Jour. Fac. Sci., Hokkaido Univ., Ser. IV,
vol. 18, nos. 1-2, Feb., 1978, pp. 85-104

CHARGED-PARTICLE TRACKS IN YAMATO-74 METEORITES

by

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(with 2 tables and 9 text-figures)

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Abstract

Fossil charged-particle tracks and uranium contents were examined in major silicate phases in Yamato-74013, -74080, -74094, -74362 and -74459 chondrites.

The tracks recorded in bronzite in diogenites and olivine in chondrites are expected to be mostly due to cosmic-ray heavy primaries, because of their extremely low uranium contents. Assuming that the cosmic-ray exposure age, 31 my, of Yamato-6902 is also applicable to other diogenites, the distance from the preatmospheric surface to the test crystals is estimated to be 10, 17 and 15 cm for Yamato-74013, -74037, and -6902, respectively. For Yamato-74014 and -74080 chondrites, the exposure age of about 3 ~ 5 and 14 my, each, can be evaluated, assuming the shallow burial depth of the samples, which have a fusion crust on one side.

A small polished section with a fusion crust was etched to investigate the effect of the ablation heating. Cosmic-ray tracks were survived in olivine grains at the depth of more than 0.9 mm from the meteorite surface. According to the high-temperature annealing experiments, the temperature higher than 550°C had not continued for 1 sec at the position.

Pyroxene in chondrites usually contains much higher uranium contents and fossil tracks than in olivine. These tracks cannot be explained only by cosmic-ray and the spontaneous fission of ^{238}U during 4.6×10^9 yrs. On the assumption that the excesses are due to the spontaneous fission of the presently extinct isotope, ^{244}Pu (half life, 82 my), the time intervals between the end of nucleosynthesis and the onset of track retention, ΔT, were calculated. They are ranging from 3×10^7 to 3×10^8 yrs for five chondrites. No apparent relations were found between the results and the chemical and petrologic types of the chondrites.

Introduction

Narrow trails of damage left by massive energetic charged particles in insulating solids were first discovered by Silk and Barnes (1959) within a flake of mica bombarded with fission fragments. The width of the linear damaged region was about 10 mμ, which annealed out and disappeared under prolonged observation under electron microscope. The usefulness of particle tracks has been extremely extended since the discovery that charged particle tracks can be

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enlarged to the micrometer range by means of proper chemical etching, where they are readily visible under the optical microscope (Price and Walker, 1962). Since then, the particle track technique has been used by a number of investigators of various fields, that is, geological and anthropological dating, microanalysis or mapping of fissionable elements or alpha-particle emitters, study of cosmic-ray nuclei using artificial solid state track detectors (SSTD) or extraterrestrial materials and so on.

Fossil tracks recorded in terrestrial samples have been almost excrusively produced by the spontaneous fission of uranium-238 (Price and Walker, 1963a). Fission track ages of natural crystals or glasses are readily calculated on the basis of both fossil track abundance and uranium content (Fleischer and Price, 1964; Fleischer et al., 1964). On the other hand, it is rather complicated in extraterrestrial materials, bacause there are such other possible sources of particle tracks as cosmic-ray or presently extinct fissionable superuranium elements.

In meteoritic menerals, particle tracks are generally caused by the following three main sources (Fleischer et al., 1967a): (1) spontaneous fission of uranium-238 and presently extinct isotopes, (2) very heavy nuclei in cosmic-ray primaries and (3) cosmic-ray incuced fission.

(1) is intimately related to the uranium content of the specimen at the present time. (2) depends upon cosmic-ray exposure age and the preterrestrial shielding, i.e., the burial depth of the sample. (3) is the function of cosmic-ray exposure age, preterrestrial depth and content of heavy elements. It is one of the main problems for the nuclear track studies on the meteorites how to distinguish the tracks of different origins.

Uranium concentrations can be measured by exposing the sample to a flux of thermal neutrons in a nuclear reactor and counting the resulting density of induced fission tracks of uranium-235 (Price and Walker, 1963b). If the fossil tracks are observable in the minerals with extremely low uramium contents, the cosmic-ray heavy primaries are the most possible source of those tracks because the fission events can be ignored. The tracks from cosmic-ray primaries are naturally common in adjacent minerals, because of almost the same preterrestrial depth and exposure history. When the exposure age are independently known, the contribution from the cosmic-ray induced fission can be estimated in many cases. Then, the spontaneous fission components in the natural tracks in the adjacent uranium-bearing minerals can be evaluated by the subtraction of these contributions. If the spontaneous fission track densities are less than those expected from ^{238}U during 4.6×10^9 yrs, the fission track age would be calculated in the same manner as the terrestrial samples. If not, the spontaneous fission of presently extinct nuclides must be taken into account.

In this paper, the fossil particle tracks observed in main mineral constituents, olivine and pyroxene, in seven Yamato-74 meteorites (Yamato-74013, -74014, -74037, -74080, -74094, -74362 and -74459) and Yamato-6902 (Yamato (b)) meteorite are discussed. Detailed discussion of the mineral assemblage and classification of the Yamato-74 meteorites are given in the previous paper (Yabuki et al., 1977) except for Yamato-74037 meteorite, which belongs to diogenite with the same structure as Yamato-6902 (Okada, 1975) and Yamato-74014 meteorites.

Experimental Method

Sample preparation

A few hundred milligram of each sample was crushed into less than a few tenth millimeter in size in the agate mortar, diluting with ethyl alcohol. Metals were then picked up with a hand magnet. Fine-sized powders were also eliminated by shaking and skimming in ethyl alcohol. Each sample was separated into two parts, i.e., one for the observations of fossil tracks and another for the measurements of uranium content by induced fission track method. When pure and comparatively coarse crystals were obtained such as bronzite from diogenites, the tracks were counted on a polished surface. These were mounted in epoxy resin, sanded to a smoothed surface with 8 and 3μ alumina and then polished carefully with 1 and 0.3μ alumina. In order to observe the effect of abration heating on tracks, a small chip of the Yamato-74014 meteorite with a fusion crust was also embedded in a epoxy resin, from which a polished section of about 0.1 mm thick was made.

