A STUDY OF THE VESTIGIAL RECORDS OF COSMIC RAYS IN LUNAR ROCKS USING A THICK SECTION TECHNIQUE

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Abstract

An experimental technique has been developed for systematic measurements of fossil tracks along selected planes cut from grains and rocks. With controlled etching, the technique allows successive revelation of tracks in different minerals in the same section, a typical sequence being olivine, anorthite, clinopyroxene. It thus becomes possible to study precisely the cosmic ray track density variations over dimensions much greater than those of individual crystals. The technique also provides accurate information on the relative recording characteristics of different minerals present in a rock and cosmic ray tracks can be studied with a minimum interference of tracks due to spontaneous fission of uranium and transuranic elements.

Continuous chains of sections, each section measuring approximately 1 cm., have been cut along several different planes in fifteen rocks from Mare Tranquillitatis, Oceanus Procellarum and Fra Mauro region. The cosmic ray track measurements from these sections have provided dramatic evidence for a number of processes affecting lunar rocks. The statistical, and non-uniform nature of erosion by micrometeorite bombardment can be seen in sections intersecting exposed surface which show regions of very steep track density gradients interspersed with eroded regions having lower track densities. The thick section technique permits determination of the energy spectrum of VH nuclei from track density gradients that extend over distances limited only by the dimensions of the rock, and, more important, in samples of identical orientation. The latter is particularly important in higher energy regions (deeper within the rock) where variations in crystal orientation cause track density differences of the same order as real changes in the gradient. Also in the near surface regions of rocks where low energy particles produce steep track density gradient, the thick section method has proved indispensable since it permits accurate depth determinations not possible in the spot sampling procedure.

In this paper the technique of studying track profiles in thick sections is described. Although developed primarily for studying lunar samples, the thick section technique is also useful for similar studies in meteorites, particularly for gas-rich meteorites containing irradiated grains. In contrast to single grain studies, thick sections preserve the grain boundaries and permit accurate depth—density measurements. In addition thick section studies have revealed occasional large uniformly irradiated lithic fragments which would not have been possible to discover by spot sampling methods.

INTRODUCTION

PREHISTORIC cosmic rays have been extensively studied using meteorites as probes. Specifically, the meteorites St. Severin, Johnstown and Patwar have been examined for fossil tracks (Cantelaube *et al.*,[1] 1967; Lal *et al.*,[2] 1969; Maurette *et al.*,[3] 1969; Lal and Tamhane,[4] 1972) in order to deduce the energy spectrum and flux of cosmic ray iron group nuclei. Similar attempts were made (Crozaz *et al.*,[5] 1970; Fleischer *et al.*,[6] 1970; Lal *et al.*,[7] 1970; Price and O'Sullivan,[8] 1970) to determine the energy spectrum of iron group nuclei using lunar rocks as detectors. However, all these studies were based on the conventional method of studying fossil tracks by batch etching of spot samples (Fleischer *et al.*,[9] 1967; Cantelaube *et al.*,[1] 1967; Lal *et al.*,[10] 1968), where a good deal of useful information is lost. Firstly, the cosmic ray track density observed in a crystal at any location inside a meteorite or a lunar rock depends on the orientation of the crystal with respect to the rock surface.[9] The track production rate, $\rho(\beta, \eta, X)$ (cm^{-2} my^{-1}), at a given depth X usually varies by factors of upto 2 depending on the orientation angles η and β. η, defines the geometry of exposure to cosmic rays and is the angle between zenith and the normal to rock surface. Orientation β is defined as the angle which the tangent to the nearest exposed rock surface makes with the etched surface of the crystal. The earlier track density measurements therefore referred to an average value, ρ_{av},

$$\rho_{av} = \frac{1}{n} \sum_{i=1}^{n} \rho(\beta),$$

based on study of n crystals of unknown orientation. Secondly, the spot sampling technique did not permit precise measurements of $\rho(X)$ for values of X, larger than the crystal dimension. The observed variations in lunar rocks are however very large, particularly for $X < 0 \cdot 1$ cm, where $d \ln \rho / dX \simeq -1 \cdot 4/X$ so that track density variation over depths of tens of microns are greater than a factor of two.

