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INVESTIGATIONS OF LUNAR MATERIALS

FINAL REPORT

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The Particle Track Record of the Ocean of Storms

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ABSTRACT: In Apollo 12 rocks the numbers of tracks from the solar and galactic iron group cosmic rays imply surface residence times that range from <10,000 years to ~30 million years. The presence of steep track gradients at exposed surfaces shows that some rocks have been on the lunar surface in only one position, while others have been turned over and moved more than once. For example, rock 12017 was raised to within one meter of the surface, later thrown to the very surface, then flipped over and recently splattered with molten glass (just 9,000 years ago). The abundance of nuclear interaction (spallation) tracks induced by the penetrating galactic protons provides residence times for different rocks in the top meter of soil of ~20 to 750 millions of years. Since there is great variation of the track densities from grain to grain in the soil we conclude that it has been well stirred down to ~60 cm depth at the site of the deepest Apollo 12 core sample. A model in which thorough stirring is most frequent at shallow depths and less and less frequent at greater depths fits the observed track density distributions; stirring ages of 1 to 2 billion years are required. The erosion of lunar rocks is estimated by comparing the cosmic ray track distributions in lunar rocks with the one found in (uneroded) glass detectors exposed in Surveyor III. Erosion at a rate of about one atomic layer per year is inferred. By inducing uranium-235 fission tracks we have measured widely ranging uranium concentrations: less than 10^{-3} parts per million in pyroxenes, ~1ppm in glass, and up to 170 ppm in zircon. The fossil track abundance in the zircon gives no evidence for the presence of extinct radioactivity by plutonium-244 or by superheavy nuclei. Deformation-produced track erasure has been seen in some soil grains.

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The abundant particle tracks found in most lunar samples constitute a highly detailed record of the diverse chronology of lunar samples: solidification ages are recorded by uranium-238 fission tracks(1); times of exposure on the lunar surface (_surface residence_ times) are given by tracks of iron group nuclei in the cosmic rays(2,3); and we shall see that nuclear interaction (spallation) tracks(2,4) measure the total time spent near and at the lunar surface.

Uranium contents and fission track dating: Since fission track dating requires the presence of uranium, the induced fission track measurements(5) given in Table I are relevant(6). In the cases shown, uranium is too low to allow fission track dating of any of the samples except for zircon LZ where an upper limit can be given. Since the fossil track content was 1 to 3 x $10^8/\text{cm}^2$, the ages would be 1.3 to 3.3 x 10^9 years if these were all fission tracks, and less if an appreciable fraction were of other origin. There is thus no evidence for an excess of fission tracks from presently extinct fission activity by Pu-244 or super-heavy elements.

Surface chronology of rock 12017: We have shown previously(2,3) how the dominant cosmic ray tracks - from the iron group nuclei - can be used to measure the surface residence times of rocks and rock fragments and how (from steep track density gradients near space-exposed surfaces) former orientations of rocks can be inferred. As an example, the results shown in Figure 1 for rock 12017 allow us to derive the complicated and varied history described in Table II.

Spallation tracks indicate the period over which the rock was exposed to galactic cosmic rays and are responsible for the first two entries in Table II. The increase in cosmic ray tracks near each surface show that both sides have been exposed to space, and the slight asymmetry in the profile shows that the bottom received the longer exposure, roughly 1 million years, than did the top. At the very top is a glass coating that apparently was splashed on after the rock was positioned with that side up. From crystals trapped within the coating its space exposure is inferred to be only ~9,000 years. The glass itself(7) is less retentive of tracks (allowing fading in 2 years at 400°K and 500 years at 350°K) and has only preserved tracks over the last 500 years(8). In short the low energy cosmic rays (dominantly solar flare particles) have been recorded over different time intervals: the glaze over the last 40 to 50 solar cycles, the crystals within the glaze over the last ~800, and the bottom of the rock over a more ancient group of ~500,000 cycles. Track distributions in these three sites should allow the proposed(9) "solar flare paleontology", comparing ancient solar spectra at different periods of time.,

Surface residence times: Table III summarizes cosmic ray track information for Apollo 12 rocks and gives the most current data on 10049. This is an Apollo 11 rock of special interest because its surface time of 29 m.y. agrees with the 24 m.y. inferred from radioactivity measurements of spallation-produced nuclides(10) and the 21 m.y. inferred here from spallation tracks. In short this sample spent all of its near surface time directly exposed to space and underwent very little erosion (which would have lowered the track density). The limit on erosion ($<3 \times 10^{-8}$ cm/year) is consistent with what we will infer later in this paper from our Surveyor III results. Table III shows a wide range of surface exposure times - from $\sim 10^4$ to 3×10^7 years - for samples some of which have been in a single surface position, some in at least two, and one in at least three.