Track etching

Ething of pyroxenes was carried out in boiling 60% NaOH solution (about 159°C) for 50 ~ 60 min in the same manner as reported by Lal et al. (1968).

Olivine was etched for 5 ~ 6 hrs by boiling "WN" etchant, which was prepared by the following prescription (Krishnaswami et al., 1971): 40g of the disodium salt of EDTA (ethylenediamine tetra acetic acid) is added into 100 ml of distilled water with 1g of oxalic acid and 1 ml of orthophosphoric acid (85%), then the pH of the solution is adjusted to be 8.0 ± 0.3 by adding NaOH pellets. Boiling point of WN etchant is 105°C.

Reflux arrangement after Lal et al. (1968) was used for etching of both olivine and pyroxene. Etching apparatus used in this work is schematically shown in Fig. 1.

Charged-particle tracks acrossing the etched surface were counted under the optical microscope of 1000 – 1500 magnification by using a reticulated

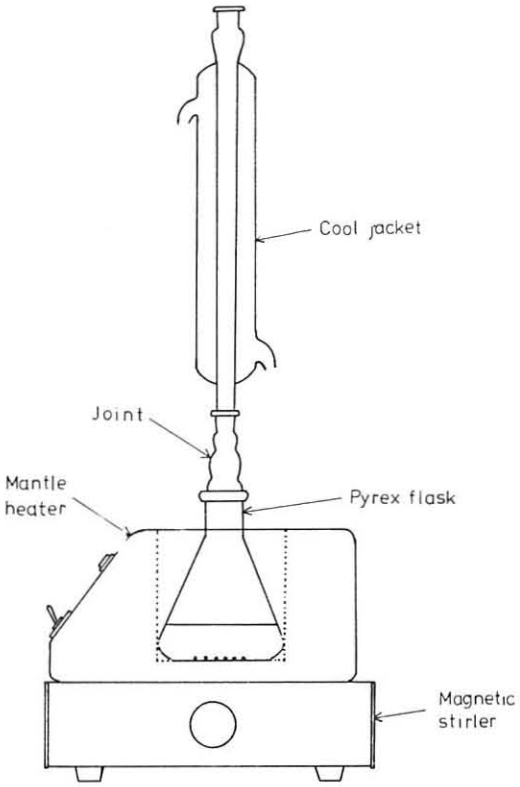

Fig. 1 Etching apparatus.

template.

Uranium Content

The uranium content was determined by exposing the sample to a flux of neutrons and counting the induced fission tracks of uranium-235. Prior to neutron irradiation, samples were heated in air at 700°C for 2 hrs to remove all fossil tracks recorded in it. The samples were placed in aluminum foils and sent to reactors. Thermal neutron irradiation were carried out on one-half of each sample in JRR-2 reactor of Japan Atomic Energy Research Institute and on another-half in TRIGA Mark-II reactor of Rikkyo University. In the latter case, neutron flux was measured by induced fission tracks recorded in polycarbonate detectors placed in contact with epoxy resin in which 3.0 ppb of uranium was mixed in advance in the form of ether solution of uranyl nitrate. Polycarbonate detectors were etched by 6N NaOH for 40 min at 55°C. In the former cace, gold foil monitors were used. Thermal neutron doses in the two irradiations were 5.4×10^{17} neutrons/cm^2 and 1.3×10^{17} neutrons/cm^2, respectively. Samples were then etched and track densities were measured in olivine and pyroxene grains. The weight fraction, C, of uranium in the material is given by

the following equation (Price and Walker, 1963b).

$$C = kW/(I_{235}\ A\ \sigma_F Rdf)\ (\rho_i/\Phi)$$

where, k is a geometric factor $\cong 1$ or 1/2 when fission tracks are counted on internal or external surface after irradiation, W is the molecular weight of uranium, I_{235} is the isotopic abundance of ^{235}U, A is Avogadro's number, σ_F is the cross section for thermal neutron-induced fission of ^{235}U, R is the range of the fission fragments, d is the density of the material, f is the efficiency factor of etching and counting of the tracks, ρ_i is the induced track density, and Φ is the integrated neutron flux. Errors can be reduced by comparing the measured track densities with those of a standard material simultaneously irradiated (Fisher, 1970):

$$C = C_s(\rho_i/\rho_{is})\ (R_s D_s/Rd)$$

where the subscript s refers to measurements in the standard. f was canceled out because $f_s/f \cong 1$.

Experimental Results

Yamato-74013, Yamato-74037 and Yamato-6902 meteorites

These meteorites are diogenite and almost entirely composed of equigranular orthopyroxene grains. Many other fragments of this kind were also found in the same area. Assuming that these diogenites were originated from an identical parent body, the same solidification and exposure ages but different shielding against cosmic radiations are expected for each fragments.

The natural track densities in orthopyroxene grains in Yamato-74013, Yamato-74037 and Yamato-6902 meteorites are $(4.0 \pm 0.7) \times 10^5$, (7.1 ± 1.7)

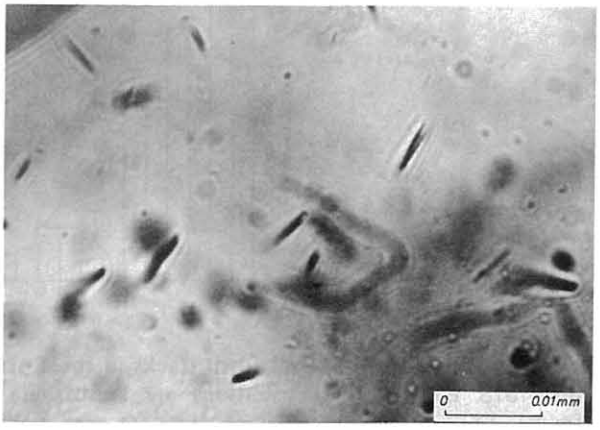

Fig. 2 Fossil tracks in orthopyroxene from Yamato-74013 meteorite. Long dimention of photograph = 0.06 mm.