It was suggested earlier[12] that the registration characteristics of different minerals like feldspars and pyroxenes may be different. Elsewhere,[13–15] we have discussed the total recordable track lengths due to induced and spontaneous fission in a variety of terrestrial and extraterrestrial minerals. The differences in track lengths are significant enough to result in a variation in areal tack densities from mineral to mineral, in the case of a sample exposed to an identical dose of track forming nuclei.

To distinguish and properly account for the variation in track densities due to the three parameters (orientation, depth, and track recording characteristics) we have developed the thick section technique for successive revelation of tracks in different crystals of a large (cm × cm) rock section.

Another factor which influences the observed track densities in lunar rocks is spontaneous fission tracks from uranium and other fissionable elements. Although the major rock forming minerals generally contain very little uranium, fissioning elements are often concentrated along grain boundaries so that observed track densities, particularly in small grains from low cosmic ray track density regions, may contain a substantial fission contribution. Because grain boundaries and grain-to-grain relationships are preserved in the sectioning technique, such contributions are more easily distinguished using this method than the spot sampling method.

In this paper we describe in detail the experimental techniques used towards thick section studies, and present the results of measurements in several lunar rocks as illustrations of the information that can be obtained. Implications of these results to long-term flux and energy spectra of VH-nuclei, rates of erosion on the lunar surface, etc., are discussed elsewhere.[16–18]

Experimental Technique

The principal requirement of the present studies is that track density measurements be made in the various mineral grains in a manner so that the orientation and the distance of the etched mineral from the surface is known. Chemical techniques for revealing tracks in different mineral species have been discussed by several authors (Fleischer *et al.*,[12] 1965; Lal *et al.*,[10] 1968; Krishnaswami *et al.*,[19] 1971). Techniques to etch and study tracks in random surfaces of grains from meteorites consist of batch etching crushed samples and later embalming them in a viscous optical medium, such as silicon-grease, for an optical examination (Cantelaube *et al.*,[1] 1967; Lal *et al.*,[10] 1968). An alternate method is to mount selected mineral grains or a representative sample in epoxy resin (Lal *et al.*,[10] 1968). Whenever grains are mounted in epoxy, it is necessary to expose and polish the mounted specimens in order to make a reasonable surface area available for the study of tracks.

In this paper, we describe the various steps for preparing rock sections and revealing fossil tracks in the different minerals present. It is necessary that the section be thin enough to permit transmitted light microscopy (usually 100–300 microns depending on mineralogy) yet thick enough to withstand etching and reprocessing. Successive observations of fossil tracks in the different mineral species also necessitate use of epoxy healing techniques which are discussed here.

Below we describe techniques for spot sample analyses which are necessary to determine proper locations and orientations for the cutting of thick sections. Such a survey is desirable since a large number of lunar rocks show multiple exposure histories; for example, the track densities near the " bottom ", *i.e.*, the buried surface regions of Apollo 14 rock 14321 show, that it was at one time the " top ".

(i) *Spot Sample Analysis Method*

Small chips of a few milligram size are picked from carefully recorded positions on the rock surface, crushed gently and individual grains are deposited on a sticky surface within the hole of a silver holder: *see* Fig. 1. A double-sided tape or a freshly dried rubber solution (Maxifix, Dunlop Rubber of India) is used as the sticky surface to hold the grains in place. We have found the double-sided scotch tape manufactured by Fasson Products, Painesville, Ohio, U.S.A., to be the most satisfactory. Its surface is smooth within about 20 microns and the tape offers very strong adhesion. However, this tape should not be subjected to a temperature exceeding 75° C. when it warps. A drop of freshly prepared epoxy mixture, resin R-86 and catalyst 304 in 20: 1 proportion (Epoxylite Corporation, South El Monte, California U.S.A.) is then put into the hole and cured at 60° C. for 15–20 hours.

The cured sample mount is then ground successively on 600,2/0, 3/0 and 4/0 emery papers so that the desired surfaces are exposed. Subsequently, the crystal faces are polished on a lapping machine using 15 and 3 micron diamond paste and 1, 0·3, 0·05 micron alumina powder.