Spallation ages: We have noted previously(4) that spallation tracks produced by nuclear interactions of penetrating primary cosmic ray particles increase in number with the time of exposure in the top 1-2 meters of soil. We have now assembled sufficient data to show that useful spallation ages can be calculated, as shown in Table IV. The computed fluence of high energy particles ("proton exposure") is the ratio of the observed spallation track densities to the production rate measured after bombardment of samples by specified doses of 3 GeV protons. An assumed cosmic ray proton flux of $3 \times 10^7/\text{cm}^2$-yr leads to the ages given as "surface ages" - the time samples were on the lunar surface if the entire exposure occurred there.

Burial depths: The ages are uncertain, however, because we do not know the samples' depths of burial during proton exposure. As other accelerator experiments have shown(11), a cascade of nuclear-active, secondary protons and neutrons builds up with depth and then attenuates. For spallation reactions in which 5 nucleons can be ejected from the struck nucleus(12) the maximum flux is ~2.5 times the primary proton flux and occurs at a depth of about 50 cm of soil (or 25 cm of rock). The column labeled "minimum spallation age" in Table IV gives minimum times - corresponding to burial at a 50 cm soil-equivalent depth. It should also be evident that the observed track densities could have been produced by much longer exposures than we have listed, if the samples were located at greater depths where the high energy particle flux is corresponding lower.

By comparing track spallation ages with track surface residence times and with radiometric spallation ages, permissible burial depths can be inferred. Thus for rock 10049, where all three agree, the entire exposure must have been at the surface.

For rocks 10017 and 10044, where the surface residence was short, the samples must have been buried over most of their spallation exposure times. In the case of 10044 burial must have been at ~50 cm of soil as judged by the low radiometric spallation age.

At present track spallation ages are of low precision. They do, however, give reasonable agreement with the radiometric ages and give track workers an additional dimension for assessing radiation exposure histories. By measuring spallation ages for more than one mineral an improved internal check on the accuracy of such ages will be possible.

Core sample and soil mixing: Primary cosmic ray track densities were counted in 112 individual pyroxene, olivine and feldspar soil grains from 13 depths distributed through the 40 cm length of core samples 12025 and 12028. About a third of the samples were counted from electron microscope replicas(4); we determined that these counts should be reduced by a (variable) factor of 2 to 3 for comparison with light microscope counts. The counts in pyroxene crystals need to be corrected for 70% etching efficiency. With these adjustments we have plotted in Figure 2 the median track density observed at each depth and limit bars which show the spread of the 70% of the samples that are closest to the median.

It will be seen that there is no significant correlation with depth and the spread at each depth is about a factor of 10. The statistical counting error for each sample grain is less than 10%. The track density spread due to uncertainty in the orientation of the etched surfaces was investigated by breaking up a large pyroxene grain; the fragments yielded a ± 1σ spread of a factor of 2, as expected from the anisotropy of the attenuated cosmic ray beam.

If the soil had not been subjected to any mixing then the expected track density would be proportional to the steep curve in Figure 2, with a factor of 2 spread for uncertain orientation. This is clearly not the case. A Monte-Carlo mixing calculation shows(13) that continual stirring due to crater formation will result in a much shallower depth dependence, as observed, and a 70% track density spread at each depth of a factor of about 30, as indicated in Figure 2.

The calculations were performed in the following manner. For the "slow mixing" curve in Figure 2 we start with 1800 hypothetical samples, containing no tracks, distributed throughout the top 60 cm of soil. As the system evolves with time, these samples accumulate tracks at a depth-dependent rate determined from the average primary cosmic ray spectrum(4). Every 100 m.y. those samples which have depths of 0-10 cm are assigned new depths at random between 0-10 cm, keeping account of the accumulated tracks. Similarly samples 0-25 cm deep and 0-60 cm deep are assigned new depths every 250 m.y. and 600 m.y., respectively. At each such "characteristic mix" 1% of the samples mixed are re-assigned 0 track density to simulate shock annealing.

These mixes simulate in one process the physically separate mechanisms of excavation and continual overlaying while demonstrating the effects of periodically bringing material up from lower depths and of mixing the shallow depths more frequently. The rate at which these "slow" mixes occur is derived from the maria crater distribution function, corrected for obliteration(13). For the "fast mixing" curve in Figure 2 we assume a mixing rate ten times faster.