$\times 10^4$ and $(9.4 \pm 3.5) \times 10^4$ tracks/cm^2, respectively. On the other hand, uranium contents measured for Yamato-74013 and -74037 were 0.02 and 0.03 ppb. Although the uranium contents of the Yamato-6902 bronzite were not measured, almost the same result would be expected. The spontaneous fission of ^{244}Pu may have contributed significantly to the natural tracks at least in Yamato-74037 and -6902, because the ^{244}Pu tracks can be about 2×10^4 and 4×10^4/cm^2 in Yamato-74013 and -74037, if the track retention had started 4.6×10^9 yrs ago. However, it is assumed for the present that all of the natural tracks observed in these diogenites were caused by cosmic-ray primaries, since the actual track retention age cannot be evaluated in the present work, in which the tracks in only one mineral were counted.

To investigate whether observed tracks are actually cosmic-ray origin or not, following parameters were examined for tracks in orthopyroxene grains in the Yamato-74013 diogenite.

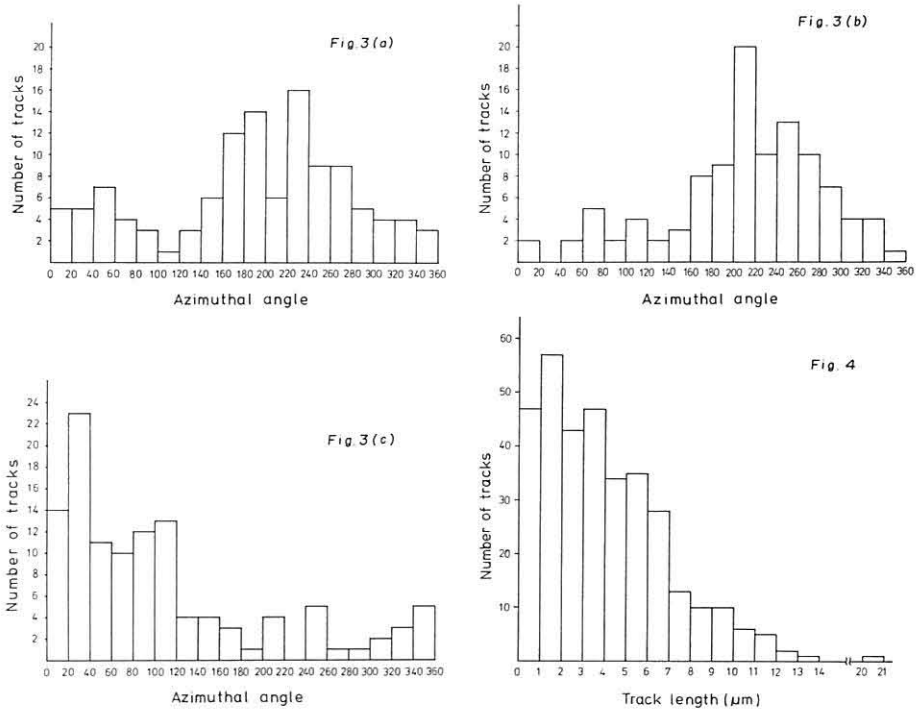

Fig. 3 (a), (b) and (c). Angular distribution of fossil tracks in three orthoproxene grains from Yamato-74013 meteorite. Distributions are anisotropic as expected for cosmic-ray tracks. The origins of azimuthal angle for each grains were arbitrarily determined.

Fig. 4 Track length distribution of Yamato-44013 bronzite. It resembles a pure cosmic-ray track distribution from the Clovis meteorite (Fleischer et al., 1967).

Angular distribution

Azimuth angle distribution of natural tracks in three bronzite grains are given in Fig. 3(a), (b) and (c), in which origins of azimuthal angles defined arbitrarily for each sample. As seen in the figures, tracks in each grain show apparent anisotropic distribution with one or two peaks. This feature is characteristic of the tracks of cosmic-ray primaries (Fleischer et al., 1967b).

Length distribution

Fig. 4 shows the length distribution of natural tracks intersecting the surface in the same bronzite grains in Yamato-74013 meteorite. This distribution shows a characteristic rise at shorter length and resembles a pure cosmic-ray distribution observed in the Clovis meteorite (Fleischer et al., 1967b). Tracks of fission origin usually show a flat length distribution.

Both angular and length distribution support that the natural tracks in orthopyroxene grains are mostly cosmogenic. It seems then most probable that the difference of over factor five between the natural track densities in the samples from these diogenites in due to the difference of the shielding against cosmic-ray flux.

Assuming the constancy of cosmic-ray flux, preterrestrial depth of each sample within a preatmospheric body can be estimated on the basis of the calculated curves of track production rate vs. depth by Fleischer et al. (1967a). Approximately 10 cm, 17 cm and 15 cm of depth are obtained for the Yamato-74013, -74037 and -6902 meteorites, on the assumption that the cosmic-ray exposure age measured on the Yamato-6902, 31 my (Shima et al., 1973), are also applicable to other diogenites.

Yamato-74014 meteorite

This meteorite is an ordinary chondrite of H5 or 6 group, and the studied sample had a fusion crust on one side. The natural track densities measured in olivine and orthopyroxene grains show sharp peaks at different densities (Fig. 5), and $(2.6 \pm 0.6) \times 10^6$ and $(4.4 \pm 0.7) \times 10^6$ tracks/cm^2 on the average. On the other hand, uranium content was determined to be (2.9 ± 0.6) ppb in orthopyroxene, but was insufficient to detect in olivine grains (< 0.1 ppb). Therefore, it seems most likely that natural tracks in olivine are mostly origniated from cosmic very heavy nuclei and those in orthopyroxene are the sum of the tracks from spontaneous fission, cosmic-ray primaries and cosmic-ray induced fission.

Assuming that the studied sample was located at less than 1 cm from the preatmospheric surface, the corresponding track production rate by cosmic-ray very heavy primaries is $0.5 \sim 1 \times 10^6$ tracks/cm^2/my. (Fleischer et al., 1967b).

