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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LUNAR SAMPLE ANALYSIS PROGRAM

RADIATION EFFECTS

Final Report Proposal SC 33-045-(028)
Period: August 31, 1968 -- July 31, 1969

By

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11 September 1969

Prepared Under Contract NAS 9-7898

By

Physical Studies Branch
General Physics Laboratory
Research and Development Center
General Electric Company
Schenectady, New York

For

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ABSTRACT

This report summarizes the work under contract NAS 9-7898 directed at preparation for examination of lunar samples for stored particle tracks of whatever types may be present, whether from internal or external origin. The particle track work reported here falls into six categories: 1) examination and fission track dating of terrestrial impact produced materials; 2) examination and identification of tracks in extraterrestrial materials; 3) improvement in techniques for identification of individual particles in minerals; 4) a search for heretofore unidentified natural tracks; 5) accelerator simulation of cosmic ray effects in likely lunar mineral types, and 6) study of the effects of heating and of shock on tracks in minerals. The completed portion of this work is described in seven papers which are included as appendices to this report. Other work, not yet prepared for publication, is described in brief form.

DESCRIPTORS

GENERAL:

Lunar Material

Radiation Effects

Dating

Charged Particle Tracks

Cosmic Rays

Meteorites

Tektites

Glasses

SPECIFIC:

Impact Crater Glasses, Ages

Schenectady Meteorite

Particle Identification

Particle Track Techniques

Fission Tracks

Track Fading, Thermal

Superheavy Nuclides

Shock Effects

Extinct Radioactive Nuclides

Accelerator Simulation of Lunar Environment

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SUMMARY

This report describes the series of particle track studies made in preparation for analysis of lunar samples. In general, the purpose was to acquire what special techniques and knowledge are needed to extract the maximum of useful information from stored radiation tracks in lunar material. Consequently, studies have been made on materials in which effects and environments expected on the moon have been produced or simulated.

INTRODUCTION

As indicated in the summary, the objective of the work to be described here was to enhance the quantity and variety of useful information to be extracted from lunar material. Toward this end a series of experiments have been done which allow us to use better the particle tracks that we know will exist in lunar material (U^{238} fission tracks, cosmic ray tracks). We have exposed particle tracks to some of the unique conditions expected on the moon (intense shock and heating). We have found and examined material which has undergone some of the lunar-like conditions (meteorites, tektites, impact glass). We have sought unusual new natural tracks which might be encountered in lunar rock (fission tracks of now extinct superheavy nuclides).

Since an over-all statement of the perspectives, accomplishments, related work, and significance of our work is best presented part-by-part, we now proceed to discuss the work under appropriate subtopics.

SPECIFIC STUDIES

1. DATING OF TERRESTRIAL IMPACT MATERIALS

Impact-produced glass is expected to be encountered in abundance on the lunar surface because of the many crater-producing encounters between the moon and smaller objects in the solar system. We therefore examined a number of terrestrial impact glasses--Clearwater Lakes, Manicouagan, Darwin Glass, and Macedon Glass. The results are described in Appendices I and II.

The Clearwater Lakes and Manicouagan results lead to new emphasis on the possible importance of track annealing (thermal fading) for certain glass compositions and point out the usefulness of laboratory annealing experiments. These studies have led naturally to a simple, improved method for correcting heat-affected glasses to obtain solidification ages (described in subsection 6). The Darwin Glass and Macedon Glass work is summarized in subsection 2.

2. EXTRATERRESTRIAL MATERIALS

We include here studies on meteorites, which are known to be extra-terrestrial, and on tektites, whose origin is unknown but is thought by many scientists to have been by impacts upon the lunar surface (in which case tektites are melted and solidified droplets of lunar material). If the

hypothesis of lunar origin is correct, tektites are directly relevant to the moon; regardless, they are relevant to impact events, which in turn are important on the moon.

a. The work on Darwin Glass and Macedon Glass included dating of a number of tektites from the Far East. The ages for all three groups of glass samples were identical, implying that a single event was responsible for their origin. This result, however, does not allow a decision as to whether the origin was on the earth or the moon. The agreement between the ages of Darwin Glass and the Far Eastern tektites was independently, and apparently simultaneously, arrived at by Gentner, Storzer, and Wagner, also using fission track dating, and was reported at the same conference on tektites at Corning, New York, in April 1969.

b. Dating of samples from a chemically unique group of Australian tektites recognized by Chapman and Scheiber has revealed that they constitute samples of a distinct tektite group that fell $\sim$4 million years ago. This brings to five the number of different tektite falls that are known (Appendix III).

c. Studies on a newly fallen meteorite (the Schenectady Meteorite) have shown it to be a representative of a moderately rare subclass (H-4), to have U-He and K-Ar ages of $4.1 \cdot 10^9$ and $4.35 \cdot 10^9$ years, and to have sufficient cosmic-ray-induced radioactivities and cosmic ray tracks to allow its position in the preatmospheric body to be inferred. Appendix IV represents one of the very few cases where the cosmic ray tracks have been examined in samples whose locations are precisely known relative to

ones in which the cosmic-ray-produced activities and rare gas contents have been measured.

3. TECHNIQUES FOR PARTICLE IDENTIFICATION

One of the more useful functions of lunar material may turn out to be its ability to record tracks of the incident cosmic radiation. The chemical composition and energy spectrum of heavy cosmic ray particles are the prime bits of information which can be determined in principle. With this objective, we have developed a method for identifying individual particles by the use of glass or other inorganic solids such as are present on the lunar surface. The work (described in detail in Appendix V) makes use of a technique we developed first in plastics [P. B. Price, R. L. Fleischer, D. D. Peterson, C. O'Ceallaigh, D. O'Sullivan, and A. Thompson, Phys. Rev. 164 (1967) 1618] and in Appendix V have now shown to apply to inorganic solids. It is the only method of which we are aware that will identify individual cosmic ray particles in lunar glass samples.

4. SEARCH FOR PREVIOUSLY UNIDENTIFIED TYPES OF NATURAL PARTICLE TRACKS

If the recovered lunar rocks preserve tracks created near the time of condensation of matter to form the solar system, there is a chance that the existence of now extinct radioactive nuclides such as Pu^{244} can be detected. Recently the nuclear stability of super-heavy nuclei (of atomic number 110 or 114, or ~126) has been calculated. The encouragingly long half-lives predicted have spurred attempts at locating such nuclei or observing their effects. We have been searching for such tracks in several old, heavy-

element-rich natural minerals, with no positive results. We have written a paper (Appendix VI) which points out what distinguishing characteristics such tracks should have and notes that the natural fission track excess previously recognized by us in certain meteorites appears to be incompatible with fission of superheavy nuclei--but are compatible with our original identification as Pu^{244} fission.

5. ACCELERATOR SIMULATION OF LUNAR COSMIC RAY ENVIRONMENT

As we have noted elsewhere [R. L. Fleischer, P. B. Price, R. M. Walker, and M. Maurette, J. Geophys. Res. 72 (1967) 331] a number of the charged particle tracks which might be expected in extraterrestrial matter exposed to cosmic ray effects can be produced by a high-energy proton beam from existing accelerators. If the production rates of such tracks are known for a given material, its radiation exposure age can be measured.

For irradiation we selected a group of terrestrial samples that were thought to be similar in structure and/or composition to lunar samples. These materials--including feldspars, olivine, pyroxenes, basaltic glasses, and acidic glasses--have been given doses of 3 GeV protons that are equivalent to those encountered during several hundred million years of exposure to primary cosmic rays. The irradiation at the Princeton-Pennsylvania Accelerator has been completed and the examination of samples begun. Although it is premature to attempt to summarize results, it is already clear that glasses, being the most sensitive of the inorganic track detectors, are also the most sensitive to registration of the spallation recoil nuclei that

result from nuclear interactions with medium-weight nuclei within the solid. Whereas in olivine no tracks are seen after exposures equivalent to ~30 million years (previous work), the present exposures give track densities in glass that cannot be resolved in the optical microscope.

6. EFFECTS OF HEATING AND OF SHOCK ON CHARGED PARTICLE TRACKS

Shock effects on fission tracks have been studied using two experimental approaches: to obtain rocks which have experienced shock during underground nuclear explosions; and to expose single mineral grains of nicely defined geometry to specified shock pressures. The purpose of these experiments is to assess the shock pressures and/or temperatures which will lead to track fading or removal. Given such information, it should be possible to use fission track dating as a pressure measuring and mapping technique.

a. Shock Effects in Rocks (with N. Short). In order to obtain samples that had experienced a range of shock pressures, we obtained from the U. S. Geological Survey a set of granidiorite samples taken from an assortment of distances from the detonation point of the Hardhat nuclear explosion site in Nevada; these were supplemented by selected samples, supplied by N. Short, of the same rock that had been exposed to higher shock pressures at another nuclear detonation, the Sedan event. Useful minerals for dating (sphene and apatite) were separated from the rock samples and fission track dated.

From the Hardhat event, samples from six positions near the explosion and one control sample were examined. The four apatite samples closer than 30 meters to the detonation point gave ages significantly (25%) lower

than that of the control sample; four of six sphene samples gave altered ages (≈40% lower) relative to the sphene control, but showed no regular pattern with distance from the detonation. Among the samples from the Sedan event, tracks were present in an apatite sample described by N. Short as exposed to "> 250 kbar" on the basis of petrographic evidence; for a "> 300 kbar" sample none were present. For sphene identifiable crystals could be found only in the "> 350 kbar" sample, and no tracks were present.

Butkovich [J. Geophys. Res. 70 (1965) 885] has computed shock pressures around the Hardhat event. Using his results together with those just given we infer the following pressure thresholds for track partial and full erasure:

Table I

TRACK ERASURE THRESHOLDS IN ROCK SAMPLES

	Beginning of Erasure	Completion of Erasure
Apatite	~20 kbar	> 300 kbar
Sphene	< 10 kbar	> 350 kbar

b. Shock Effects in Minerals and Glasses (with T. Ahrens). Samples of known geometry are being given controlled shock pressure pulses and subsequent inspection for possible fission track erasure. Work has been completed on an ordinary silicate glass and is in progress on biotite, sphene, apatite, and tektite glass. Samples of all of the latter have been prepared and, where necessary, neutron-irradiated to ensure that an adequate density of fission tracks is initially present. Biotite samples have been shocked but not yet examined for tracks.

For the silicate glass, tracks were unaltered at 31 and 33 kbar, reduced by ≈75% in track density at 45 kbar, and totally erased at 57 and 67 kbar.

These results (subsections 6a and 6b) indicate the existence of a region of intermediate pressures which effects partial but incomplete track fading. If such effects are found in natural samples, they should be useful in specifying within a limited range the pressures to which the samples were exposed.

c. Thermal Track Fading and Age Determination. A not uncommon effect in certain natural glass samples is the finding of thermally lowered fission trackages. Storzer and Wagner [Earth Planet Sci. Let. 5 (1969) 463] have made a valuable contribution to our ability to detect such effects and determine the corrections needed to yield proper ages. What they have done is to observe that for a fixed etching treatment the diameters of the etched tracks decrease with increased heating time and temperature at the same time that the track density decreases, giving rise to a diameter-track density variation that may be described by a single empirical, monotonic function. Since this function allows one to compute the number of tracks that have been lost for a given measured decrease in track diameter relative to fresh, unheated tracks, a correction of the observed track density to what it would have been in the absence of fading can be made and gives self-consistent age results.

An awkwardness exists, however, in that the procedure requires that many separate annealing experiments be made for each glass composition used. Consequently, it is of interest to attempt to simplify the procedure.

Work now in progress indicates that the diameter-track density relation can be calculated directly using only one experimental quantity, the cone angle characterizing the particular glass and etchant.

The calculation is based on the simplifying assumption that the dominant effect of annealing is to decrease the intensity of damage along particle tracks, with the length left essentially unaltered. If this description is realistic, the diameter (D) and the track density (ρ) depend only on the cone angle (θ) for the tracks; and since both are calculable from the cone angle, the function $D(\rho)$ can be computed. The curves in Figure 1 indicate how the relation is affected by the cone angle.

We have tested this calculation experimentally using Cf^{252} fission fragments incident on glass microscope slides; the results are given in Figure 2. For the etching conditions used $\theta = 33^{\circ}$, from which the curve shown in Figure 2 was computed. Although the agreement is not perfect, it appears to be adequate to allow age corrections to be made with an accuracy comparable with those of the individual experimental points in Figure 2.

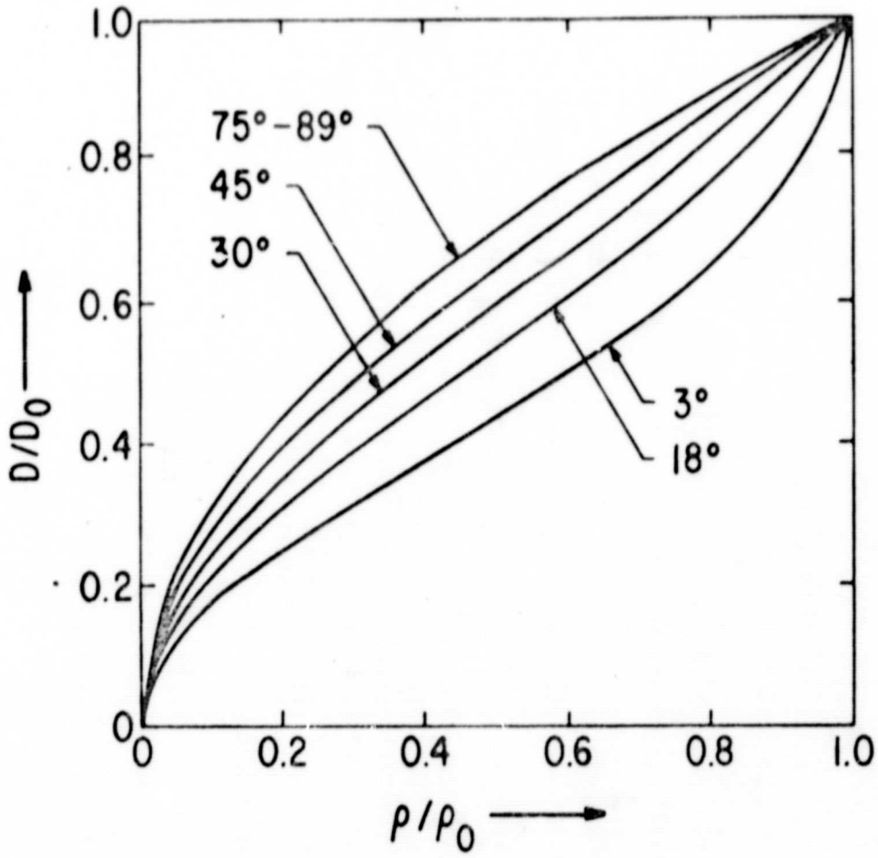


Figure 1. Calculated relation between the track diameters and track densities. The ordinate is the etched track diameter for an annealed track at normal incidence divided by its original value. The abscissa is the ratio of the observed track density to that observed if no annealing were present.