References and Footnotes

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6. For experimental procedures used on lunar samples throughout this work see ref (4).

7. Microprobe analysis gives the following composition by wt %: SiO_2, 46.4; FeO, 17.7; Al_2O_3, 10.5; MgO 11.0; CaO, 9.30; TiO_2, 2.80.

8. There is additional fading in the top 30μ, a distance that corresponds to two or three optical depths for visible light in this glass.

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12. This is estimated to be the minimum mass loss that will yield optically visible, etched tracks from spallation recoil nuclei.

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Figure Captions

Figure 1: Cosmic Ray Track Distribution in Rock 12017. The top of this rock was coated with glass of maximum thickness 0.15 cm. Tracks in crystals within the glass show it to be recently formed. Pyroxene and glass track densities are corrected for the measured etching efficiencies of 0.7 and 0.08.

Figure 2: Cosmic Ray Track Distribution in Core 12025 and 12028. The data points are observed optical and (adjusted) electron microscope counts. The curves have been calculated for the three models of soil history described in the text.

TABLE I:

Uranium Content of Lunar Samples

Mineral	Sample No.	Uranium* (wt fraction x10^9)	Notes
Augite	12017,17,6,3	0.4 (± 60%)	Not including visible inclusions
Augite	12017,17,6,3	1.5 (± 30%)	Including visible inclusions
Augite	12021,1,4,5	1.0 (± 50%)	Not including visible inclusions
Augite	12021,1,4,5	4.5 (± 20%)[†]	Including visible inclusions
Augite	12065,6,6	0.5 (± 70%)	Including visible inclusions
Glass	12017,8,6	1,230 (± 8%)	
Zircon**	LZ (from Apollo 11 fines)	167,000 (± 12%)	
Zircon**	Z-2 (from Apollo 11 fines)	<10,000	90% confidence

* tracks observed on interior surfaces, except as noted.
** tracks observed in Lexan adjacent to sample.
[†] most uranium-rich inclusion scanned contained ~3 x 10^6 atoms of uranium.

Table II:

Simplest Track Chronology for Rock 12017

TIME (Years before Present)	EVENT
up to ~70,000,000	Buried >100 cm
~70,000,000	Moved to <100 cm and >15 cm
~1,700,000	Moved to surface
~700,000	Flipped over
~9,000	Splattered with hot glass
~500 to 0	Glass records solar flare particles

Table III

Minimum Cosmic Ray Track Densities and Surface Residence Times for Lunar Samples

Sample	Mineral	Track Density (cm^{-2})	Depth in Sample (cm)	Surface Residence Time (million years) (top/bottom)
10049	Pyroxene	1.55×10^7	.90 cm	(29 total)
12002	Pyroxene	2.8×10^6	5.0	(24/0)
12017	Feldspar	1.51×10^6	.45	(.7/1.0)
12017	Feldspar in Glaze	8×10^5	.02	(.009/0)
12021	Pyroxene	5.0×10^6	4.0	(13/13)
12065	Pyroxene	2.2×10^6	6.4	(14/0)
12025 (Soil) 12028	Pyroxene Feldspar	3×10^7*	-	(110 total)**
12025,4,54-8.5,9,9	Pyroxene	5×10^7	.002	(.01/0)***

* average of 100-400μ diameter grains.