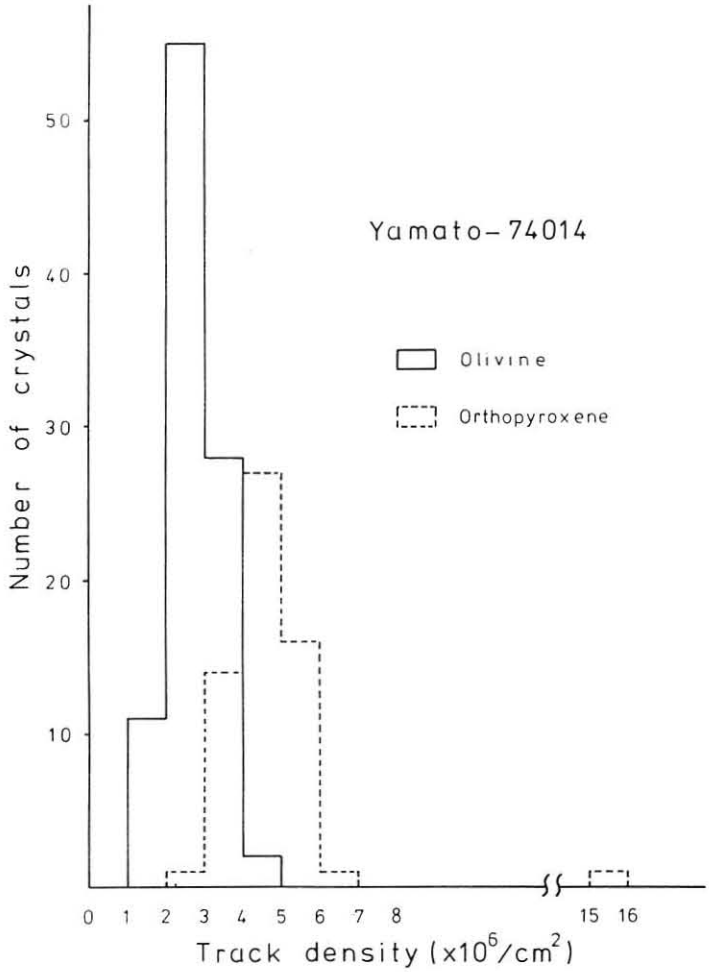

Fig. 5 Track density distribution in olivine and bronzite crystals from Yamato-74014 meteorite. The distribution of bronzite has a peak at higher density than that of olivine.

Under this chondition, it would required 3 ~ 5 my to accumulate the cosmic-ray tracks observed in olivine grains. Though it may be accidental, this time interval is in good agreement with the cosmic-ray exposure age determined for Yamato-6904 (Yamato(d)) meteorite (Shima et al., 1973), which belongs also to H-group chondrite with recrystallized texture (Okada, 1975). If this exposure age and shallow depth are true, the effect of cosmic-ray incuced fission on the total track density is quite small. Namely, the difference between the track density of orthopyroxene and olivine, about 1.8×10^6 tracks/cm^2, is considered to be derived from spontaneous fission. However, uranium content of (2.9 ± 0.6) ppb in orthopyroxene will cause fission tracks of only (1.8 ± 0.4)

$\times 10^4$ tracks/cm^2 during 4.6×10^9 yrs. Actual contribution of ^{238}U is still slightly less than this value, because orthopyroxene must have retained tracks in a period somewhat less than 4.6×10^9 yrs. The excess fission tracks must be due to the spontaneous fission of extinct radionuclides, such as ^{244}Pu. ^{244}Pu/^{238}U ratio at the beginning of track retention can be calculated by the ratio of track densities due to ^{244}Pu to ^{238}U, on the assumption that all of the residual fission tracks after subtraction of those expected from ^{238}U in 4.6×10^9 yrs are contributed from ^{244}Pu. For bronzite grains in this meteorite, the ratio is estimated to the 0.0084, corresponding to ΔT of 8×10^7 yrs.

Yamato-74080 meteorite

This meteorite is an equilibrated chondrite of L-group with strongly shocked feature and most of olivine and pyroxene grains are highly fractured. The studied sample was a chip of 5 x 5 x 2 mm in size and had a black fusion crust on its one side.

Both olivine and pyroxene record a number of charged particle tracks. The fossil track density in orthopyroxene was $(1.4 \pm 0.3) \times 10^7$ tracks/cm^2, and that in olivine was also in the same order, but could not be counted with sufficient accuracy because of the samll grain size. The uranium contents in olivine and orthopyroxene from this chondrite were < 0.1 ppb and (1.0 ± 0.3) ppb, respectively. According to this measured uranium concentration, the expected track densities from the spontaneous fission of ^{238}U and ^{244}Pu during 4.6×10^9 yrs are about 6×10^3 and 1×10^5 tracks/cm^2 in orthopyroxene grains. In addition to this, it is also possible that reheating by several heavy impacts in late stage, which is expected by the texture of this chondrite, have completely or partly erased the tracks stored until the event. Thus, the high densities of natural tracks in both minerals cannot be explained by the spontaneous fission at all. The most possible source of the fossil particle tracks is considered to be cosmic-ray heavy primaries, because the track density in olivine grains with very low uranium content is also high. Assuming that all of observed tracks in orthopyroxene were originated from cosmic very heavy nuclei and the present sample was near the surface of the preatmospheric mass, the cosmic-ray exposure age of this chondrite can be estimated approximately to be 14 my, according to the calculated curve of the track production rate vs. depth by Fleischer et al. (1967a). This value of 14 my falls within the range of the cosmic-ray exposure ages of usual chondrites, between $1 \sim 25$ my.

Yamato-74094 and -74459 meteorites

These meteorites are H-group chondrites with well recrystallized texture and are highly oxidized in most part by atmospheric weathering. The studied

samples for both meteorites were about 9 x 7 x 2 mm and 5 x 5 x 4 mm in size without fusion crust. Measurements of track densities were carried out on a polished surface of coarsely crushed samples. The measured track densities and uranium contents of olivine and pyroxene grains from these chondrites are given in Table 1. The natural tracks in olivine from Yamato-74459 meteorite are considered to be mainly originated from cosmic-ray heavy primaries, because the summation of the spontaneous fission of ^{238}U and ^{244}Pu and cosmic-ray induced fission tracks would be less than 6×10^4 tracks/cm^2, even if the storage during 4.6×10^9 yrs is assumed. According to the similar arguments, the present sample of the Yamato-74094 meteorite must have been well shielded against cosmic-ray primaries.