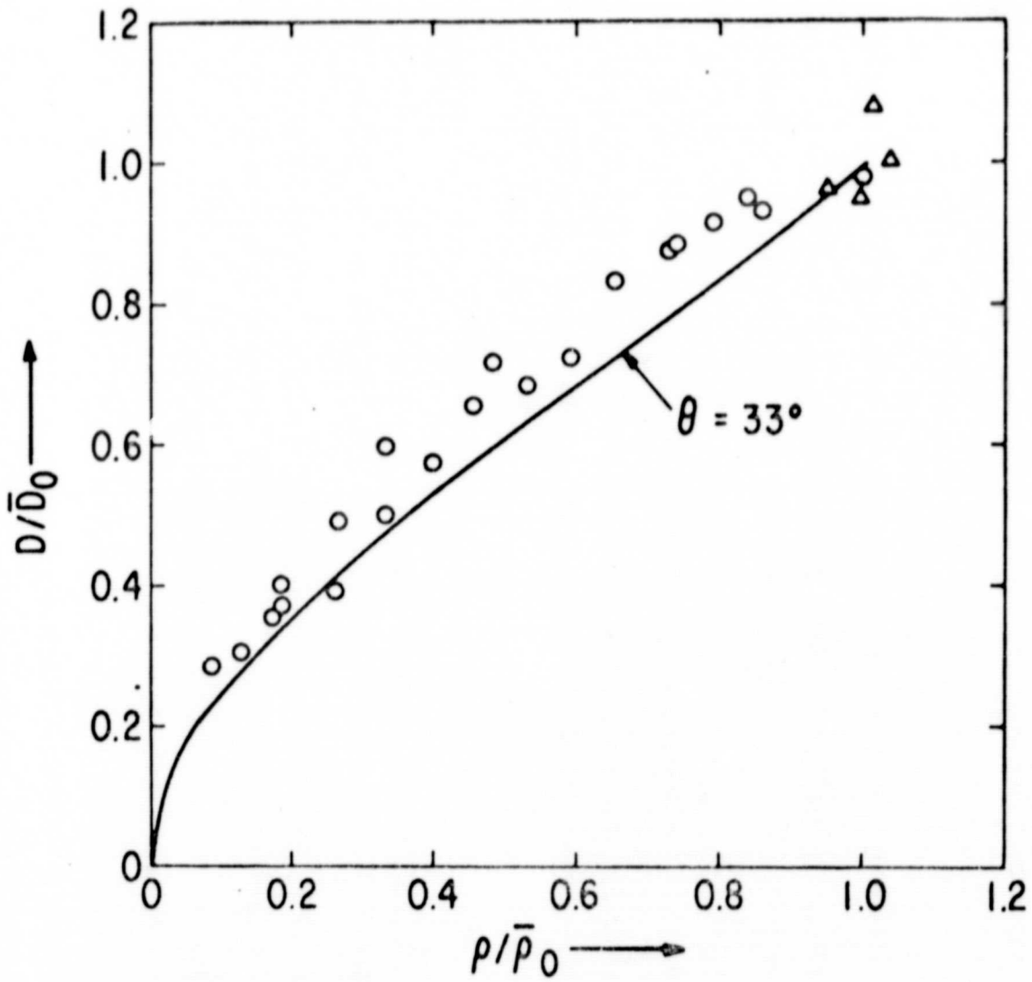


Figure 2. Experimental diameter-track density relation for Cf^{252} fission fragments incident on hard crown glass microscope slides. The data points indicated by triangles are for unannealed control samples; the averages of these points yield $\bar{D}_o$ and $\bar{\rho}_o$, the normalizing quantities for the data. The cone angle of 33° was determined for this glass and etching condition in a separate experiment.

APPENDIX I

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Age of the Manicouagan and Clearwater Lakes craters

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Abstract—Track dating of Manicouagan Crater glass gives 208 (±25) m.y. Partial track fading in a Clearwater Lakes sample yields results consistent with the K–Ar age: 290 (±30) m.y. The Clearwater Lakes Craters are, therefore, not contemporaneous with any known tektite fall. Track annealing studies are important to the determination of reliable fission track ages.

INTRODUCTION

THE CANADIAN shield bears a multiplicity of structures (BEALS *et al.*, 1963), which are the remnants from a series of energetic events spread over the last $\sim 10^9$ yr. Most observers (BEALS *et al.*, 1963; DENCE, 1964, 1965; INNES, 1964; BEALS and HALLIDAY, 1965) regard these "fossil craters" as evidence that the earth has been bombarded by meteoritic, asteroidal, and/or cometary bodies. Although the inferred impact origin of these craters has been questioned (CURRIE, 1965), it is clear that a measurement of the ages of known impact structures would allow a lower limit to be measured for the integrated flux of crater-forming objects in the vicinity of the earth over geological times.

One immediate application of such information is to set a lower bound also on the fraction of lunar craters that were formed by impact events, since the flux of objects at the moon (when suitably adjusted for the different gravitational effect of the moon) would be indistinguishable from that at the earth. Alternatively if the identification of the major portions of the larger lunar craters as due to primary impact is accepted, ages of different portions of the lunar surface can be inferred (OPIK, 1960; KREITER, 1960; SHOEMAKER *et al.*, 1961).

With these ends in mind we have directed fission track studies toward measuring the ages of two of the largest "probable" (DENCE, 1964; DENCE *et al.*, 1965) impact craters on the North American continent, the Manicouagan crater (40 miles in dia.) and Clearwater Lakes West (it is the larger—20 miles in diameter—of the two Clearwater Lakes craters). A previous fission-track age of 33·4(±4·5) m.y. (FLEISCHER and PRICE, 1964) has been determined for Clearwater Lakes, as well as K–Ar whole rock ages of 300 (±30) and 285 (±30) m.y. (WANLESS *et al.*, 1966). A whole rock K–Ar age for Manicouagan (WANLESS *et al.*, 1965) was given as 225 (±30) m.y.

Of four optically glassy Manicouagan samples that were examined, two were found suitable for dating. Two of the four were supplied by K. L. Currie: 14K8, a plagioclase glass, was found to be too non-uniform to be useful; 16-G was found suitable for track etching. This sample was taken from a vein that was about 4 in. wide, and exposed over a vertical height of 60 ft. The vein cuts crumbly biotite gneiss, and was intruded into the position where it was found, about 300 yards from the outer ring fault bounding the structure. Two samples were supplied by M. R. Dence: M-1 was found by X-ray examination to be microcrystalline; M-2 was suitable for dating. M-2 is from a glassy dyke which cuts the basement gneisses (which are of Grenville age) near the margin of the crater.

The details of the dating method have been described previously (FLEISCHER and PRICE, 1964 a,b), as has the neutron dosimetry procedure (FLEISCHER *et al.*, 1965b), and the uranium measurement calibration (FLEISCHER, 1968). Track annealing studies such as described by FLEISCHER and PRICE (1964a) were carried out both on the two Manicouagan samples described here and on the Clearwater Lakes sample reported by FLEISCHER and PRICE (1964b). In each

case the annealing work was done on neutron-irradiated samples in order that each sample contain a conveniently high density of tracks. Typical etching conditions were 3–5 min in ultrasonically stirred 5% HF, followed by a 1-min rinse in 50°C tap water.

Results and Discussion

(a) *Manicouagan*

Results for the Manicouagan samples are given in Fig. 1 and Table 1. Two items are noteworthy. The first is that one of the two samples (M-2) gives an age that agrees with the K–Ar determination on a fine-grained andesite, while the other sample (16-G) has a lower age. The second point is that the sample having the lower age possesses a significantly lower track retentivity than does M-2.

Assuming, as is inferred, that both samples were produced in the same crater-producing event, there are in principle two alternatives—the age found for M-2 is too high or that for 16-G is too low. The first possibility is highly unlikely since no discordantly high fission track age has ever been measured on a terrestrial sample, and no means (short of a nuclear blast) exist for obtaining such a result. The other possibility—that the age of 16-G is low—is supported by various data. The annealing results tell us that at ~60°C tracks should fade in 30–40 m.y. in 16-G but would be retained over the age of the solar system in M-2, a situation which would be consistent with the results obtained. The age of 16-G would then be a track fading age and that of M-2 a true age, which agrees with the K–Ar date and with paleomagnetic data (Robertson, 1967; Larochelle and Currie, 1967). We conclude that the true age is 200–230

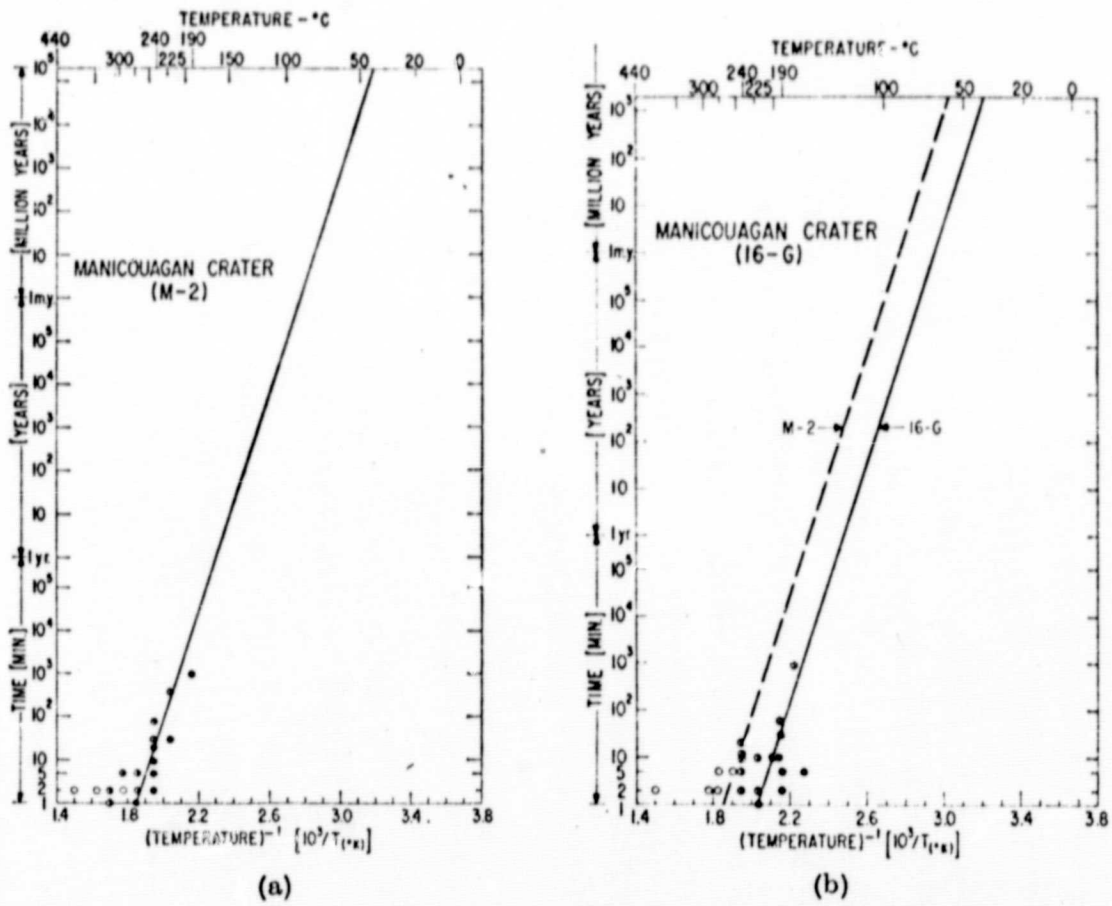


Fig. 1. Track annealing data for Manicouagan samples. Open circles represent total fading, half shaded circles partial fading, and solid circles total retention. At 60°C sample M-2 (Fig. 1a) should retain tracks over the age of the solar system while tracks would last only ~30 m.y. in 16-G (Fig. 1b). In (b) the dashed line shows for reference the relation drawn in (a).

Table 1. Ages of the Manicouagan structure

Sample	Uranium (ppm)	ρ_s (cm^{-2})	Age (m.y.)	Supplied by
M-2	0·21 (±0·03)	1508 (±6·6%)	208 (±25)	M. R. Dence
16-G	0·36 (±0·05)	685 (±7·8%)	36 (±3·5)*	K. L. Currie
CP-63-905†	—	K–Ar	225 (±30)	K. L. Currie

* Track-fading age; see text for discussion.
† Wanless *et al.* (1966).

m.y. and that sample 16-G shows evidence of moderate heating to ~60°C for a few tens of millions of years or for shorter times at slightly higher temperatures. It should be added that no proof exists or is directly obtainable for the validity of the lengthy extrapolation from laboratory annealing times to much greater times. However the fact that no contradictions have been found in the numerous such studies that have been made suggests that such an extrapolation is the best working hypothesis available at present. The inference of heating to 60°C is subject to the obvious uncertainty of an extrapolation which spans 11 or 12 orders of magnitude.

It should be noted that a temperature of 60°C is by no means an implausible one since with thermal gradients that are typical for the earth (Holmes, 1965) such a temperature would be reached as a result of burial to a depth of 1 to 2 km. Alternatively, exposed surface rocks on a warm day can easily be heated to 60°, though this is a less likely possibility. Clearly also, very modest perturbations of normal thermal patterns could easily produce the inferred heating.