When only limited numbers of sample mounts are prepared tracks are studied in different mineral grains in the same mount by successively etching for olivines, feldspars and pyroxenes. The same order is followed in the case of thick sections. During the procedure required to etch olivines there is no visible chemical attack on the feldspar and pyroxene mineral grains. The etching conditions for anorthite and bytownite do not reveal tracks in the pyroxene group of minerals. However, tracks in olivines (in certain planes) get over-etched. Also, while etching for the pyroxenes most of the feldspar grains get over-etched. Therefore, it is essential to complete all track measurements in one group of minerals before revealing tracks in the next.

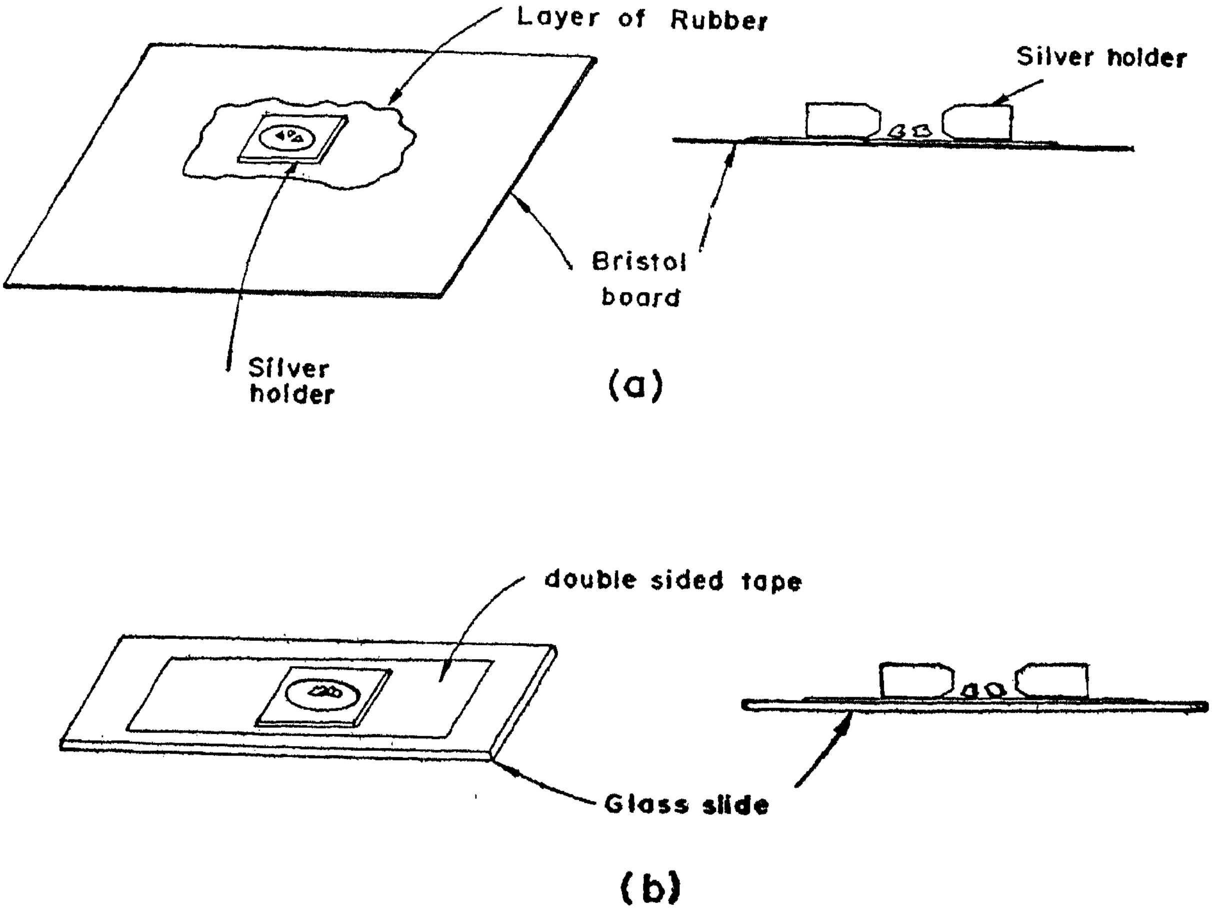


FIG. 1. Schematic of the spot sample mounting technique; the grains to be mounted, are placed within the hole (6 mm. diameter) of a silver holder (typically 1 cm. × 1 cm. × 0·2 cm. thickness). A dumb-bell-shaped hole in the silver holder prevents movement of epoxy during processing.