Assuming that the cosmic-ray exposure ages of these chondrites are almost equal to that determined for Yamato-6904 (Yamato (d)) H-group chondrite, 4.3 my (Shima et al., 1973), the depth from the preatmospheric surface to the test crystals are estimated to be > 28 cm and 2 cm for Yamato-74094 and -74459 meteorite, respectively.

In both chondrites, bronzite grains are recording much higher fission track components than those expected from the spontaneous fission of ^{238}U in 4.6×10^9 yrs.

The contributions from neutron induced fission events can be ignored in comparing with the total fission tracks in Yamato-74459. In Yamato-74094, however, the natural tracks in bronzite can be explained by thermal neutron induced fission of ^{235}U and the spontaneous fission of ^{238}U without the aid of ^{244}Pu, if the exposure age was as long as 4.6×10^9 yrs. Though the possibility of this extremely long exposure age of this chondrite cannot be thoroughly ruled out, it seems more probable that these excesses are also due to the spontaneous fission of presently extinct nuclide, ^{244}Pu. Then, the ratio of $^{244}Pu/^{238}U$ at the beginning of track retention of bronzite in Yamato-

Table 1 Results on the chondrites

Meteorite		Natural track density (cm^{-2})			Orthopyroxene		
Name	Type	Orthopyroxene	Olivine	Uranium content (ppb)	pU† (cm^{-2})	^{244}pu / ^{238}U	ΔT (yrs)
Yamato							
-74014	H5	$(4.4 \pm 0.7) \times 10^6$	$(2.6 \pm 0.6) \times 10^6$	2.9 ± 0.6	1.8×10^4	0.0084	8×10^7
-74080	L6	$(1.4 \pm 0.3) \times 10^7$	$\sim 10^7$	1.0 ± 0.3	6.3×10^3	n.d.	n.d.
-74094	H6	$(4.6 \pm 1.9) \times 10^4$	$< 10^3$	0.4 ± 0.1	2.5×10^3	0.0014	3×10^8
-74362	L6	$(1.2 \pm 0.2) \times 10^6$	$(3.4 \pm 1.8) \times 10^5$	0.9 ± 0.2	5.7×10^3	0.013	3×10^7
-74459	H6	$(2.3 \pm 0.4) \times 10^6$	$(9.0 \pm 1.6) \times 10^5$	1.5 ± 0.4	9.5×10^3	0.011	5×10^7

† Maximum contribution of the assumption that tracks were stored for 4.6×10^9 yrs.
†† At the onset of track retention.

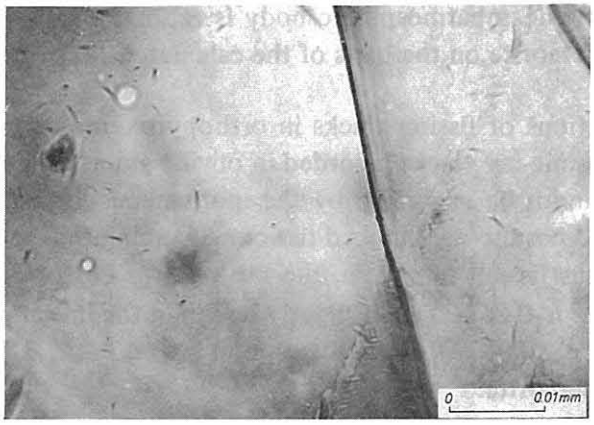

Fig. 6 Cosmic-ray tracks in olivine grains near the fusion crust. Yamato-74014 meteorite. Long dimention of photograph = 0.06 mm.

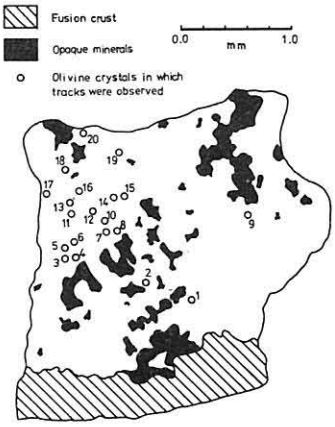

Fig. 7 The view of the positions of the olivine grains in which cosmic-ray tracks were observed. Yamato-74014 meteorite.

74094 and -74459 are 0.0014 and 0.011, which are corresponding to the ΔT's of 3×10^8 and 5×10^7 yrs, respectively.

Yamato-74362 meteorite

Yamato-74362 meteorite is L-group chondrites in equilibrated state. The studied sample was about 200 mg and irregular in shape without a fusion crust. The fossil track density and uranium content measured in olivine and orthopyroxene from this chondrite are listed in Table 1. Also in these samples, the observed tracks in olivine grains are considered to be originated mostly from cosmic-ray heavy primaries, although their scattering from grain to grain is rather large. If the cosmic-ray exposure age of this chondrite is lying between 1 ~ 25 my as in the case of stony meteorites in general, the depth of the

present sample in the preatmospheric body is estimated to be 2 ~ 11 cm for Yamato-74362 meteorite on the basis of the calculated curve given by Fleischer et al. (1967a).

The contributions of fission tracks in orthopyroxene are evaluated by the subtraction of cosmic-ray tracks recorded in olivine grains. The obtained fission track densities cannot be explained by the spontaneous fission of ^{238}U during 4.6×10^9 yrs and cosmic-ray induced fission. Assuming that the excess are due to the spontaneous fission of ^{244}Pu, the ratio of ^{244}Pu to ^{238}U at the onset of track retention is 0.013. This is slightly less than the initial ratio in the solar system (0.0154 ± 0.0014) and correspond to ΔT of 3×10^7 yrs for Yamato-74362 meteorite.