(b) *Clearwater Lakes*

Annealing studies were undertaken because of the apparent discrepancy noted in the introduction between the fission-track age of 33 m.y. and the more recent K–Ar results of 285 and 300 m.y. The results shown in Fig. 2 remove this apparent contradiction. They indicate that a large fraction of the tracks are unstable in the glass tested previously (Fleischer and Price, 1964b) so that at ambient temperatures tracks fading would begin to be detectable after a few hundred years and 70–80 per cent of the total number of tracks formed over geological time would be gone after a 300 m.y. waiting time. If only a fraction f of the tracks are retained over the true age of the samples, the observed natural track density ρ_s gives an age that is low by the factor f. To obtain correct results ρ_s must be replaced by ρ_s/f in the age equation. The result of such a correction is given in Table 2, where the K–Ar results are listed along with the original fission track age. The age limits of the corrected determination are wide since f is only known approximately. The values quoted allow f to range from the 0·25–0·30 estimated for storage at 20°C to a value close to 0·1 if storage (like the Manicouagan sample) was at 60°C for appreciable lengths of time.

The corrected age limits are consistent with the K–Ar results (and with paleomagnetic and geological observations—K. L. Currie, personal communications, 1967). We conclude the age of the Clearwater Lakes West crater is approximately 300 m.y.

We have previously noted (Fleischer and Price, 1964a,b; Fleischer *et al.*, 1965a) associations between the ages of various tektite groups and those of certain impact glasses. Clearwater Lakes was listed as one such case, having apparently a fission track age compatible with the 34 m.y. age of the North American tektites. The results here indicate that there is in fact no connection between the two events. It leaves the Libyan Glass as the only impact-produced substance whose age is, within the experimental limits, contemporaneous with the North American tektites. We have two age determinations there, 33·8 (±2·5) m.y. (Fleischer and Price, 1964a) and 37·5 (±2·4) (Fleischer *et al.*, 1965a). Both are consistent with the tektite ages; and since the material—a nearly pure SiO_2 glass—is highly retentive of tracks, the ages are almost surely valid ones.

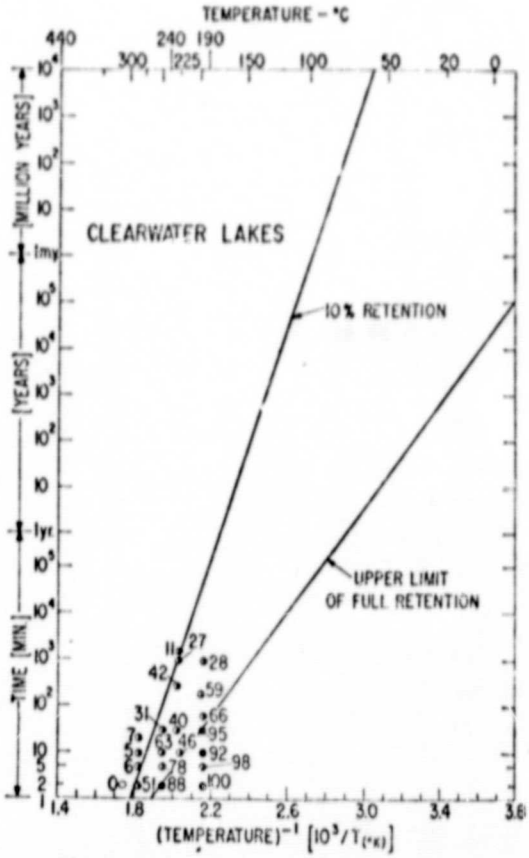


Fig. 2. Track-annealing data for Clearwater Lakes sample dated by FLEISCHER and PRICE (1964b). Symbols as in Fig. 1; numbers represent % of tracks retained. Lines correspond to 10% and 90% track retention. In 30 m.y. at room temperature approximately 70% of the tracks would fade.

Table 2. Ages of Clearwater Lake West

Method	Age (m.y.)
K–Ar*	300 (±30)
K–Ar*	285 (±30)
Fission track† apparent age	33·4 (±4·5)
Fission track corrected‡ age	100–300

* WANLESS *et al.* (1965).
† FLEISCHER and PRICE (1964b).
‡ Above age corrected as described in text.

CONCLUSIONS

1. Fission-track dating and track-annealing studies on Manicouagan glass samples give an age of 208 (±25) m.y. and suggests an ambient temperature of 60°C or slightly above for significant periods of time.

2. Track-annealing studies show that most of the fission tracks had not been retained in a previously dated Clearwater Lakes glass sample and are consistent with a revised age of 100–330 m.y. Other results (Wanless *et al.*, 1965) suggest ~300 m.y. as the most likely age. This result makes it clear that the Clearwater Lakes Craters are not contemporaneous with any known tektite fall.

3. The results serve to emphasize the need to assess the track-retention properties of samples used for fission-track dating.

Acknowledgments—We are indebted to M. R. Dence and K. L. Currie for supplying samples used in this work and for helpful and stimulating correspondence and discussions. This work was supported in part by NASA under contract NAS 9–7898.

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GENERAL ELECTRIC

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AGE OF THE MANICOUAGAN AND CLEARWATER LAKES CRATERS

BY

R. L. FLEISCHER, J. R. M. VIERTL, and P. B. PRICE

APPENDIX II

GENERAL ELECTRIC

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CLASS 1

AGES OF DARWIN GLASS, MACEDON GLASS, AND FAR EASTERN TEKTITES

by

R. L. Fleischer, P. B. Price, J. R. M. Viertl, and R. T. Woods
General Physics Laboratory

Report No. 69-C-130 March 1969

GENERAL ELECTRIC
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SCHENECTADY, NEW YORK

TECHNICAL INFORMATION SERIES

AUTHOR	SUBJECT	NO.
Fleischer, RL et al.	space sciences	69-C-130
		DATE: March 1969
TITLE: Ages of Darwin Glass, Macedon Glass, and Far Eastern Tektites		GE CLASS: 1
		NO. PAGES: 3
ORIGINATING COMPONENT: General Physics Laboratory		RESEARCH & DEVELOPMENT CENTER SCHENECTADY, N.Y.

SUMMARY: A group of possibly related glasses from the Far East, including seven samples of Darwin glass and the two known samples of Macedon glass, have been dated by the fission-track technique. With the exception of a lower age for one Darwin glass sample and one Muong Nong tektite all ages are indistinguishable, suggesting that the Darwin and Macedon impact glasses are related to the Far Eastern tektites.

KEY WORDS: space sciences, tektites, impact phenomena

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N70-11067

AGES OF DARWIN GLASS, MACEDON GLASS, AND FAR EASTERN TEKTITES[†]

R.L. Fleischer, P.B. Price, J.R.M. Viertl, and R.T. Woods

INTRODUCTION

One of the very few generally accepted hypotheses concerning the origin of tektites is that they in some manner result from high-velocity encounters of large objects incident either upon the earth or upon the moon. Regardless of whether the original collision was lunar or terrestrial, the ultimate result could be a shower of objects of assorted sizes reaching the earth--the small objects consisting of (or at least including) the tektites. The accompanying large objects would be capable of producing craters on earth and creating at the same time impact glass--material which can be used to determine the time of impact.

A striking fact concerning the chronology of tektites is that for each of the four tektite falls there exists an impact glass whose age (within the uncertainties of the dating methods used) is indistinguishable from that of the formation and fall to earth of the tektites. The best dated of the four groups is the Ries Kessel-Moldavite association where both K-Ar [Gentner, Lippolt, and Schaeffer (1963)] and fission-track dating [Fleischer and Price (1964a); Fleischer, Price, and Walker (1956a)] give good agreement with small errors. The Ashanti Crater-Ivory Coast tektite pair also has been dated by both methods [Zähringer (1963); Gentner, Lippolt, and Muller (1964); Fleischer, Price, and Walker (1965a); Gentner, Kleinmann, and Wagner (1967)] but with lesser precision. Although the North American tektites-Libyan Desert glass pair has been examined only by fission-track dating [Fleischer and Price (1964a); Fleischer, Price, and Walker (1965a)], as we have noted previously [Fleischer, Viertl, and Price (1969)] these ages should be particularly reliable ones. This contrasts with the previously noted coincidence in ages between the North American tektites and Clearwater Lakes glass [Fleischer and Price (1964b)] which we have shown [Fleischer, Viertl, and Price (1969)] was purely a coincidence, brought about by track fading in the particular glass composition involved.

The fourth coincidence is the subject of this work: the Darwin glass-Far Eastern tektite pair. Previous work on Darwin glass consists only of K-Ar upper limits of 1.5 million years (m.y.)[Zahringer (1963)] and 1 m.y. [Taylor and Solomon (1964)], and a single fission track age of 0.65 ± 0.10 m.y. [Fleischer and Price (1964)]; impact glasses could have experienced similar conditions, and therefore we felt it to be desirable to do further dating work. We have consequently dated a group of seven Darwin glass samples, plus the two known samples of Macedon glass, which are chemically identical material found in Australia [Chapman, Keil, and Annell (1967)]. For the purpose of normalization a group of tektites were dated, six of which had been previously examined [Fleischer and Price (1964a)] and two of which are Nuong Nong tektites.

EXPERIMENTAL PROCEDURE AND RESULTS

Experimental procedures for track counting [Fleischer and Price(1964a,b)] and neutron dosimetry [Fleischer, Price, and Walker (1965b)] have been described elsewhere and need not be elaborated further. Results appear in Table I.

TABLE I

Age Determinations

Sample	Supplied By	Uranium (ppm)	ϕ_s (cm^{-2})	Age* (m.y.) (±10%)
	Tektites[†]			
Bediasite C (Lee County)	C. Schnetzler, W. Pinson	2.1	15,200	34.9
Bediasite D (Lee County)	C. Schnetzler, W. Pinson	1.6	15,200	32.1
Moldavite (Stripi, Bohemia)	J. Lipson, A. Cohen	2.4	9,690	16.9
Philippinite	D.S. Miller	3.1	335	[illegible]
Philippinite	C. Moore	2.6	381	.78
Thailandite (Phang Daen)	Am. Met. Lab.	2.0	278	.70
	Muong Nong Tektites			
Phang Daen (Thailand)	V.E. Barnes	2.5	525	0.78
Kan Luang Dong (Thailand)	V.E. Barnes	1.9	156	.45
	Darwin Glass			
DG-3	D.R. Chapman	2.5	215	0.37
DG-16	D.R. Chapman	2.1	443	.75
DG-17	D.R. Chapman	2.2	349	.66
DG-18	D.R. Chapman	2.2	442	.76
DG-24	D.R. Chapman	2.1	337	.59
DG-80	D.R. Chapman	2.0	308	.68
DG-E[†]	V.E. Barnes	~2.5	459	.69
	Macedon Glass			
MG-3530	D.R. Chapman	2.8	235	0.60
MG-3531	D.R. Chapman	2.5	292	.59

*All ages relative to 33.5 m.y. taken as average for the bediasites.

[†]Re-runs on previously dated samples [Fleischer and Price (1964a)].

[†]This study was supported in part by NASA under Contract No. NAS 9-7898.

The one unusual aspect of the procedure concerns sample DG-80.* The first neutron irradiation of sample DG-80 produced what was apparently a spuriously low track count--implying a uranium content of about 0.5 ppm and an apparent age of 3.0 m.y. Since the uranium content is greatly different from the consistently nearly identical values for the other Darwin glass (and Macedon glass) samples and since the 3.0 m.y. would contradict the K-Ar upper limits at 1.0 and 1.5 m.y., this result was examined further. A low induced track count could result from an unusual U^{235}/U^{238} ratio (which is being checked but is an unlikely explanation) or from a physically unreasonable but conceivable process--leaching out of uranium by the etching process. This possibility was checked in two ways and found not to occur: (1) taper sectioning of the irradiated sample showed no gradient of induced tracks. (2) Two further fragments of sample DG-80 were examined. One was polished, etched, and counted as before, the other was not polished or etched, and the two were irradiated together. This time the induced track counts of both samples corresponded to ~2 ppm uranium, as in the other Darwin glass; and there was no difference between the previously etched and the previously unetched samples. The latter results were used to obtain the age given in Table I for DG-80.

DISCUSSION AND CONCLUSION

Table I allows the triple conclusion to be drawn that the ages of Darwin glass, Macedon glass, and the Far Eastern tektites are indistinguishable. A real association between the first two was to be expected since the structural and chemical similarities are quite striking [Chapman, Keil, and Annell (1967)]. By contrast, the agreement between their ages and those of the Far Eastern tektites may be coincidental, but the geographical overlap of the regions where the two groups of samples are found and the existence of the previously cited matching pairs of ages for tektite groups and impact glasses suggests that the Far Eastern tektites and the Far Eastern impact glasses studied may have a joint origin in a single event or in a series of nearly simultaneous events. Figure 1 shows the locations of presumably matched groups of glasses and their ages.

ACKNOWLEDGMENTS

We are indebted to D.R. Chapman and V.E. Barnes for supplying samples, and are pleased to thank E. Stella for skillful work in sample preparation.

*DG-80 is discussed in detail because of the discrepancy it previously presented, noted orally at Am. Geophys. Union Meeting, Washington, D.C., April 11, 1968.

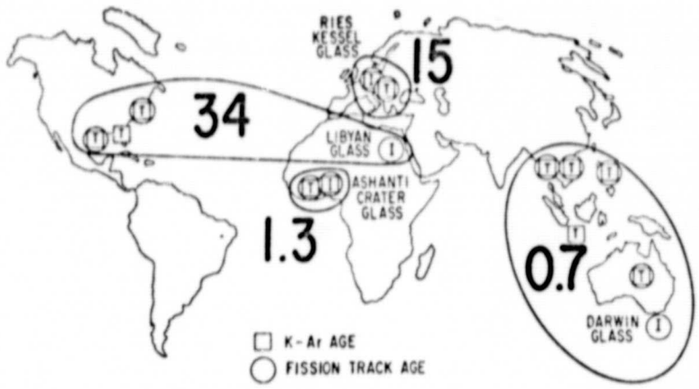


Fig. 1 Distribution of tektite groups and associated impact glasses. The numbers are the ages in millions of years of the glasses indicated within the encircled areas. In all cases where both K-Ar and fission track dating have been done (except for the Georgia tektites), the fission-track dating confirms the K-Ar results. In no case is there a known contradiction.