Two particular advantages of mounting and etching spot samples rather than studying them as loose powder are that it is possible to (i) decorate track holes with silver for high contrast study (in the case of an unmounted sample, it is difficult to remove excess silver from the surface of the grain), and (ii) conveniently preserve them for a future study with a documentation of the co-ordinates of crystals and interesting regions.

The technique of silver-plating track holes is commonly employed by us for measuring track lengths in both spot samples and thick sections. It is however not usually applicable to measuring track densities since after the chemical-plating a part of the surface is lost when excess silver is cleaned from the surface. This results in removal of short tracks. For high contrast measurement of track densities, we therefore use one of the following techniques:

1. Put a drop of a solution of distilled water and a few per cent of surfactant solution (*e.g.*, Kodak PHOTOFLO 200) on the crystal surface and cover with a thin mylar film or cover glass (Macdougall *et al.*,[20] 1971). High magnification observations of tracks are then carried out using oil immersion objectives of (80–100) × magnification.

2. Fill the track holes[10] with a concentrated dye solution (ball-point pen fluid, gentian violet, etc.), apply a drop of viscous silicon grease and then cover with mylar or a cover glass.

3. Plate the track holes with iron-gallic-tannic complex. This is carried out by successively placing drops of concentrated solutions of pyrogallic and tannic acids, crystals of ferrous sulphate and finally a small drop of concentrated sodium hydroxide solution on the crystal surface. The excess material is either wiped off immediately or after some time depending on the required coating of the track holes (the deposit can be cleaned off with nitric acid).

The above techniques are particularly necessary in the case of feldspar which exhibit extremely poor optical contrast with high magnification oil immersion objectives.

Several examples of tracks revealed in grains mounted from spot samples are shown in Fig. 2 (*a*, *c* and *d*).

(ii) *Preparation of Thick Sections*

Based on the results of track density measurements in spot samples from the rock, the orientation of various rock sections to be cut are chosen to correspond to orthogonal slices, usually β_0 (or XY plane) and β_{90} (XZ and YZ planes). In case of spherical meteorites, the β_{90} planes, *i.e.*, XZ and

YZ are equivalent because of isotropic irradiation in space. However, for rocks exposed on the moon, β by itself does not suffice to characterise the track production, except when $\eta = 0$. For this reason we have usually examined two slices in β_{90} plane, orthogonal to each other. The designation of X, Y and Z directions is arbitrary; in this paper, we assign Z to the radial or the maximum track density gradient direction.