** average time in top 60 cm of soil, calculated in same manner as in ref (4).

*** using solar spectrum from Surveyor III glass (14) after adjustment for solar cycle.

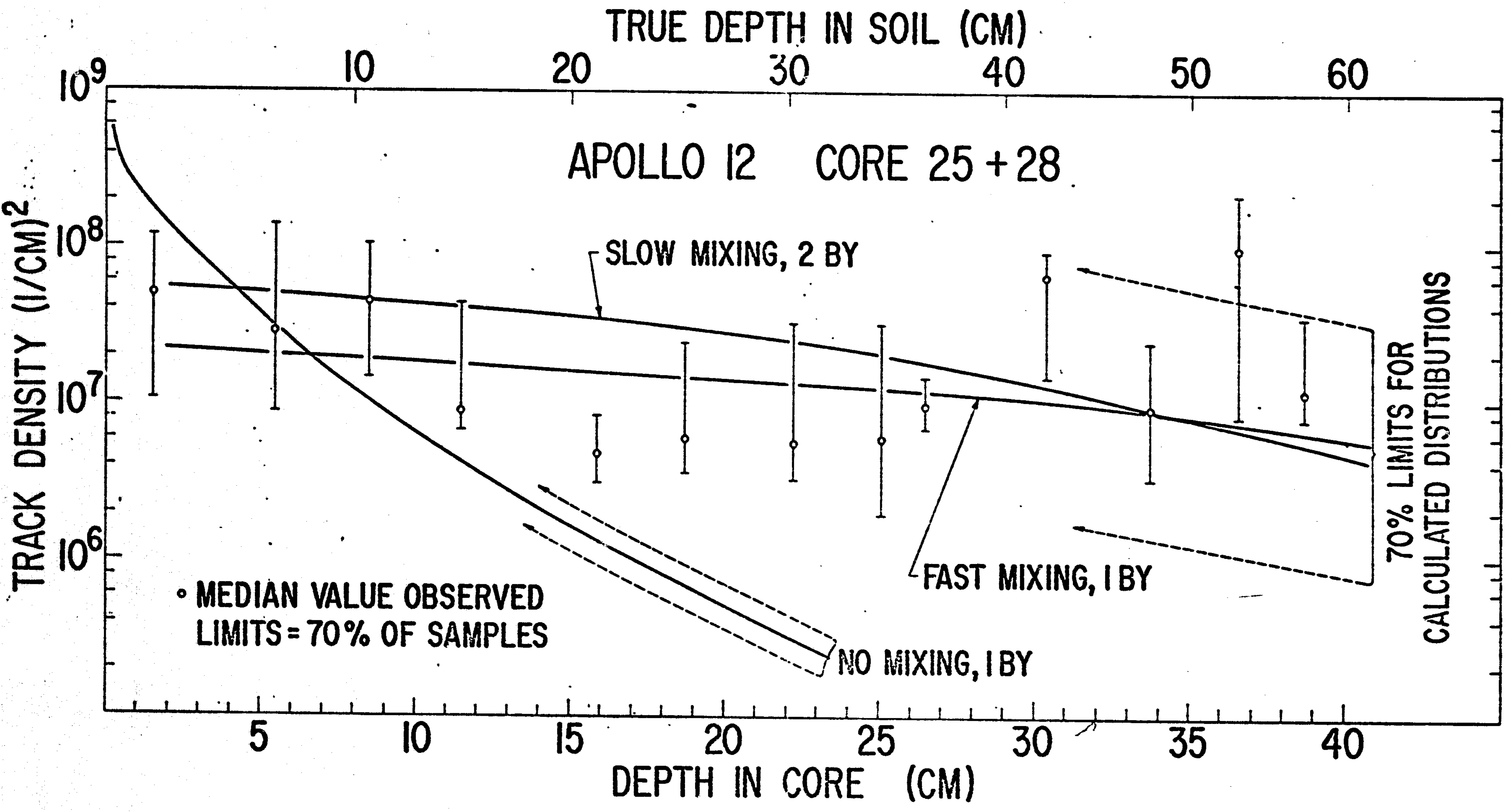
Table IV:

Track Spallation Ages of Lunar Pyroxenes

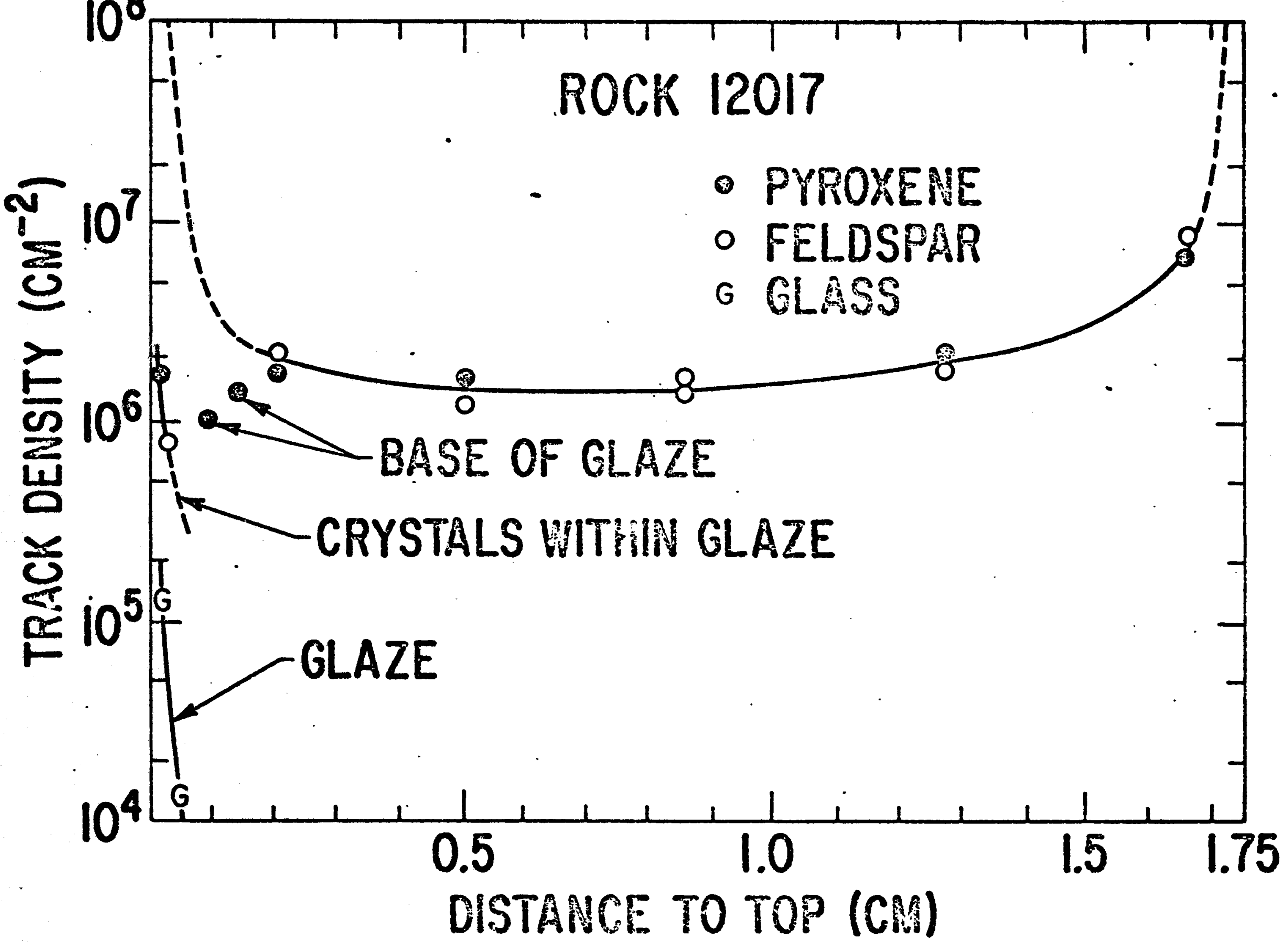
Sample Number	Production Rate (P)* (tracks/10^9 protons)	Observed Track Density (ρ_{sp}) (cm^{-2})	Proton Exposure (ρ_{sp}/P) (protons/cm^2)	Surface Age (10^6 yr)	Minimum Spallation Age (10^6 yr)	Radiometric Spallation Ages (refs in ref 4) (10^6 yr)
10017	1.7**	$2.1(\pm.1)\times10^7$	1.2×10^{16}	420	170	200-640
10044	1.0	$8.2(\pm1.2)\times10^6$	8.2×10^{15}	270	110	56-100
10049	2.39	$1.49(\pm.15)\times10^6$	6.2×10^{14}	21	8.5	22.5-25
12002	1.7**	$2.66(\pm.25)\times10^6$	1.6×10^{15}	55	20	
12017	1.45	$4.57(\pm.32)\times10^6$	3.2×10^{15}	105	40	
12021	2.31	$5.1(\pm.3)\times10^7$	2.2×10^{16}	740	300	
12065	1.35	$6.81(\pm.28)\times10^6$	5.1×10^{15}	170	70	

* absolute values uncertain to ±30%, but relative values are valid for 10049, 12002, 12017, 12021, and 12065.

** average of other values.


TRUE DEPTH IN SOIL (CM)
10
20
30
40
50
60
APOLLO 12 CORE 25 + 28
SLOW MIXING, 2 BY
FAST MIXING, 1 BY
NO MIXING, 1 BY
70% LIMITS FOR CALCULATED DISTRIBUTIONS
∘ MEDIAN VALUE OBSERVED
LIMITS = 70% OF SAMPLES
TRACK DENSITY $(1/CM)^2$
10^9
10^8
10^7
10^6
5
10
15
20
25
30
35
40
DEPTH IN CORE (CM)

NASA — MSC


ROCK 12017
● PYROXENE
○ FELDSPAR
G GLASS
BASE OF GLAZE
CRYSTALS WITHIN GLAZE
GLAZE
G
G
TRACK DENSITY (CM^{-2})
10^8
10^7
10^6
10^5
10^4
0.5
1.0
1.5
1.75
DISTANCE TO TOP (CM)