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APPENDIX III

GENERAL ELECTRIC

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CLASS 1

N70-11068

A SECOND TEKTITE FALL IN AUSTRALIA

by

R. L. Fleischer, P. B. Price, and R. T. Woods
General Physics Laboratory

Report No. 69-C-245

July 1969

GENERAL ELECTRIC

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SCHENECTADY, NEW YORK

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AUTHOR	SUBJECT	NO.
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		NO. PAGES: 2
ORIGINATING COMPONENT: General Physics Laboratory		RESEARCH & DEVELOPMENT CENTER

SUMMARY

Tektites of a chemical subgroup found in Australia (Chapman's "high sodium" tektites) have fission-track ages of approximately 4 m.y. and hence are part of a distinct tektite fall, one that preceded the formation of the well-known Australasian strewn field 0.7 m.y. ago.

KEY WORDS

fission-track dating, tektites, space sciences

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RD-54 (4/68)

N70-11068

A SECOND TEKTITE FALL IN AUSTRALIA*

R. L. Fleischer, P. B. Price, and R. T. Woods

One of the striking facts about tektites is their distribution over four rather well-defined geographical areas, each one of which includes samples of a single, discrete age group: 0.7 m.y. in the Far East, ~1 m.y. in the Ivory Coast, 15 m.y. in Czechoslovakia, and 34 m.y. in the United States (Refs. 1-5). These results have been taken as evidence of four distinct impact events, separated both in space and time. Here we point out that a chemical subgroup of tektites recently found in Australia must be the result of a fifth impact event, which in fact preceded the one which created the vast Far Eastern strewn field 0.7 m.y. ago.

Chapman and Scheiber[6] have identified a chemical subgroup ("high sodium tektites") of nine glass samples from Australia as being tektites on the basis of three characteristics: (1) they are glass samples having a single, unique composition found over a rather wide area; (2) they have the common shapes and sizes of tektites; and (3) they contain lechatelierite inclusions.

Chapman supplied us with samples of three of the nine known tektites of the group for fission-track dating [2, 7, 8] the results of which are given in Table I. The measured ages range from ~3 to ~4 m.y. and are unabiguously greater than those of the tektites normally found in Australia (0.7 m.y.).

TABLE I

Age Data on High Sodium Tektites from Australia

Sample*	Uranium (ppm)	ρ_s (cm^{-2})	Age (m.y.)
AN 87	0.7	412	4.25 (± 0.43)
(Williams Creek)	.9	370	4.65 (± .50)
AN 245			
(Raspberry Bore)	1.1	297	3.10 (± 0.30)
AN 370			
(S. of Lake Wilson)	1.3	346	3.54 (± 0.35)

*Supplied by D. R. Chapman.

This age discordancy being unique among tektite fields, we must ask whether there is any means by which a spuriously high apparent age could have been found. Although for terrestrial samples spuriously high ages are not possible,[7] for extraterrestrial materials there are several potential sources of excess tracks as a result of the cosmic radiation.[9] Most of the natural tracks we found might in principle have resulted from fission of heavy elements, induced by cosmic ray protons and heavier nuclei. We have shown that such irradiation produces identifiable V-shaped events in tektites.[10] We searched sample AN-245 for such events and found none. Alternatively, the tracks might be from spallation recoil nuclei. Again we have previously identified such tracks;[11] they are too short to be confused with fission tracks.

Finally, the tracks could be due to heavy cosmic ray nuclei, many of which might produce tracks of the same length as do fission events. If the tracks were of this origin, the track distribution through the tektites would be nonuniform,[10, 11] resulting from the nature of the cosmic ray energy spectrum (greater abundance and more rapid slowing down at lower energies) and from the short interaction mean free path of heavy nuclei (typically ~8 cm). Figure 1 shows the spatial distribution of tracks to be expected in a tektite "core" if tracks originated from cosmic ray particles, if from spontaneous fission after arrival on earth, and as observed in sample AN-245.

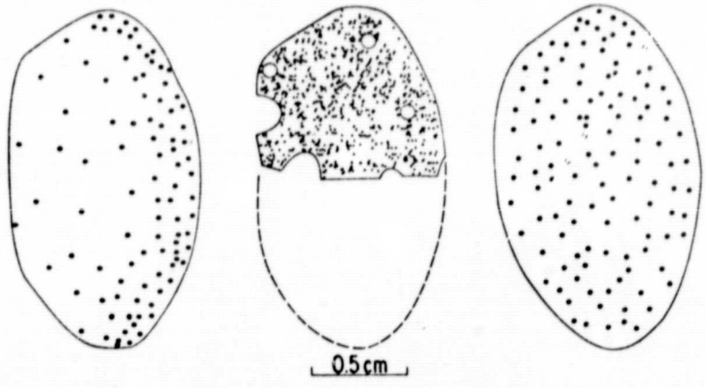


Fig. 1 The track distribution in sample AN-245 (center) compared with those expected from cosmic ray tracks (left) and spontaneous fission tracks (right). The results agree with those expected for spontaneous fission.

A core is the shape remaining after one side of a sample is first ablated and then rapidly cooled during atmospheric entry. The heated and cooled layer (which was adjacent to the left side as viewed) has spalled off by the high internal stresses. The right-hand side is the original pre-atmospheric surface. The gradient expected in the cosmic ray track density arises here primarily from the factor $d\varepsilon/dx$ [in Eq. (6) of Ref. 9] which varies by a factor of more than 4 between the surface and a position 1 cm in the interior. If in addition the cosmic ray spectrum for the energies involved (0 to 190 MeV/

*Work partially supported by NASA under Contract NAS 9-7898.

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nucleon) is a simple extrapolation of the sparce data just above this energy range,[12] the gradient in track density would be further enhanced. The observations shown in Fig. 1 are clearly incompatible with the cosmic ray hypothesis. We conclude that, as assumed in calculating the ages appearing in Table I, the tracks are from spontaneous fission. It follows that the high-sodium group represents a distinct separate fall whose age is at least 4 m. y.

To many observers it may appear odd that a newly identified fall should exist in the very region where a previously known fall had occurred. Presumably, however, this second fall in Australia was identified solely because of the extensive search for more tektites and examination of them in an area already known to contain many samples. It would appear likely that other areas of the earth contain tektites from other, as yet unidentified, falls.

ACKNOWLEDGMENTS

We are pleased to give thanks to E. Stella for experimental assistance, and to D. R. Chapman for helpful comments and for supplying the three high sodium tektites.

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APPENDIX IV

GENERAL ELECTRIC

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CLASS 1

SCHENECTADY METEORITE

by

R. L. Fleischer, P. B. Price, and R. T. Woods, General Physics Laboratory
Eric Lifshin, Metallurgy and Ceramics Laboratory
R. W. Carter, Schenectady Museum
E. L. Fireman, Smithsonian Astrophysical Observatory

Report No. 69-C-295 August 1969

GENERAL ELECTRIC

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SCHENECTADY, NEW YORK

TECHNICAL INFORMATION SERIES

AUTHOR R. L. Fleischer, E. Lifshin, P.B. Price, R. T. Woods, R. W. Carter, and E. L. Fireman	NO. 69-C-295
	DATE August 1969
TITLE Schenectady Meteorite	GE CLASS 1
	NO. PAGES 3
ORIGINATING COMPONENT General Physics Laboratory; Metallurgy and Ceramics Laboratory	RESEARCH & DEVELOPMENT CENTER

SUMMARY The fourth meteorite recovery in the United States during the past decade (and only the second since 1961) occurred on 14 April 1968, in Glenville, New York (a suburb of Schenectady). The exterior of the single stone of mass 283.3 g consists primarily of a dull, black fusion crust, plus a fracture surface that was apparently produced by breakup in the atmosphere. Measurements of the densities of cosmic-ray tracks in olivine and pyroxene crystals at four positions in the meteorite, together with our measured cosmic-ray exposure time of 31 million years, are evidence that the specimen came from a depth between 4 and 9 cm in a preatmospheric body of greater than 20 cm radius. The U-He^4 and the K-Ar^{40} ages, 4.1×10^9 and 4.35×10^9 years, respectively, indicate that the meteorite underwent very little heating in space.

Subject: meteorites

Key Words: space physics, cosmic rays, particle tracks

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RD-54 (4/68)

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N70-11069

SCHENECTADY METEORITE

R. L. Fleischer, Eric Lifshin, P. B. Price, R. T. Woods, R. W. Carter, * and E. L. Fireman†

At 8:30 p.m. Friday, 12 April 1968, a meteorite struck the roof of the home of Joseph W. Kowalski, 265 Swaggertown Road, Glenville (Schenectady), New York (42°51'39"N 73°57'1"W), splintering a portion of the eaves and rebounding onto the ground.(1) Mr. Kowalski, who was watching televison at the time, heard what he later described as a sound "like a firecracker going off in the attic," and then resumed watching television. Two days later, on returning home from church, he observed the broken eaves, noted the nature of the damage, searched the grounds adjacent to his home, and recovered from alongside his house the single chondritic stone meteorite of mass 283.3 g shown in Fig. 1.

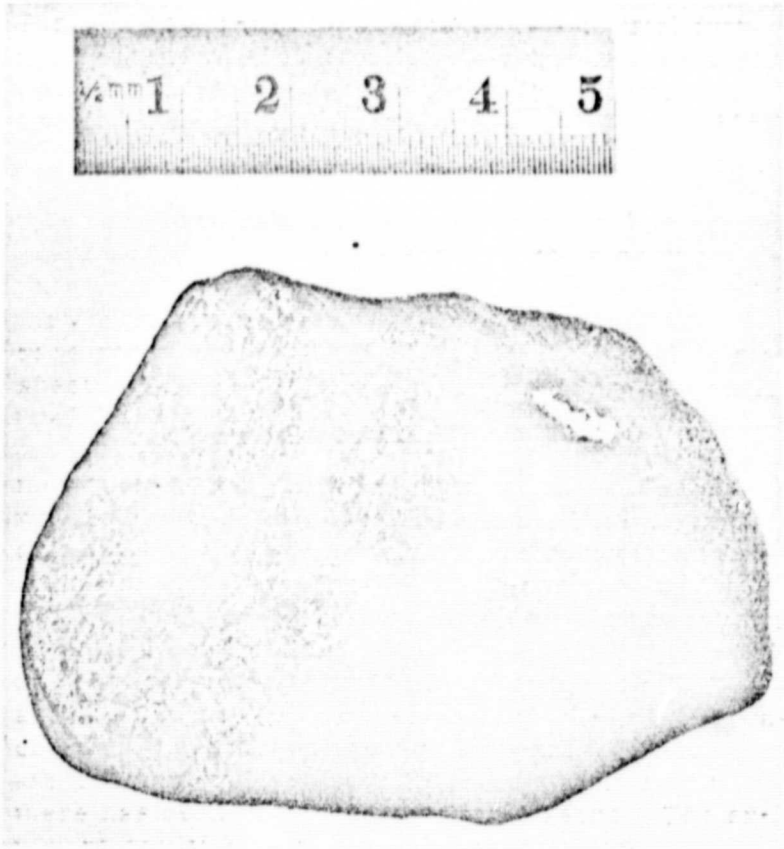


Fig. 1 The Schenectady Meteorite. The fresh (white) surface was produced on impact; the darker fracture surface at left was produced during descent through the earth's atmosphere and is dotted with dark globs of asphalt roofing material.

Because the fall occurred in early evening on the night of an eclipse of the moon, it was widely observed. Sightings were reported as far away as Poughkeepsie, Binghamton, and suburban New York City. A number of reports described a breakup into two or more luminous trails during descent. Reports from 11 different sites included notation of the apparent motion (right to left, or left to right), data that in principle allow one 180° sector of possible azimuth of the fall to be eliminated for each observation. From the 11 reports, the full 360° is eliminated, leading to the inference that the meteorite did not fall. However, a self-consistent result, that the fall was from the East and close to the zenith, can be obtained if one of the observations is discarded. The observer involved is the one trained scientist among the group but is known to have been on his back drinking beer at the time of the sighting.

Although most of the surface of the meteorite is covered with a veneer of dark, vesicular, glassy fusion crust, there is one slightly darkened fracture surface, as well as two fresh fractures where small chips were lost on impact with the roof. The slightly darkened fracture surface is inferred to have been produced during flight through the atmosphere both because the color is different from that of the freshly broken areas and because a portion of the darkening consists of fragments of tar-like roofing material, assumed to be terrestrial in origin.

Chondrules up to at least 1 mm in diameter are present, with distinct, well-defined borders. By a point-counting technique we find a free-metal content of 12.0 (±0.8) per cent by volume and 25.9 per cent by weight. X-ray and microprobe examinations have revealed the presence of olivine, clinopyroxene, troilite, and Ca-feldspar. Careful x-ray examination using LiF and $NaWO_3$ standards and the methods of Yoder and Sahama and of Jackson(2) has shown that the fayalite in the individual olivine fragments varies from 12 to 28 per cent, with most of the values between 17 and 23 per cent. Thus, the meteorite is what Dodd and Van Schmus would term an unequilibrated chondrite (3). The average iron content in the olivine, the finite but modest disequilibrium, and the well-defined chondrules suggest that this should be classified as an H-4 chondrite(4).

Cosmic-ray tracks(5), such as are shown in Fig. 2, were etched in samples taken from four positions roughly equally spaced around the perimeter of the meteorite; three were taken from 3 mm beneath the fusion crust, and one from a thin-section oriented at approximately 45° to the surface at the large fracture shown in Fig. 1. Just beneath the crust, densities of 7.5, 8.0, and 8.9 x 10^6 tracks/cm^2 were found, and at the fracture surface, 1.3 x 10^6 tracks/cm^2, the last indicating that this region of the meteorite was at a greater depth before ablation and breakup in the earth's atmosphere(6).

The cosmic-ray tracks, radioactivities and rare gases have rarely been measured on adjacent

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†E. L. Fireman, Smithsonian Astrophysical Observatory.