Effect of ablation heating

As meteorites enter the atmosphere of the earth at very high velocity, probably 11 ~ 30 km/sec, the surface is rapidly heated to the melting point of various constituents. But, major phase of stone meteorites, i.e., silicate minerals, are very poor conductor of heat and sharp gradient of temperature

Table 2 Track densities in the olivine crystals

No. of olivine crystals †	Distance from the surface (mm)	Track density ($\times 10^6/cm^2$)
1	0.94	0.1
2	1.2	1.7
3	1.5	2.4
4	1.5	2.0
5	1.6	2.2
6	1.7	2.5
7	1.7	2.0
8	1.7	2.8
9	1.7	2.5
10	1.8	2.1
11	1.9	2.6
12	1.9	2.0
13	2.0	2.0
14	2.0	2.2
15	2.0	2.1
16	2.1	2.4
17	2.1	2.1
18	2.3	2.1
19	2.4	2.2
20	2.6	2.5

† See Fig. 2-15.

must arise between the molten surface and the cold core. For the purpose of estimating the effect of the ablation heating, particle track observation is a useful method. Olivine grains in Yamato-74014 meteorite record cosmic-ray tracks of the order of $10^6/cm^2$, as noticed above. A small chip of this meteorite with a fusion crust was embedded in epoxy resin and a polished section was prepared. Olivine was etched by boiling WN etchant for 5 hrs and the fossil tracks were counted by scanning the etched sample. The photomicrograph of the obtained cosmic-ray tracks is given in Fig. 6. The fusion crust is 0.3 ~ 0.5 mm thick. Tracks are generally short but the longest one reaches about 0.6 mm in length, which are probably caused by VVH nuclei in cosmic-rays. Fig. 7 and Table 2 show the position of investigated olivine grains and track density in each of them. As is obvious in Table 2, the track densities are nearly costant in the grains at a distance more than about 1.2 mm apart from the surface, namely, the temperature was not enough high to erase cosmic-ray tracks registered in olivine. Whereas, the olivine crystals closer to the fusion crust have no tracks.

The effect of temperature on cosmic-ray tracks in olivine grains in this meteorite was evaluated by the following annealing experiment. A series of powdered samples in a small amount were placed in tiny platinum boats and were heated in air on the conditions of different time-temperature combination. Later, olivine grains were etched and the thermal alterations of tracks were observed. The results were plotted in a relationship between logarithm of

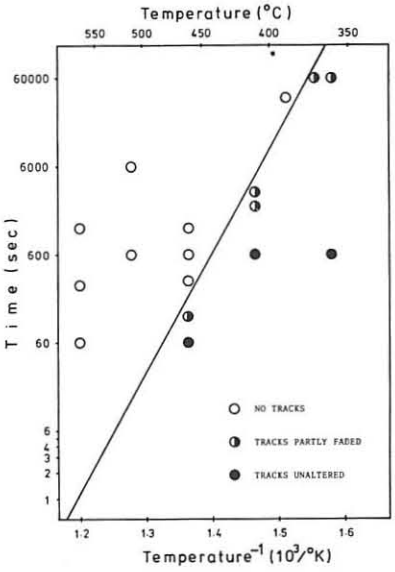

Fig. 8 Arrhenius plot of the annealing results of the cosmic-ray tracks in olivine grains from Yamato-74014 meteorite.

annealing time and T^{-1}, where T is the absolute temperature (Fig. 8). As is usually seen (Fleischer et al., 1965c), a single straight line can be drawn to separate the region in which apparently all tracks were faded from the region in which tracks were unaltered or partly faded. Cosmic-ray tracks in the present work, however, were annealed out at temperature of about 100°C lower than the fading temperature of the fission tracks in olivine crystals from the Red Sea (Fleischer et al., 1965). The difference may be due to the fact that fission fragments ($Z \geq 40$) produce more heavy radiation damage than the cosmic-ray nuclei (usually $Z = 20 \sim 30$) do (Kapuscik et al., 1966; Perelygin et al., 1969; Maurette, 1970). Carver and Anders (1976a, b) successfully used this difference of the stability as selective annealing method to estimate fission track ages in the presence of cosmic-ray tracks.

Extraporating the line separating fading and no-fading region to shorter duration, we can estimate the temperature at which cosmic-ray tracks were annealed out during the flight in the earth's atmosphere. Assuming that the heating continues for $3 \sim 5$ sec, tracks must disappear at the temperature higher than about $530 \sim 520$°C, although the temperature changed momentarily as discussed later.

Discussion

In this work, particle tracks were observed on a polished surface or a cleaved surface of crushed samples into less than a few tenth mm in size, and different crystals were used for counting the fossil and induced tracks. Although there are some advantages in such treatments, e.g., only a small amount of sample is necessary, any shape of samples can be used and etching is easy, several methodological limits on the accuracy of measurements described as follows cannot be avoided. (1) The variations in uranium content in each grain are directly reflected on the statistical errors of the averaged values. (2) The identification of the effect from adjacent track-rich grains is difficult. (3) In the case of low track densities, the averages tend to be higher than real values since the grains without tracks are ignored. (4) Cleaved surfaces are not always flat.

Practically, significant scattering was not observed in the natural track densities in most samples, and the influence of adjacent crystals seemed to be slight, juding from the fact that the grains with abnormal track densities were very small in number. The obtained uranium contents may be a little higher than real averages since the fission tracks induced by reactor neutrons were rather low to observe in small samples.

Diogenites

Yamato-74013, -74037 and -6902 meteorites are diogenites with granoblastic texture and composed almost entirely of equigranualr grains of orthopyroxene. Many other fragments with almost the same appearance were also collected in the same area. However, diogenite is comparatively rare type among meteorites and especially the granoblastic texture is thought to be rather unique in contrast with brecciated structure of usual diogenites (Mason, 1962). It seems to be very probable that each of these diogenites were once located at the different positions in the identical parent body. The distance from the surface of the preatmospheric mass were studied by means of cosmic-ray particle tracks. The estimated depth for the sample of the Yamato-6902 meteorite were about 15 cm on the basis of the exposure age of 31 my given by rare gas measurement (Shima et al., 1973). Since the original size of the Yamato-6902 meteorite is 7 cm in diameter, the obtained result means that this meteorite was located at the depth of more than 8 cm at least from the surface of a larger object before the entrance into the earth's atmosphere. On the other hand, the exposure age of Yamato-74013 and -74037 has not yet been determined. If the exposure age of Yamato-6902 meteorite is applicable to these diogenites, the distance below the preatmospheric surface to the measured crystals are estimated to be 10 cm and 17 cm for Yamato-74013 and -74037 diogenites. Comparing with the size of these meteorites, i.e., 14 x 10 cm and 8.6 x 8.2 cm, each, it seems possible that at least Yamato-74037 meteorite was apart more than 9 cm from the preatmospheric surface.

