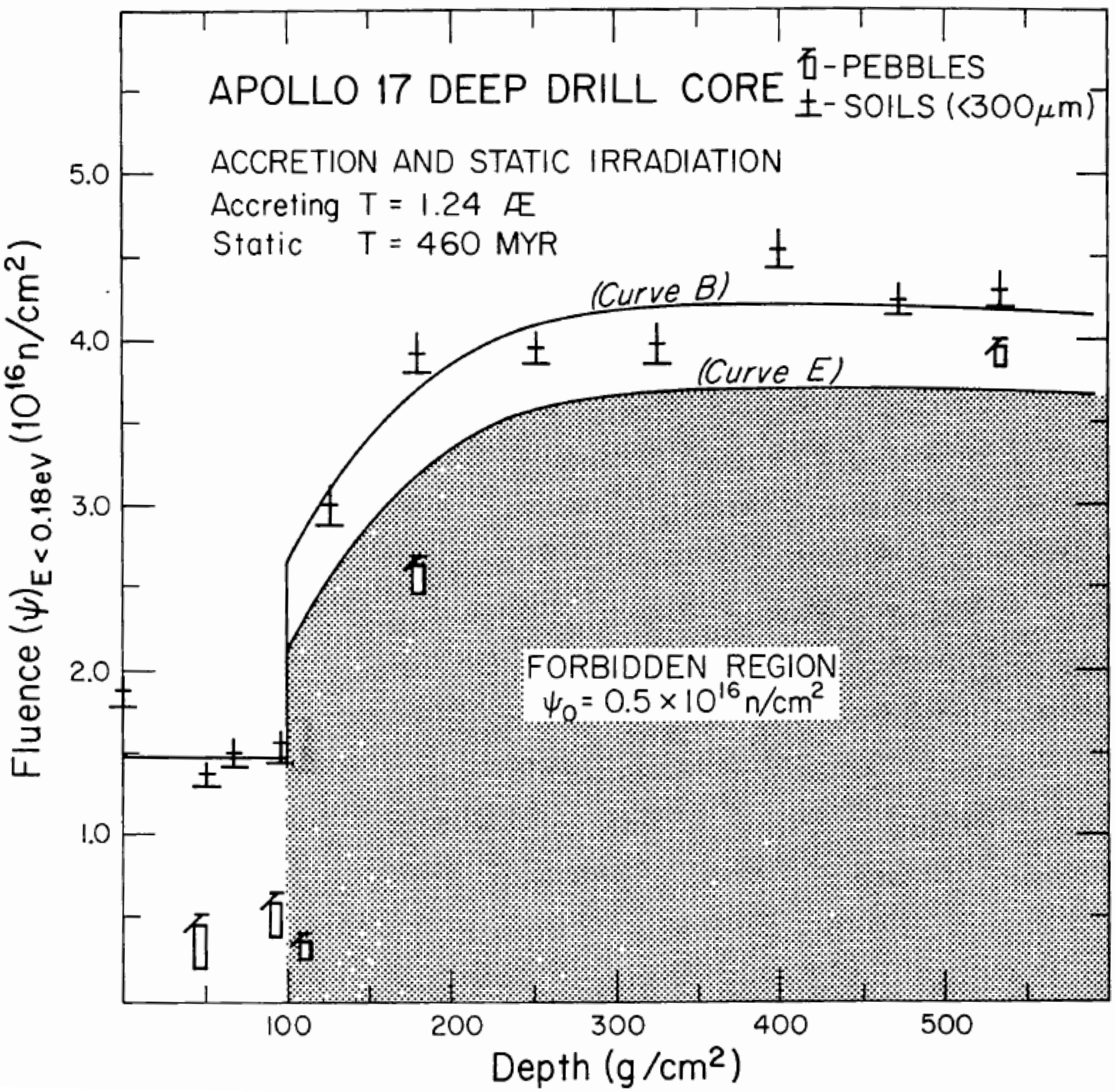
Basalt fragments below the curve indicate lack of pre-irradiation.

Curtis and Wasserburg 1977



Apollo 16 deep drill stem soil samples: The data can be fit by a model of continuous accretion of pre-irradiated regolith at a rate of ~70 g/(cm^2 x10^8 yr) or by models of as few as two slabs of material in which the first slab would have been deposited as long as 10^9 yr ago.

Russ, 1973 *EPSL*



Model:
Slow accretion followed by static irradiation (curve B):

OK for soils; but invalidated by pebble at 180 g/cm^2

Curtis and Wasserburg 1977

Current State/Conclusions

- Basalt fragments (several mm in size) have, on the average, lower exposure to lunar neutrons than bulk, fine grained soils, from the same locations in the deep cores
- Average residence time of pebbles is 300 My less than the average of fine grained soils
- Pebbles consisting of soil breccias have the same exposure to fine-grained lunar soils and, therefore, reflect the residence times of the grains welded together to form the breccias, rather than exposure of the breccias as pebbles
- Apollo 15 drill stem is virtually undisturbed for 400Ma
- Apollo 17 sampled two thick ejecta blankets of very similar exposure ages
- Lunar gardening processes are capable of producing regularly 2-3 meter-thick ejecta blankets of well mixed pre-irradiated materials on time scales of 100 My.