Fig. 2 Cosmic-ray tracks etched in a crystal from the Schenectady Meteorite. The tracks are dagger-shaped and consequently appear as V-shaped lines when viewed in transmitted light. 805X

meteorite specimens. When these measurements are done, the depth of the sample, the size of the preatmospheric body, and the hardness of the incident cosmic radiation can be estimated. The rare gases were measured with a 6-inch nuclide mass spectrometer with a procedure previously described (Ref. 7). Table I gives the results in 10^{-8} cc/g. The gamma-ray activities Na^{22}, Al^{26}, and Co^{60} were measured by the gamma-gamma coincidence method with 3- x 3-inch NaI crystals. Table II gives these activities at the time of fall and the cosmic ray and gas retention ages. The Ne^{22}/Na^{22} cosmic-ray exposure age was obtained by taking the Ne^{22} production rate to be equal to the $Na^{22} + Al^{26}$ activity; the U-He^4 age was calculated with U and Th contents of 0.012 and 0.043 ppm, respectively; and the K-Ar^{40} age was calculated with a K content of 850 ppm. The large and concordant U-He^4 and K-Ar^{40} ages indicate that there has been no helium loss for 4 aeons. The exposure age of 31.4 m.y. is long for a meteorite of this type, H-4; only 10 percent of 115 cases of H chondrites have exposures of greater than 30 m.y. The He^3/Ne^{21} which is an indicator of the hardness of the incident cosmic radiation and of the depth of the sample, is unusually high. Less than 10 per cent of the chondrites have He^3/Ne^{21} ratios this high or higher. A high He^3/Ne^{21} ratio indicates a small preatmospheric size and hard (high-energy) incident radiation. It is of interest to calibrate the He^3/Ne^{21} indicator by the cosmic-ray-track method.

The track data, together with the exposure age, determine the depth and preatmospheric size of the meteorite[6]. These data give 260,000 ± 10,000 tracks/cm^2 - m.y. at three sites in the meteorite, and at the fourth, which is 5.4 cm distance from the others, 41,000 ± 2,000 tracks/cm^2 - m.y. Calculations[6] indicate that for the track formation rate to be as low as 43,000/cm^2 - m.y., the preatmospheric meteorite must have had at least a 14-cm radius. These calculations place the samples with 260,000 tracks/cm^2 m.y. at about 4 cm from the preatmospheric surface. For there to be a four-fold increase[8] in track density over a 5.4 - cm distance, the preatmospheric radius would have had to be larger than 20 cm. Thus according to these calculations, a likely position of the recovered sample would have been between 4 and 9 cm deep in a body of 20-cm radius. The low Co^{60} content is consistent with this picture. For a 20 - cm radius and the measured density of 3.610 we conclude that the original mass must have exceeded 47 kg - a factor of 160 times the covered mass.

At a depth of 5 to 10 cm, the production of isotopes by solar flares is negligible, so that galactic cosmic rays and their secondaries are solely responsible for the He^3 and Ne^{21} contents. Target measurements[9] indicate that an He^3/Ne^{21} ratio of 7 corresponds to an average energy of 600 Mev for the bombarding particles. Secondary neutrons enhance the Ne^{21} production; and since there are a considerable number of secondary neutrons at a depth of 5 to 10 cm, the average energy of the incident cosmic rays must be greater than 600 Mev. Since less than 10 per cent of the He^3/Ne^{21} ratios that have been measured in chondrites have values above 6.6, meteorite samples from less than 5 - cm depth in the preatmospheric chondrites are rare[10].

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10. We are indebted to A. Davis and E. Stella for experimental assistance, to B. Mason for helpful correspondence, and to NASA for support under contract NAS 9-7898.

TABLE I

RARE GAS CONTENTS (10^{-8} cc/gm) AND ISOTOPIC RATIOS IN THE SCHENECTADY METEORITE

He^3	He^4	Ne^{21}	Ne^{20}/Ne^{21}	Ne^{22}/Ne^{21}	He^3/Ne^{21}	Ar^{36}
52 ± 2	1920 ± 50	7.6 ± 0.3	0.96 ± 0.03	1.15 ± 0.01	6.8 ± 0.4	2.32 ± 0.13

Ar^{36}/Ar^{38}	Ar^{40}/Ar^{36}	Xe^{132}	Xe^{129}/Xe^{132}
1.38 ± 0.05	2440 ± 100	0.018 ± 0.003	1.34 ± 0.02

TABLE II

RADIOACTIVITY AND AGES OF THE SCHENECTADY METEORITE

Na + Al^{26} (dpm/kg)	Na^{22} (dpm/kg)	Al^{26} (dpm/kg)	Co^{60} (dpm/kg)	Ne^{22}/Na^{22} age (m.y.)	U-He^4 age (m.y.)	K-Ar^{40} age (m.y.)
140 ± 5	80 ± 10	60 ± 10	<8	31.4 ± 2.5	4100	4350

APPENDIX V

GENERAL ELECTRIC

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NUCLEAR PARTICLE TRACK IDENTIFICATION IN INORGANIC SOLIDS*

by

R. L. Fleischer, P. B. Price, and R. T. Woods
General Physics Laboratory

Report No. 69-C-253 July 1969

* This work was supported by NASA under Contract NAS 9-7898.

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TECHNICAL INFORMATION SERIES

AUTHOR	SUBJECT	NO.
Fleischer, RL Price, PB Woods, RT	particle detectors	69-C-253
		DATE July 1969
TITLE Nuclear Particle Track Identification in Inorganic Solids		GE CLASS 1
		NO. PAGES 7
ORIGINATING COMPONENT General Physics Laboratory		RESEARCH & DEVELOPMENT CENTER

SUMMARY The unique feature of track-recording plastics which allows them to be used to identify particles is that the chemical rate of attack V_T along a track is an increasing function of ionization rate. This same characteristic is shown to extend to inorganic dielectric solids. The relation between V_T and ionization rate has been measured for five different glasses, using fission fragments of different energies. The variation of V_T is least for ordinary lime glass and much the greatest for a phosphate glass, suggesting that the latter should be useful in resolving atomic numbers and energies of fission fragments and other very heavy, energetic nuclei. Equations are derived that allow the shapes of etched tracks to be calculated as a function of etching time and particle ionization rate. The calculations agree well with recent experimental results.

KEY WORDS
particle detectors, particle registration, track etching, glass, space sciences

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N70-11070

NUCLEAR PARTICLE TRACK IDENTIFICATION IN INORGANIC SOLIDS*

R. L. Fleischer, P. B. Price, and R. T. Woods

I. INTRODUCTION

Particle identification by measurements on etched tracks in solids is possible because the chemical attack rate V_T along a particle track is a unique, measurable function of the localized damage caused by a particle.[1-3] This function has been inferred in a number of plastics,[1, 3] and sheets of these plastics have been used to demonstrate that identification of neighboring elements is possible for particles of atomic number Z as high as 28[3] and that under proper circumstances neighboring isotopes as heavy as B^{10} and B^{11} may be clearly distinguished.[1]

The purpose of this work is to demonstrate that in inorganic glasses V_T is also an increasing function of ionization rate and to indicate how and where such glasses might be used for particle identification.

One notable difference between the inorganic and the organic solids in their characteristics for particle track registration is that the ionization threshold is considerably higher for the inorganic solids--glasses and crystals.[4] The result is that while heavy ion accelerators are able to supply a variety of particles of known mass, charge, and energy necessary for calibration of the registration threshold of plastics, for the less sensitive minerals and glasses the choice is more limited. Particles that can presently be used include fission fragments and heavy ions such as I and Br, which are available at low energies per nucleon from certain tandem van de Graaff accelerators.[5] In this work we use fission fragments of various energies from a Cf^{252} source as a means of displaying the widely differing registration characteristics of a group of glasses.

II. RELATION OF CONE-ANGLE-TO-ETCHING RATIO

Particle identification by solid-state nuclear track detectors depends on the facts that the velocity of etching V_T along the damaged material comprising a particle track is greater than the general attack rate V_G of the undamaged material and is a unique function of the charge, mass, and energy of a particle. These facts lead to a geometry of etched tracks that can be understood with the aid of Fig. 1. Assume for simplicity [as sketched in Fig. 1(a)] that V_G is isotropic and that V_T is constant over the length $V_T t$ etched in time t. A surface layer of thickness $V_G t$ is etched away, and a conical etched track is produced of cone angle $\theta = \arcsin(V_G/V_T)$ and

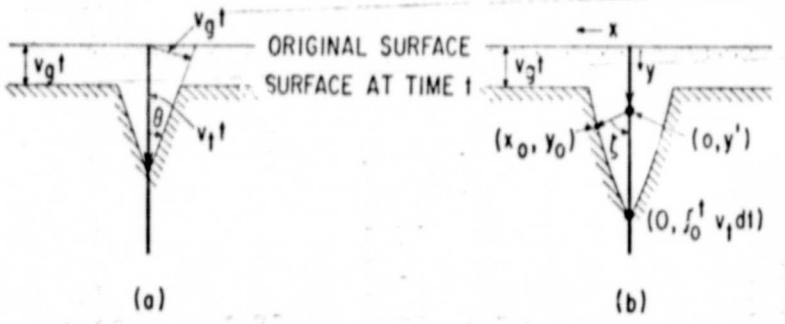


Fig. 1 Track geometry. (a) With V_T constant the cone angle is $\sin^{-1}(V_g/V_t)$; (b) with V_T decreasing, as etching continues, the shape of the etched track is more complicated.

diameter D which can readily be shown to be $2V_G t[(V_T - V_G)/(V_T + V_G)]^{1/2}$ for a track normal to the etched surface. In short, both the cone angle and the diameter are functions of V_T, which in turn is a function of ionization (previously measured for plastics and shown here to apply to glasses also). Hence knowledge of either θ or D makes particle identification possible just as the more direct quantity $L (\equiv \int_0^t V_T dt)$ has been used by methods we have previously described.[1-3, 6]

If the angle of the track to the surface, φ, is less than θ, then the rate of preferential etching normal to the surface, $V_T \sin\varphi$, is less than the rate V_G at which material is dissolved away from the surface, so that no track is revealed. This purely geometric result, described in more detail previously,[7] means that φ_c, the particular value of the angle φ at which tracks cease to be revealed, is equal to θ, and hence the etching ratio (V_T/V_G) is given by $1/\sin\varphi_c$. By measuring φ_c for particles incident on a surface at different ionization levels J, a relation between (V_T/V_G) and J may be constructed, the critical relation needed for particle identification.

III. EXPERIMENTAL VARIATION OF THE ETCHING RATIO WITH IONIZATION

We have utilized the simple geometry sketched in Fig. 2 to measure φ_c and deduce $\theta = \arcsin(V_G/V_T)$. In the simplest case [Fig. 2(a)] a rod or cylinder of detector of diameter d is exposed to a parallel beam of particles (in this case from a californium-252 source). Then the sample is etched and the chord width w is measured over which tracks are revealed by etching. θ is given by $\arccos(w/d)$. In the actual geometry used [Fig. 2(b)] a point source is spaced a distance h from the detector. The geometry in this case is such that

$$\theta = \varphi_c = \arccos(w/d) - \arctan[w/(2h + d + \sqrt{d^2 - w^2})]$$

* This work was supported by NASA under Contract NAS 9-7898.

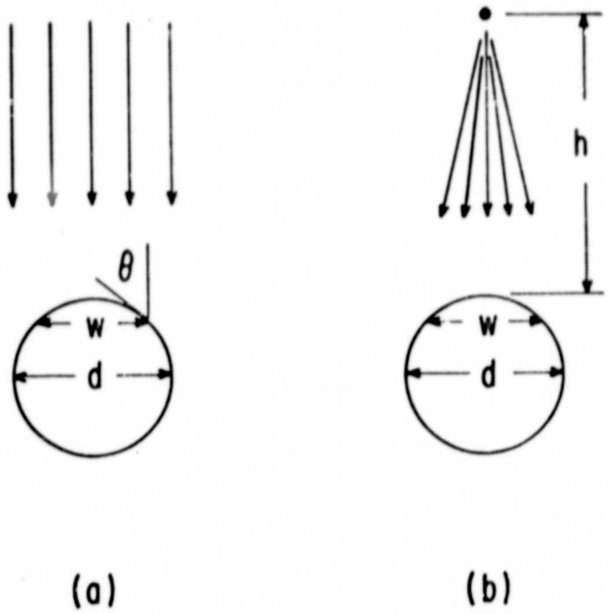


Fig. 2 Measurement of the critical angle θ for track etching. (a) Using a collimated beam of particles, tracks may be revealed over a chord width w on a cylinder (or sphere), and $\theta = \cos^{-1}(w/d)$; (b) with a point source $\theta = \cos^{-1}(w/d) - \tan^{-1}[w/(2h+d+\sqrt{d^2-w^2})]$.

Since in these experiments h = 2.6 cm and d is typically 0.6 mm, the maximum value of the second term in θ is ≤0.1 radian. This term, although significant, is normally small except for the phosphate glasses where θ can also be small.

Tubes of lime glass[8] and rods of fused quartz were obtained, and rods were made of a phosphate glass,[9] a synthetic tektite glass,[10] and a remelted obsidian.[11] The critical angle φ_c was measured either as described with reference to Fig. 2 or by directly rotating the sample through an angle $\pi - 2\varphi_c$ so as to view normal to the surface at the two edges of the region in which tracks are revealed by etching. Cf^{252} fission fragments were used either in a vacuum of 1 mm or of 2 cm [the latter equivalent to 0.088 mg/cm² of air in our geometry of Fig. 2 (b)]. Polycarbonate sheets of 0.219 and 0.950 mg/cm² were used to slow down the fission fragments by various amounts. Table I lists the thicknesses of absorbing material (foils plus air) for each experiment along with the etching ratios deduced. We used the range-energy data of Kahn and Forgue[12] to find the energies of the median light and median heavy fission fragments, and from the ionization curves deduced earlier for minerals[13] we calculated values of the ionization rate, J, in the glass. In each case the J values for the more heavily ionizing of the two fission fragment mass groups were used. Figure 3 gives the resulting curves of (V_T/V_G) vs J. For reference the thresholds of muscovite mica and the same diopside reported earlier[13] are given, threshold being defined as the value of ionization at which fission fragments at normal incidence cease to be revealed by etching.