Although the locations of the samples studied in the present work within each meteorite were unfortunately unknown, it was suggested by the cosmic-ray track studies that these diogenites had once constructed a part of a larger mass. If the crystals from several points of these meteorites are available, the spacial relation of each fragment within the preatmospheric body might also be determined.

Chondrites

In chondrites the particle tracks were counted in olivine and orthopyroxene grains. The fossil track densities were usually higher in pyroxene than in olivine except in Yamato-74080 meteorite, in which both minerals record high track densities of the same order. Judging from the fact that the studied sample of Yamato-74080 meteorite had a fusion crust on its one side and that uranium contents were not exceptionally high, these particle tracks were mostly originated from cosmic-ray heavy primaries. Provided that the sample of Yamato-74080 meteorite was located near the surface of the preatmospheric mass, the cosmic-ray exposure age of ~ 14 my was estimated.

Since this chondrite shows the several evidences of severe stress, the information on the time of the shock events may be obtained, if the samples from inner part of this chondrite were available for the particle-track studies.

Orthopyroxene in the studied chondrites containing uranium of 0.4 ~ 3 ppb. In contrast, the uranium contents of olivine were undetectablly low in all of the samples. Judging from this general tendency, the difference of the natural track densities in these minerals is considered to be due to the difference of the concentration of fissioning isotopes. Namely, the fossil tracks in olivine were originated mainly from cosmic-ray primaries and those in pyroxene came also from other sources, i.e., the spontaneous fission of ^{238}U and presently extinct nuclides, such as ^{244}Pu, and the cosmic-ray induced fission of ^{235}U, ^{238}U and ^{232}Th. The fission tracks in pyroxene, obtained by subtracting cosmic-ray contribution from total tracks were always much higher than those expected from the spontaneous fission of ^{238}U during 4.6×10^9 yrs.

The contributions from cosmic-ray induced fission could be ignored in most cases. Only in Yamato-74094 meteorite, the neutron induced fission can be a major phase, if the cosmic-ray exposure age is in the order of 10^9 yrs. The possibility that some events inducing cosmic-ray exposure took place on this chondrite at this stage cannot be ruled out, although this chondrite does not show the evident shocked features. On the assumption that these excesses are entirely due to the spontaneous fission of ^{244}Pu, the ratio of ^{244}Pu to ^{238}U at the onset of the track retention and the time interval between then and the end of nucleosynthesis, ΔT, were calculated. ΔT's of the studied pyroxene crystals were 3×10^8 yrs for Yamato-74094 and ranging $3 \sim 8 \times 10^7$ yrs for other four chondrites. These are corresponding to the $^{244}Pu/^{238}U$ ratio of 0.0014 and 0.013 ~ 0.008, when the initial ratio in the solar system of 0.0154 (Podosek, 1972) is adopted. The apparent relationships between ΔT and chemical or petrologic types of each chondrite were not found in the present results. ΔT is considered to be almost equivalent to the I-Xe age, that is the time interval between the end of nucleosynthesis and the cooling down of meteoritic minerals to the temperature under which ^{129}Xe can be retained. The obtained ΔT values in this work are approximately within the range of I-Xe ages determined for a number of meteorites (Reynolds, 1963). The varieties in the ΔT's may be resulted from the geochemical fractionation of ^{244}Pu and ^{238}U. The $^{244}Pu/^{238}U$ ratio of Yamato-74094 is possibly too low to be referred to the slow cooling rate. Complete or partial track erasure by intense reheating by shock in early stage (Carver and Anders, 1976a) may be a likely explanation, although this chondrite does not show so strongly deformed feature.

Ablation heating

The effect of aerodynamic heating during flight through the earth's atmosphere was investigated by means of charged-particle tracks. No cosmic-ray tracks were survived in olivine grains at the depth of less than 0.9 mm from the fused surface of meteorite, and the track densities were almost constant in the crystals, more than 1.2 mm in depth. On the basis of the high-temperature annealing experiments of cosmic-ray tracks in olivine, the temperature of the no-track region reaches higher than 530 ~ 520°C, if the heating continues for 3 ~ 5 sec.

The approximate temperature distribution in outer region of chondrite during the flight through the earth's atmosphere can be obtained by the following considerations.

Since ablation heating continues for only a short time and the size of meteorites is generally much greater than heated zone, the thermal conduction in meteorites can be treated approximately as the linear flow of heat in the semi-infinite solid. In order to simplify the equation, ablation of materials and moving effect are ignored. Then the temperature, w, at depth, x, in the solid at time, t, can be expressed by the following equation:

$$\frac{\partial w}{\partial t} = \kappa \frac{\partial^2 w}{\partial x^2} \qquad (0 < x < \infty) \qquad (1)$$

where, κ is the thermal diffusivity of the solid, $\kappa = k/c \cdot \rho$ (k = the thermal conductivity, c = specific heat, ρ = dencity). This differential equation is solved under following initial conditions:

$x = 0$	:	$w = T_1$
$x = \infty$	:	$w =$ finite
$t = 0$	:	$w = T_o$

That is, the solid ($x > 0$) is initially at temperature T_o and the surface of the solid ($x = 0$) is maintained at temperature T_1 after $t > 0$.