TABLE I

Relation Between the Etching Ratio (V_T/V_G) and Thickness of Absorbing Material for Various Glasses

Absorber Thickness (mg/cm²)	Etching Ratio (V_T/V_G)*				
	P_2O_3 Glass	SiO_2 Glass	Tektite Glass	Obsidian	Lime Glass
0.004	57(±10)				1.381
.088	$14.3(^{+\infty}_{-8.5})$	2.96	1.79, 1.97	2.29	
.307		2.64, 2.59			
.526		2.78			1.363
1.038	$8.8(^{+\infty}_{-4.6})$	1.98	1.46, 1.60		1.286
1.257	$5.3(^{+11.5}_{-3.4})$	1.6			
1.476		1.72	1.24, 1.33		1.248
1.695	$2.14(^{+.56}_{-.38})$	1.33	1.06, 1.11	1.125	1.15
1.914	$1.86(^{+.24}_{-.30})$	1.0	1.022		1.086
1.988	1.0	1.0			1.0

*In mica tracks are seen after 1.607 mg/cm², but not after 1.914; in diopside tracks are seen after 1.476 mg/cm², but not after 1.607.

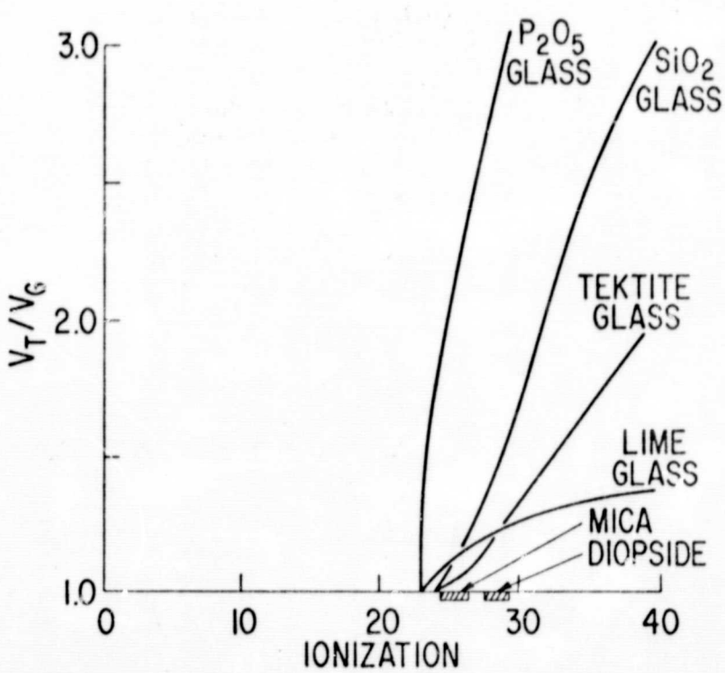


Fig. 3 Etching ratio V_T/V_G vs ionization rate J (relative values) for a group of glasses.

It is worth noting that all of the glasses have thresholds at least as low as the mica and that two--the lime glass and the tektite glass--are more sensitive than the mica.[14] In all cases the track-etching rate rises monotonically with ionization, but the rate of increase varies widely from one to an-

other and is most rapid for the phosphate glass.

IV. TRACK DIAMETER AS A FUNCTION OF V_T

As we noted earlier, track length, diameter and cone angle are all functions of V_T/V_G, hence they are related to the ionization, and therefore make possible particle identification. Where values of θ are small, tracks are long and narrow, and consequently L is the most sensitive and easily measured parameter and the one we have used in previous studies.[1-3] Where θ values are large (as in many glasses) and in cases where particles enter at right angles to the detector surface, D becomes the preferred parameter. It is of interest to know how D will vary with etching time and with the applicable relation $V_T(y)$ for the variation of track-etching rate with position along the track.

We now proceed to show how $D[t, V_T(y)]$ can be calculated for tracks at normal incidence, referring to Fig. 1(b). First using the coordinate system indicated there, we calculate the shape of the etch pit $y_0(x_0)$ for an arbitrary $V_T(y)$ describing the attack rate for a track along the y-axis. Twice the value of x_0 when $y_0 = V_G t$ gives the diameter as a function of time. The etching time to reach the point (x_0, y_0) is given by

$$t = \int_0^{y'} \frac{dy}{V_T(y)} + \frac{\sqrt{(y_0-y')^2 + x_0^2}}{V_G} \qquad (1)$$

which is composed of two terms: the time to etch along the track from (0,0) to (0, y') given by $\int_0^{y'} dy/V_T(y)$, and the time to etch from (0, y') to (x_0, y_0) is given by $\sqrt{(y_0-y')^2+x_0^2}/V_G$. Since the actual path from (0, 0) to (x_0, y_0) is that corresponding to least time we take the derivative of time with respect to y' and set it equal to zero, giving the relation

$$y' = y_0 - x_0/\sqrt{(V_T(y')/V_G)^2-1} \qquad (2)$$

which, together with Eq. (1), defines x_0 and y_0 for a given t, y', and $V_T(y)$. By noting that the angle ζ in Fig. 1 (b) is arc ctn $[(y_0-y')/x_0]$, we can write Eqs. (1) and (2) in a more useful parametric form in y' as follows:

$$x_0 = \sqrt{(y_0-y')^2 + x_0^2}\ \sin(\zeta)$$

$$y_0 = y' + \sqrt{(y_0-y')^2 + x_0^2}\ \cos(\zeta)$$

which can be rewritten

$$x_0 = V_g \left(t - \int_0^{y'} \frac{dy}{V_t(y)}\right) \sqrt{1 - \frac{V_g^2}{V_t(y')^2}} \qquad (3)$$

$$y_0 = y' + \frac{V_g^2}{V_t(y')} \left(t - \int_0^{y'} \frac{dy}{V_t(y)}\right). \qquad (4)$$

These equations are valid for all y' and t.

Although in general these two equations cannot be put into a closed expression for D(t), the procedure for calculating D(t) is straightforward. Values of y' are substituted in Eq. (4) until that value of y' for which $y_0 = V_g t$ is obtained; this value of y' in Eq. (3) gives D/2 directly. It can be readily confirmed that for the simple case, V_T = constant, the result quoted in Section II obtains.

As an example of the use of these equations, Fig. 4 shows the profiles calculated for an etched track for various etching times and a specific, simple choice of V_T (decreasing linearly to V_G to the end of the track). The track remains pointed until its end is reached and then rounds out. The diameter increases monotonically at a decreasing rate. Although larger diameter differences are obtained at long etching times, the unique, pointed character of the tracks is lost and they become difficult to discriminate from background pits.

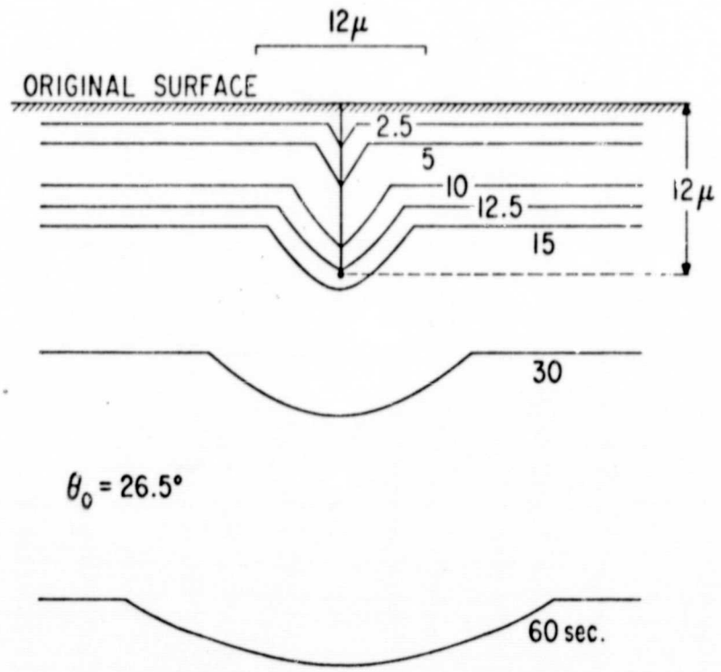


Fig. 4 Etching of a fission track in a glass of initial cone angle 26.5°. For this calculation it was assumed that V_g = 0.58μ/sec, V_T = 1.36-0.0657y' μ/sec, and R = 12μ. The initial cone angle is appropriate to obsidians.

V. COMPARISON WITH EXPERIMENT

It has been shown by Somogyi[15] for plastics, and Fiedler and Höppner[16] for glasses, that the diameters of etched tracks are a function of the energies of the track-forming particles. In both cases the results derive simply from the variation of V_T along a track [as we showed in the plastics[1] and have shown here for glasses] and from the differing ranges of different particles. Since Fiedler

and Höppner have measured diameters of tracks in glass as a function of time for Cf^{252} fission fragments, their work provides a useful opportunity to check the calculations outlined here. In Fig. 5 we have used an empirical fit to the data in Table I for lime glass to calculate diameter-time relations for fission fragments slowed down to lower energies so as to have residual ranges of 12μ, 10μ, 8μ, 6μ, 4μ, 2μ, and 1μ. Figure 6 is a comparison of the diameters so calculated with those measured by Fiedler and Höppner. The agreement is excellent, well within the probable errors of the measurements, lending strong support to the description of the etching process given by Eqs. (3) and (4).

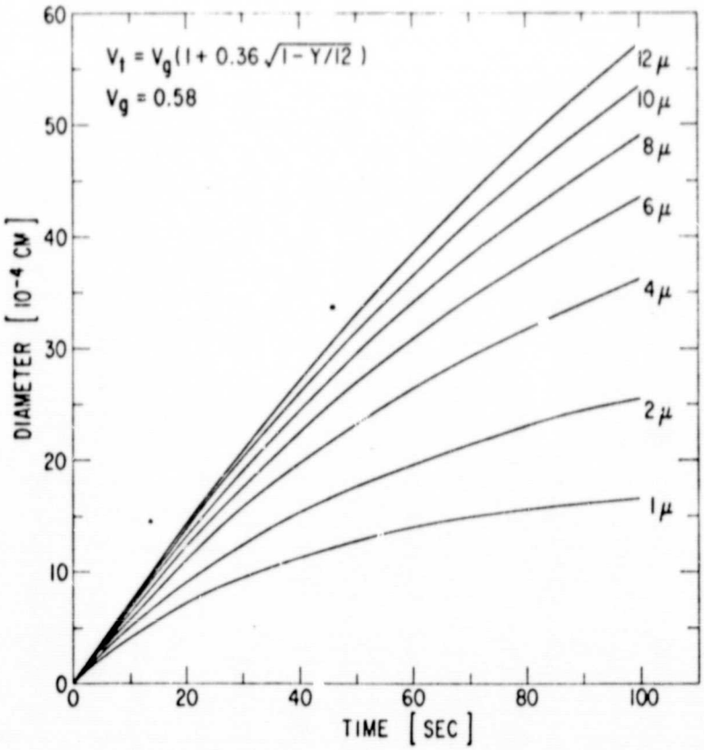


Fig. 5 Diameter vs time for etched tracks of different lengths in glass. In this calculation we assumed $V_T = V_G(1+.36\sqrt{1-y'/12})$ where y' is the distance along the etchable particle range, and starting values of y' of 0, 2, 4, 6, 8, 10, and 11 were used corresponding to fission-track lengths of 12μ, 10μ, 8μ, 6μ, 4μ, 2μ, and 1μ. $V_g = 0.58\mu$/second. The conditions considered are appropriate to ordinary soda glass (microscope slides, etc.).

VI. PARTICLE IDENTIFICATION

Particles may be identified if their energy (or residual range) and energy loss rate (or ionization rate) are known at any position along their path. It follows that, for known particles, curves such as those given in Fig. 5 allow the energy to be determined, as has been shown empirically previously (Refs. 15, 16). Where both the particle and its energy are unknown, they can be determined by making length measurements [as before[1-3, 6]] or diameter

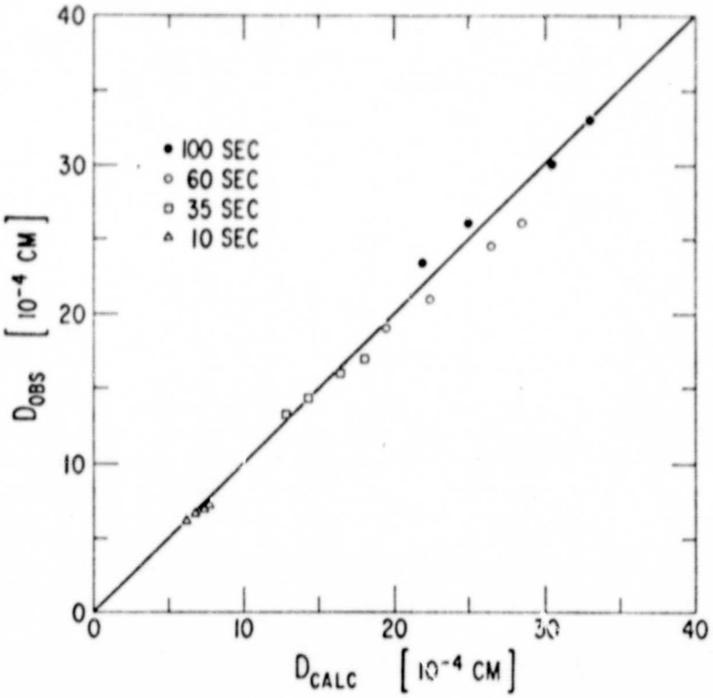


Fig. 6 Comparison of calculated diameters with those measured by Fiedler and Höppner for fission fragments of various energies in glass. We assumed $V_T = 0.43\,(1+.36\sqrt{1-y'/12})$ μ/sec etching rate along the track of full energy, light, Cf^{252} fission fragments. For each time the points correspond to fragments of energies 80, 65, 40 and 34 MeV.

measurements at two or more points along the trajectory or at two or more etching times. The energy is related to range through an appropriate range-energy relation (e.g., see Ref. 17).

Figure 7 demonstrates the decreasing ionization rate along fission tracks. A sheet of SiO_2 glass thinner than the range of fission fragments was irradiated and etched, giving rise to cone-shaped tracks on both surfaces, with obvious decreases in diameters on the lower surface resulting from the decreased ionization rate. The continuations of the particle tracks into a second piece of glass have also been observed, so that it is certain that these particles crossed the sheet shown in Fig. 7. Cone-length measurements from the glass in Fig. 7, together with measurements of track range in the second piece of glass, provide for each event two independent values of ionization rate at known residual range and thus provide two independent ways of identifying each particle.

For a detector having small cone angles [such as the phosphate glass[9] used here], Fig. 8 shows that diameter measurements after short etching times reveal only the value of V_g and hence contain no specific information on particle identification. Only after etching fission tracks long enough that the effects are felt of the larger cone angles which obtain at low residual range do the curves separate. A more

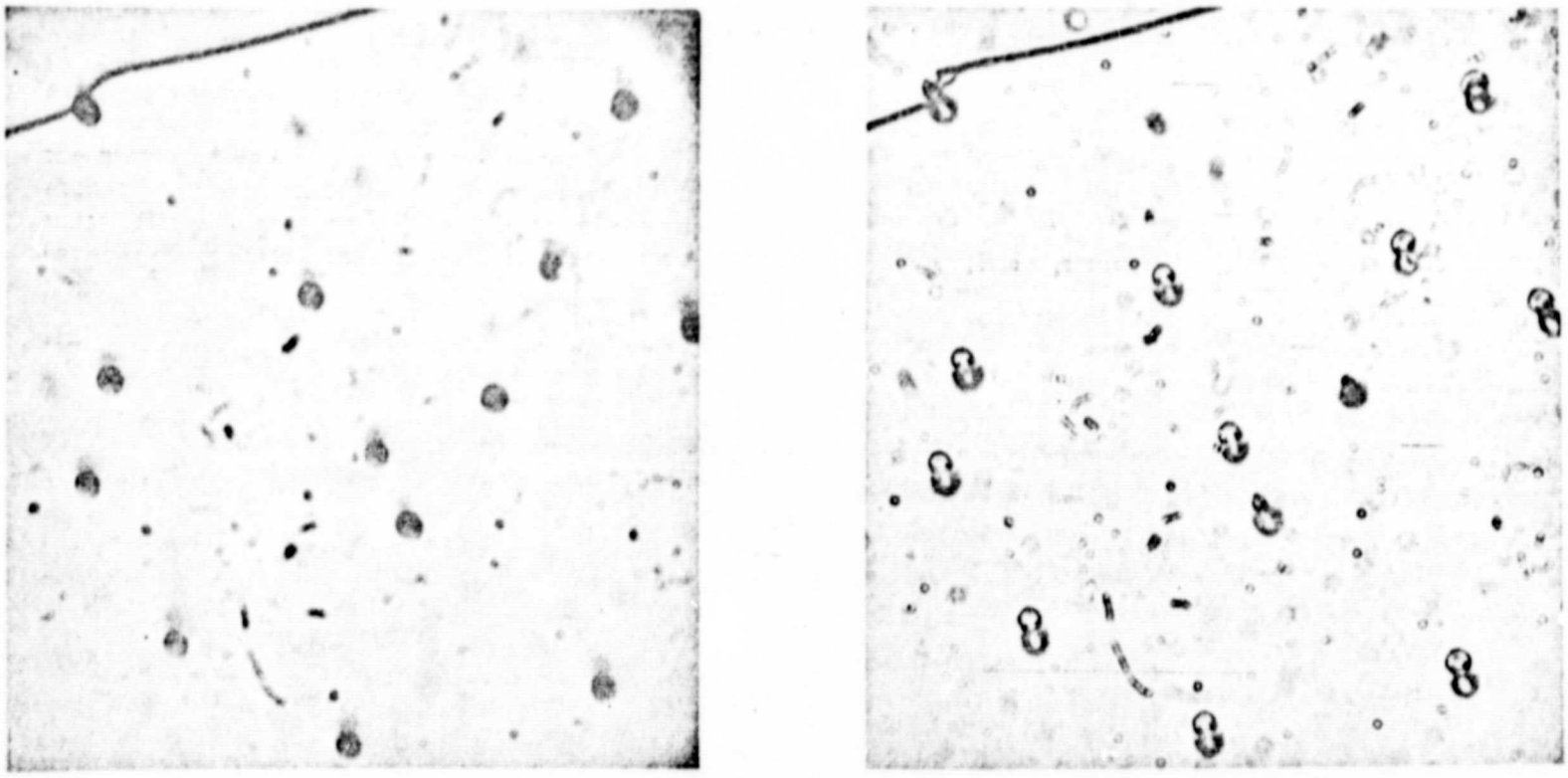


Fig. 7 Decrease in etching rate with slowing down of Cf^{252} fission fragments. Left: etched tracks on upper surface of thin sheets of SiO_2 glass viewed in reflected light. Right: the same etched tracks on lower surface viewed in transmitted light. Decreases in ionization rate during slowing down are revealed by smaller diameters of the pits on the lower surface.

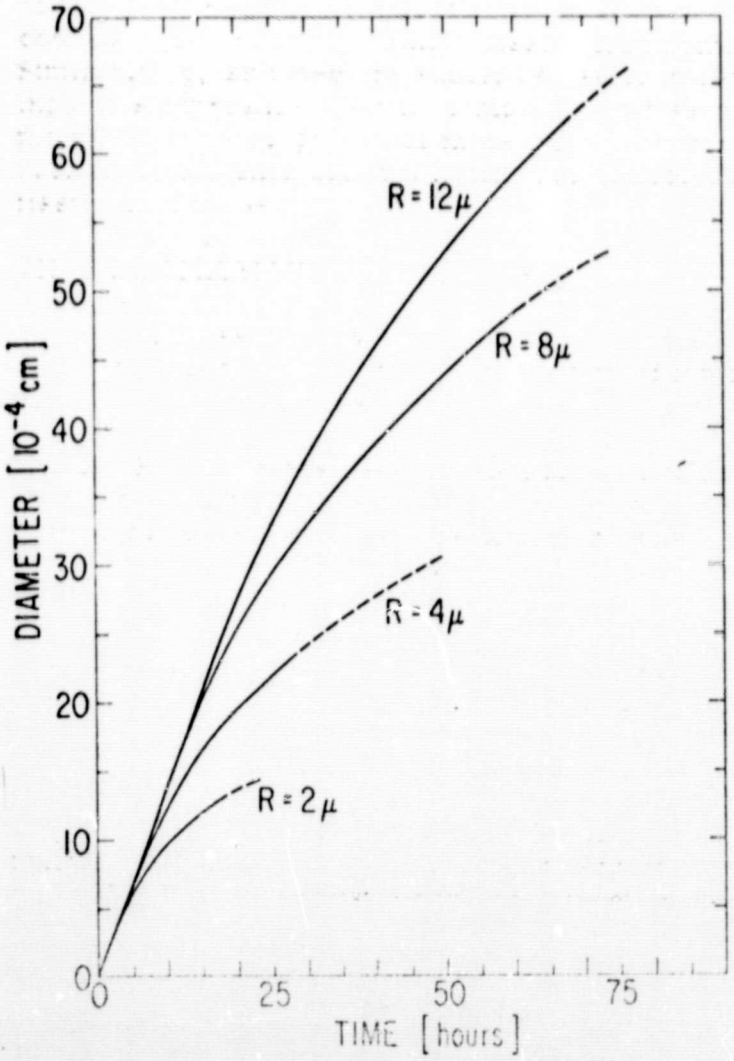


Fig. 8 Diameter vs time for etched fission tracks of different lengths in a glass with a small cone angle. In this calculation we assumed $V_T = V_G(1+14/1-y'/12$ where y' is the distance along the etchable particle range, and starting values of y' of 0, 4, 8, and 10 were used corresponding to fission track lengths (R) of 12μ, 8μ, 4μ, and 2μ. $V_g = 0.7\mu$/hour. The conditions are appropriate to P_2O_5 glass.[9] Because $V_T >> V_g$, the initial increase in diameter is given by V_g, so that differences in diameters are imperceptible. Either length measurements for short times or diameter measurements for long times are necessary to discriminate between different particles.

useful procedure for this case is to measure V_T directly.

This can be done even for short tracks in a simple manner by making sandwich structures,[18] consisting of alternate layers of detector and metal film, which can be etched through the detector layers to the metal layers which are dissolved by the same etchant. The diameters of the holes in the opaque metal films can be related to the track-etching rates (averaged over the individual thickness of the detector films).

VII. DISCUSSION

It should be clear that the inorganic glasses are detectors which are capable of particle identification by the same principle that allows identification in plastics. There are two striking differences. First, the glasses are less sensitive and hence do not respond to the passage of many of the particles that will create tracks in plastics, and for other particles will record their tracks only over a smaller fraction of the range. Secondly, the glasses are less affected by elevated temperatures and by background effects such as the ambient atmosphere or the presence of lightly ionizing and electromagnetic radiation. The glasses are therefore especially suited to observing very heavy cosmic rays in long space exposures without the need for rigid control of the ambient conditions. In studies involving heavy element synthesis glass detectors would also be appropriate for seeking occasional fission fragments from superheavy, trans-actinide elements in the midst of a copious background of ordinary fission fragments. Similarly, glass detectors should be useful in detecting any short-range, heavily ionizing particles in the midst of a background of more lightly ionizing radiation--for example, spallation recoil nuclei and fission fragments.

VIII. CONCLUSIONS

1. In glasses as in plastics, etching rates along particle tracks are an increasing function of ionization rate and thus make possible particle identification.

2. Etching rates vary with ionization level in widely different degrees for different glasses. Phosphate glass has the highest resolution; that is, it has the greatest change in etching ratio for a given change in ionization rate.

3. Calculations of track diameters based on the observed etching rate vs ionization relation for an ordinary glass agree well with recent measurements.

4. The etching rate V_T along tracks in crystalline inorganic solids is undoubtedly also an increasing function of ionization rate, although the function will probably depend on crystallographic direction as well as on ionization rate.

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APPENDIX VI

ARE FISSION TRACKS IN METEORITES FROM SUPER-HEAVY ELEMENTS?*

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Abstract

The length distribution of binary fission tracks and the low ratio of ternary to binary fission tracks in several meteorites fit the original interpretation of a ^{244}Pu origin and are inconsistent with an interpretation that they were produced by fission of super-heavy elements.

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ARE FISSION TRACKS IN METEORITES FROM SUPER-HEAVY ELEMENTS?

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The possible existence of an island of increased stability in the chart of the nuclides somewhat beyond the presently known elements is the subject of much current experimental and theoretical activity. Recent shell-model calculations[1,2] predict a closed proton shell at Z=114 or 126, with a neutron shell closure at A=184. Nilsson et al.[3] have estimated that the isotope $^{294}110$ is β-stable, has a half-life of $\sim 10^{10}$ y for spontaneous fission and $\sim 10^{8}$ y for α-decay, and thus may exist in nature. In view of the great uncertainties associated with this calculation, many workers, ourselves included, have regarded the prediction as merely indicating that a search for super-heavy, transactinide elements in nature is worthwhile, without restricting the search to any particular nuclide or range of lifetimes.

The premise on which a search for a long-lived super-heavy element ("element X") in nature is based is that it may have been synthesized along with uranium and other trans-bismuth elements by rapid neutron capture in objects such as supernovae within our Galaxy[4] and that later it could have reached earth in the cosmic radiation or could have condensed from the interstellar gas as part of the original solid matter of our solar system. Evidence for the detection of one or more atoms of super-heavy elements in the cosmic radiation has recently been obtained[5] but has not yet been established[6]. Anomalously high concentrations of Xe^{136} in certain meteorites have recently been attributed to fission

products of element X (Ref. 7). It is likely that other anomalies in nature are also being re-analyzed with element X being evaluated as the possible culprit.

The purpose of this note is to anticipate and answer negatively the question "Are fission tracks in meteorites from super-heavy elements?"

As the most primitive matter at our disposal (solidification age $\sim 4.6 \times 10^9$ y, gas-retention ages up to 4.6×10^9 y)[8], meteorites are certainly attractive objects in which to search for "fossil remains" of short-lived, extinct elements. In fact, our quantitative knowledge of their primitiveness is based on Reynolds'[9] discovery in 1960 of excess ^{129}Xe from the decay of the now-extinct isotope ^{129}I ($\tau_{1/2} = 17 \times 10^6$ y) within certain meteorites.

More recently, evidence for fission products of an extinct element in meteorites has been provided by the discovery in certain meteorites of excess neutron-rich Xe isotopes[10] (suggestive of fission) and by the discovery in several meteorites of fission tracks far in excess of the number from spontaneous fission of ^{238}U or from possible induced fission of heavy elements[11-14]. A study of the excess fission tracks in three different minerals of one meteorite[12] provided a strong case that the fissioning species was ^{244}Pu ($\tau_{1/2} = 82 \times 10^6$ y). Making the reasonable geochemical assumption of a constant initial Pu/U ratio in each mineral, Fleischer et al.[12] showed that the variation in fission track density in the three minerals was consistent with the different track-retention temperatures of the minerals if the meteorite cooled at a rate of about $1^{\circ}C$ per million years--a rate that had

been independently deduced on the basis of electron microprobe studies of the nickel-iron phases of this meteorite.

Suppose, however, that in addition to ^{244}Pu there were super-heavy fissioning species in the meteorite at its time of formation. It might even be argued that the chemical properties of "super-actinides" in the vicinity of the closed shell Z=126 should resemble those of the actinide elements[15], so that the assumption of a constant initial Pu/U ratio could also apply to the initial X/U ratio. We present two lines of evidence that the fission track contribution of element X was negligible in the meteorites studied: (1) the absence of ternary fission events in the minerals, and (2) the agreement in length distribution of fission tracks with that expected for ^{244}Pu rather than with that expected for a super-heavy element.

In discussing the first line of evidence, we note that both theory[16] and observations[17,18] of ternary fission of compound nuclei with very large values of Z^2/A indicate that super-heavy nuclei with comparable or larger values of Z^2/A should break up into three (or more) fragments in a significant fraction of fissions. Previous observations and pertinent values of Z^2/A are summarized in Table I. In the present investigation we have searched unsuccessfully for three-pronged fission tracks among the ancient fission tracks previously attributed to ^{244}Pu and ^{238}U in three meteorites. Our upper limits on the ternary to binary fission ratios are summarized in Table II.

Track lengths constitute the second set of evidence.