The solution of eq. (1) is given by:

$$w = T_1 \left\{ 1 - \mathrm{erf}\left(\frac{x}{2\sqrt{\kappa t}}\right) + T_o \mathrm{erf}\left(\frac{x}{2\sqrt{\kappa t}}\right) \right\} \qquad (2)$$

where

$$\mathrm{erf}(x) = \frac{2}{\pi} \int_o^x e^{-\beta^2} d\beta$$

Fig. 9(a) and (b) show the calculated curves of T/T_1 vs. t and T/T_1 vs. x for the case of $T_o = 0°C$. The right ordinate in the figure expresses the temperature of

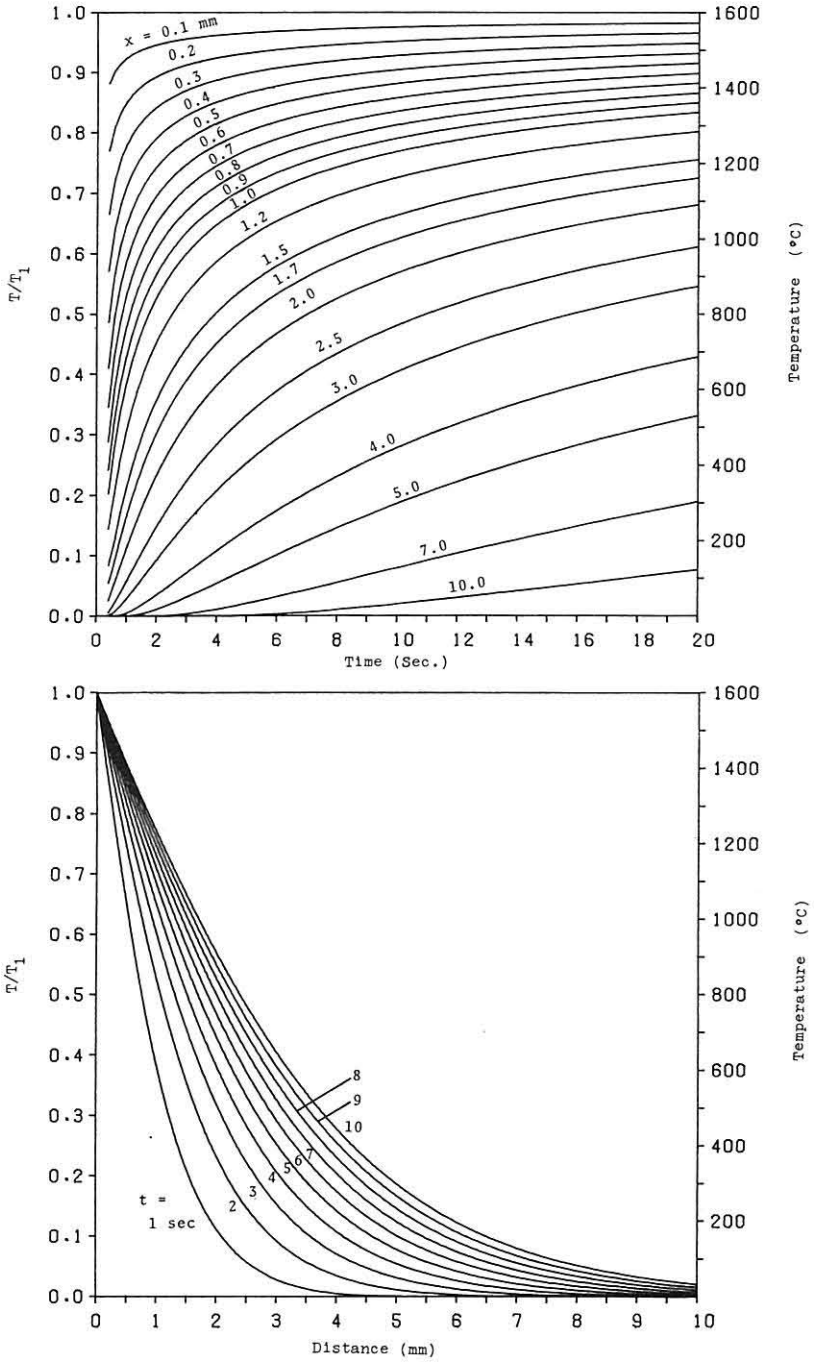

Fig. 9 (a) and (b) Calculated distributions of the temperature in outer region of stony meteorites during aerodynamic heating as a function of (a) time after heating started and (b) distance from the surface. Zero initial temperature and no mass loss were assumed.

the solid when the surface temperature T_1 is assumed to be 1600°C, which is over the melting points, of kamacite, pyroxene and troilite but slightly under that of olivine. Although the numerical calculations were carried out until t = 20 sec, aerodynamic heating continues in general case for less than 5 sec. According to the annealing experiment, on the other hand, the cosmic-ray tracks in olivine are faded out by 1 sec heating at more than 550°C. This condition corresponds to $\leq$ 1.7 mm from the surface when the heating continues for 3 sec (see Fig. 9). Since cosmic-ray tracks are actually observable in olivine grains at $\leq$ 0.9 mm from the furface of the meteorite, 1 mm of ablation may be roughly suggested by the present simplified estimation. At the surface of this meteorite, i.e., about 0.8 mm in depth from the preatmospheric surface, the temperature reaches about the melting point of troilite (1188°C) after the heating for 3 sec. This estimation agrees with the observations of the fusion crust of this chondrite.

Acknowledgement

The author wishes to express his sincere gratitude to Prof. K. Yagi of Hokkaido University for his continuing guidance and encouragement throughout the present investigation and for his critical reading of the manuscript, and to Dr. M. Shima of the Institute of Physical and Chemical Research, for his continuous support and encouragement in the present study. The author also would like to express his appreciation to Dr. K. Onuma, Dr. Y. Hariya and Dr. K. Togari of Hokkaido University, for their helpful advice and encouragement. The meteorites studied here were provided through the coutesy of Prof. T. Nagata, Director of the National Institute of Polar Research. Those meteorites are a part of the Yamato-74 meteorites, which were collected through the energetic search by Dr. K. Yanai and other members of the 15th Japanese Antarctic Research Expedition. The auther is especially indebted to Dr. A. Okada, Mrs. S. Yabuki and Dr. K. Yoshikawa of the Institute of Physical and Chemical Research for frequent, stimulating, and helpful discussions throughout the present work. The neutron irradiation of the samples were carried out in JRR-2 reactor of Japan Atomic Energy Research Institute and in TRIGA Mark-II reactor of Rikkyo University. Use of Computation Center of the Institute of Physical and Chemical Research and Hokkaido University Computing Center is appreciated. For all these individuals, the author wishes to express his hearty thanks.

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(Received on Oct. 17, 1977)