Table III gives observed most probable lengths of ancient binary fission tracks in three meteorites and Table IV gives calculated most probable track lengths for binary fission of ^{238}U and ^{244}Pu and of three proposed super-heavy nuclides. Included in the tables are measured and calculated k lengths for thermal neutron-induced fission of ^{235}U impurities in samples of the same meteorites that had been annealed prior to neutron irradiation to erase the ancient fission tracks. The calculated track lengths in Table IV were obtained using measured[19] or calculated[20] values of translational kinetic energy and numbers of emitted neutrons, a computer code[21] for the range-energy relations that predicts ranges of Br and I ions satisfactorily[22], and the threshold ionization rate for track formation in diopside crystals measured by Price et al.[22]

In binary fission within a sample, both fragments moving in opposite directions create a single observed track. However, the portion of the track length observable by the chemical etching technique is less than the sum of the ranges of the two fragments because the ionization rate of each fragment drops below the threshold for track formation in the last three or four microns of its range[22].

Tables III and IV show that the observed most probable lengths of the ancient fission tracks and induced fission tracks are about the same, 10.5 to 11μ, and agree well with calculated most probable lengths for spontaneous fission of ^{238}U and ^{244}Pu and induced fission of ^{235}U. The kinetic energy released in spontaneous fission of super-heavy elements is calculated[19] to be very large and their fission track lengths are expected to be ~ 20 to 40% longer than those from ^{238}U, ^{244}Pu, and n + ^{235}U. Our observations reinforce the original interpretation that the

majority of the tracks were produced by fission of ^{244}Pu and indicate that the abundance of spontaneously fissioning superheavy elements chemically similar to U was insignificant at the time the ^{244}Pu tracks were formed.

Armed with the two criteria of frequent ternary fission tracks and binary fission tracks 20 to 40% longer than those from neutron-induced fission of ^{235}U, we are searching for evidence of element X in other meteorites and in certain terrestrial minerals.

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TABLE I

Binary/ternary fission ratio as a function of Z^2A

Nucleus	Z^2/A	Binary/ternary	Reference
$n + {}^{235}U$	35.8	8×10^5	23
^{252}Cf	38.2	5×10^5	24
$^{40}Ar + {}^{208}Pb$	40.4	200	17
$^{40}Ar + {}^{232}Th$	43.5	30	18
$^{294}110$	41.3	?	
$^{298}114$	43.6	?	
$^{310}126$	51.2	?	

TABLE II

Lower limits on binary/ternary fission ratio in meteorites

Meteorite	Binary/ternary
Toluca (diopside)[11,12]	> 24000
Odessa (diopside)[25]	> 9600
El Taco (diopside)[14]	> 5500

TABLE III

Observed most probable etched fission track lengths in meteorites

Source	Meteorite	No. Measured	Observed Most Probable Etched Track Length
Ancient, stored tracks	Toluca	500	11.0μ
	Odessa	300	10.5μ
	El Taco	120	11.0μ
n + ^{235}U	El Taco	95	10.6μ
	Toluca	130	10.0μ

TABLE IV

Calculated most probable etched track lengths for binary fission

Nucleus	Kinetic Energy	Neutrons Emitted	Calculated Most Probable Etched Track Length
^{238}U	172 MeV	1	11.2μ
^{244}Pu	172	2.8	11.3μ
$^{294}110$	216	10.6	13.2μ
$^{298}114$	235	10.5	13.9μ
$^{310}126$	293	11.4	16.0μ
n + ^{235}U	172	2.4	11.2μ

APPENDIX VII

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IRON METEORITES: X-RAY ASTERISMS ARE NOT NECESSARILY SHOCK EFFECTS

by

R. L. Fleischer and P. B. Price, General Physics Laboratory

Report No. 69-C-120

March 1969

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TECHNICAL INFORMATION SERIES

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SUMMARY

X-ray diffraction patterns from kamacite in iron meteorites have been suggested as indicators of shock effects. It is shown that the same effects can be produced by slow deformation at low stresses, and that therefore the x-ray data are indicative of deformation but not necessarily of high strain-rate deformation.

KEY WORDS

meteorites, shock effects, x-ray diffraction

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IRON METEORITES: X-RAY ASTERISMS ARE NOT NECESSARILY SHOCK EFFECTS*

R. L. Fleischer and P. B. Price

INTRODUCTION

In an x-ray diffraction study of kamacite from iron meteorites, Jaeger and Lipschutz (1968) showed that exposure to shock pressures of 100 to 1000 kb resulted in progressive elongation and subsequent general broadening of the diffracted x-ray reflections. They proposed further that the x-ray spot elongation (which is normally referred to as asterism and was called preferred orientation by Jaeger and Lipschutz) could be used as a barometer of shock pressure experienced by a meteorite during its past.

Since x-ray asterism commonly results from static (i.e., slow) deformation of crystals [Barrett (1952)], it would be surprising if meteoritic crystals failed to show the same behavior. We have therefore compressed several samples of the iron meteorite Odessa (from the American Meteorite Laboratory) to strains of 1% to 6% and followed the development of x-ray asterism.

EXPERIMENTAL

Cubes 6 by 6 by 6 mm were compressed in an Instron stress-strain machine. Sample 5 was unloaded at strains of roughly 3% and 6%; sample 6 at 1% and 4%. At each unloading, Laue x-ray back-reflection photographs were taken of individual kamacite crystals. The stress-strain curves shown in Fig. 1 are consistent with the known behavior of iron-nickel alloys [Rees et al. (1954)]. Figure 2 shows the development of x-ray asterism with increasing strain for three crystals, each viewed from near the midpoint of a lateral free surface which was not in contact with the plates of the Instron machine.

The x-ray technique used here differed from that of Jaeger and Lipschutz in that unfiltered radiation was used so that both the white spectrum of wavelengths and the characteristic radiation were present. This procedure, the conventional one used in the Laue technique, renders all x-ray spots sensitive to distortion as the crystal orientation is disturbed, rather than solely the spot or spots corresponding to the wavelength of the characteristic radiation. To test this statement and to assess whether the strains extend throughout the volume of the deformed piece, we carefully sectioned sample 1 with a jeweler's saw, removed 270μ of material by etching in two stages so as to avoid the region deformed by the cutting operation, and x-rayed after each stage what was an interior crystal prior to sectioning. It was found that with Mn-filtered Fe radiation, as in Jaeger and Lipschutz's work, for most crystals only the spot close to the characteristics radiation was spread out into an arc, and that with unfiltered Fe radiation all spots were distorted and deformed and several arcs were visible--as in the upper right-hand section of Fig. 2. As one of the reviewers of this report has pointed out, the total strain in a strongly deformed crystal such as #1 is greater than that normally encountered under simple shock loading.

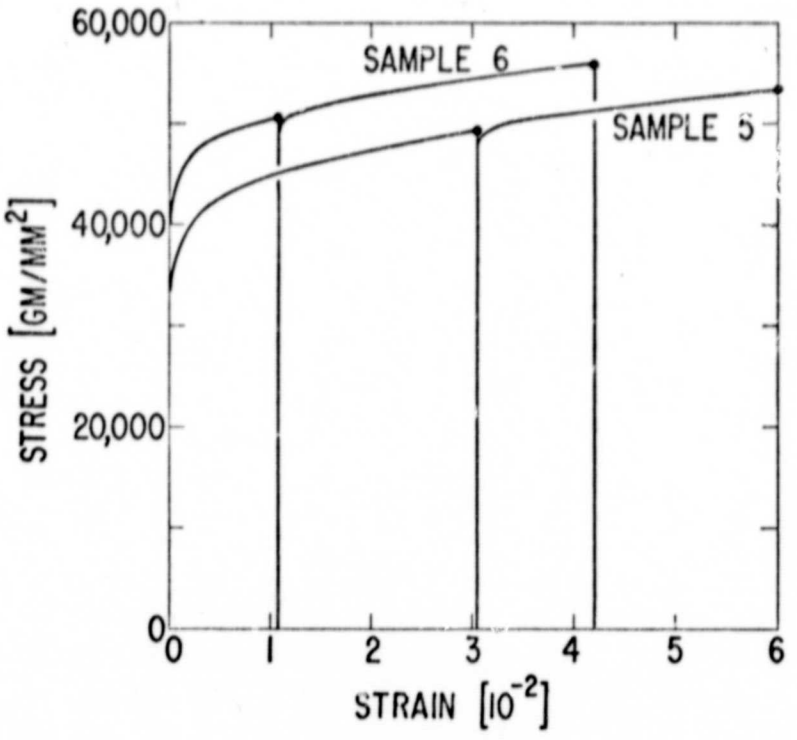


Fig. 1 Engineering stress-strain curves in compression for two samples of the iron meteorite Odessa. Sample 6 was unloaded at strains of 0.0104 and 0.042; sample 5 at strains of 0.0304 and 0.060 for x-ray examination.

DISCUSSION

Although it is clearly possible to produce the asterisms observed in meteorites by shock deformation, as shown by Jaeger and Lipschutz, it should be clear from the evidence just given that the asterism is merely evidence of strain and does not uniquely reveal the mechanism through which it took place. It is therefore worth noting that possible physical processes experienced by meteorites or their parent bodies can be described that are capable of giving the observed effects by relatively low strain-rate deformation at correspondingly low stresses (~50 kg/mm², as shown in Fig. 1).

Nonshock plastic deformation of meteorites can be envisioned either during the parent body phase or during the breakup of such a body. Judging from the meteorites, the parent bodies were far from being homogeneous and isotropic but could be better

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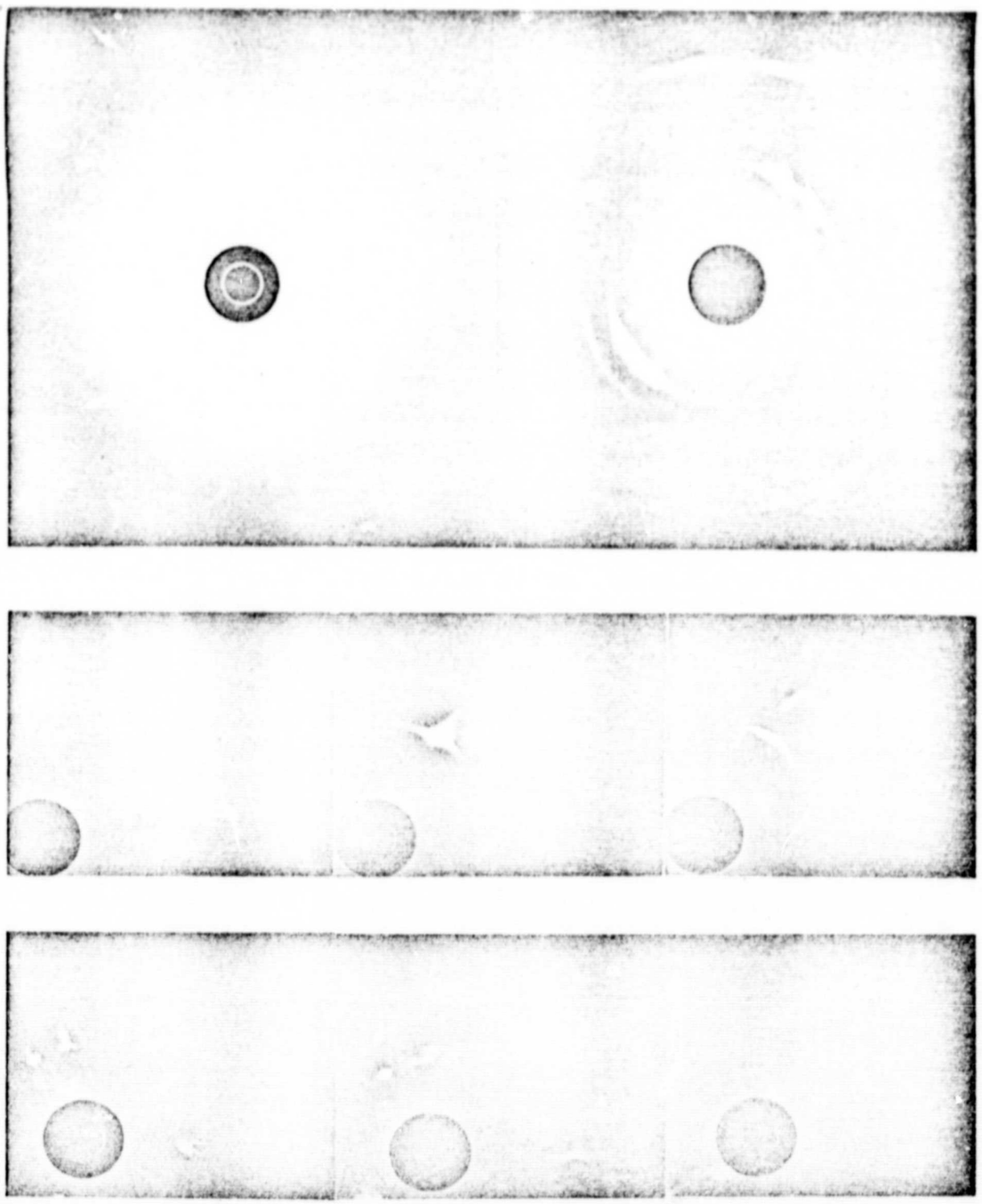


Fig. 2 Effects of compressional strains on Laue x-ray diffraction spots. Top row--a crystal in sample 1: left--unstrained, and right--$\varepsilon = 0.06$; middle row--crystal in sample 6: left--unstrained, middle--$\varepsilon = 0.01$, and right--$\varepsilon = 0.042$; bottom row--a crystal in sample 5: left--unstrained, middle--$\varepsilon = 0.0304$, and right--$\varepsilon = 0.060$. 1 was compressed in a vise; crystals 5 and 6 in an Instron stress-strain machine. Unfiltered Fe radiation. 3 cm sample to film spacing.

described as lumpy. Inhomogeneities give rise to nonhydrostatic stresses in an elastic body [Eshelby (1961)] and these in turn could give rise to plastic strains--detectable by the associated x-ray asterism.

The breakup of a parent body is normally thought of as resulting from a collision between bodies and for this reason may well involve shock. Regardless of whether the relative velocities are sufficiently great to result in shock deformation, the result could be to produce a rotation rate large enough to cause breakup of one of the colliding bodies or possibly of the combined body. Again nonshock plastic strains in the metallic phases would be expected.

CONCLUSION

The existence of x-ray asterisms in the kamacite of iron meteorites is by itself proof solely of deformation which could have occurred during either low or high strain-rate processes.

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