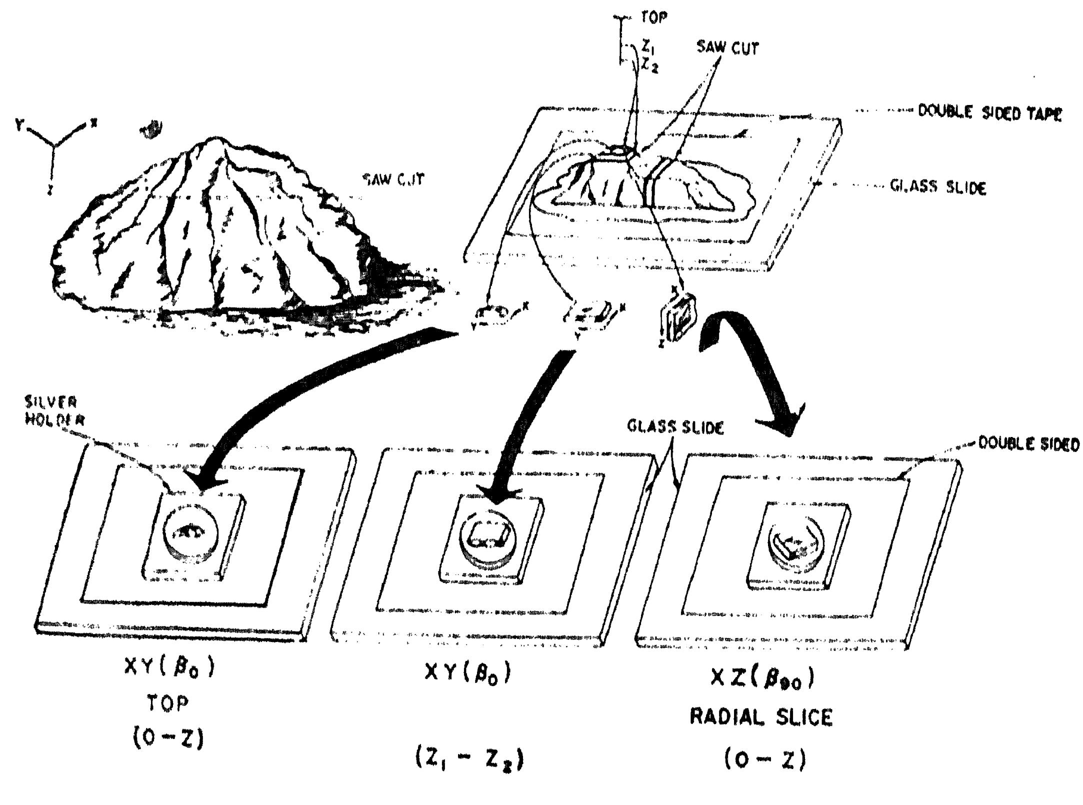


FIG. 3. A schematic representation of the rock cutting and slice mounting techniques for preparing XY (β_0) and YZ (β_{90}) sections. A surface chip is first cut and placed on a double-sided tape stuck on a glass slide. A layer of epoxy resin is painted on the surface to be cut and the rock-tape interface. Documented cut slices are then mounted within silver holders of appropriate size as shown in Fig. 1 (*see* text).

Rock sectioning is carried out using diamond discs and blades. The most versatile motor for this purpose was found to be the DREMEL Moto-tool Ball Bearing motor, Model-280 (manufactured by Dremel Mfg. Co., Racine, Wis., U.S.A.). The motor was operated with a variable auto-transformer; the cutting speed was normally of the order of 1000 RPM. A commercially available device which has been found to be very useful in preparing sections is the low speed saw No. 11 1180 AB isomet (manufactured by Buehler Ltd., 2120, Greenwood Street, Evanston, Ill., U.S.A.).

We have found HORICO diaflex stainless steel discs (5 mil. thick) impregnated with diamond (manufactured by HOPF, RINGLEB Co., Abt D 42, 1 Berlin 45, Gardeschutzenweg 82) to be the most suitable cutting wheels. These discs come in diameters up to 2·3 cm. For larger size discs, we have used the conventional thin bronze wafering blades of 5–10 cm. diameter and a thickness of $\sim$6–10 mil.

The wire-saw technique is quite satisfactory but is very time-consuming and also does not allow the flexibility available with the diamond disc cutting method. To minimise the problems of uneven slicing and the corresponding loss of valuable material, we usually make small sections of the order of 1 cm. in length. In Figs. 3 and 4, we show as an example of slicing sections along the XY, YZ, XZ directions.

The polishing and etching procedures for thick sections are similar to those discussed in the preceding section on spot sample analysis method except that, before etching for pyroxenes, we heal the section with epoxy to prevent loss of material. Feldspar etching in a hot alkali solution loosens and erodes some grains; unless the section is healed, they would fall out during the subsequent pyroxene etching leading to disintegration of the section.

The section-healing procedure consists of the following steps: firstly, a very thin film of silver is chemically deposited in the section, corresponding to 1/16 unit silvering in the procedure described by Macdougall *et al.*[20] (1971). Any excess film of silver deposited on the surface is removed using a soft pencil eraser. The silver-coated section is then successively cleaned in sodium hydroxide, distilled water and ethanol, dried in an oven at 60° C., and finally a drop of freshly prepared resin-catalyst mixture (R–86 + 304) is placed on the surface of the section. The section is briefly warmed to about 100° C. so that the epoxy will flow into cracks and eroded areas, and the excess epoxy is then wiped off. The resin is allowed to cure for 15–20 hrs. before further processing.

Photomicrographs of tracks in grains in thick sections are shown in Fig. 2 (*b*) and in Fig. 9 [*see* Section (iii) under results].

(iii) *Electron Microscope Measurement of Track Densities in the Region* 10^{8}–10^{10} *cm.*$^{-2}$

The measurement of track densities upto (5–80) $\times$ 10^{6} cm.$^{-2}$ can be done optically at a magnification of 1,800 X with fairly good accuracy.

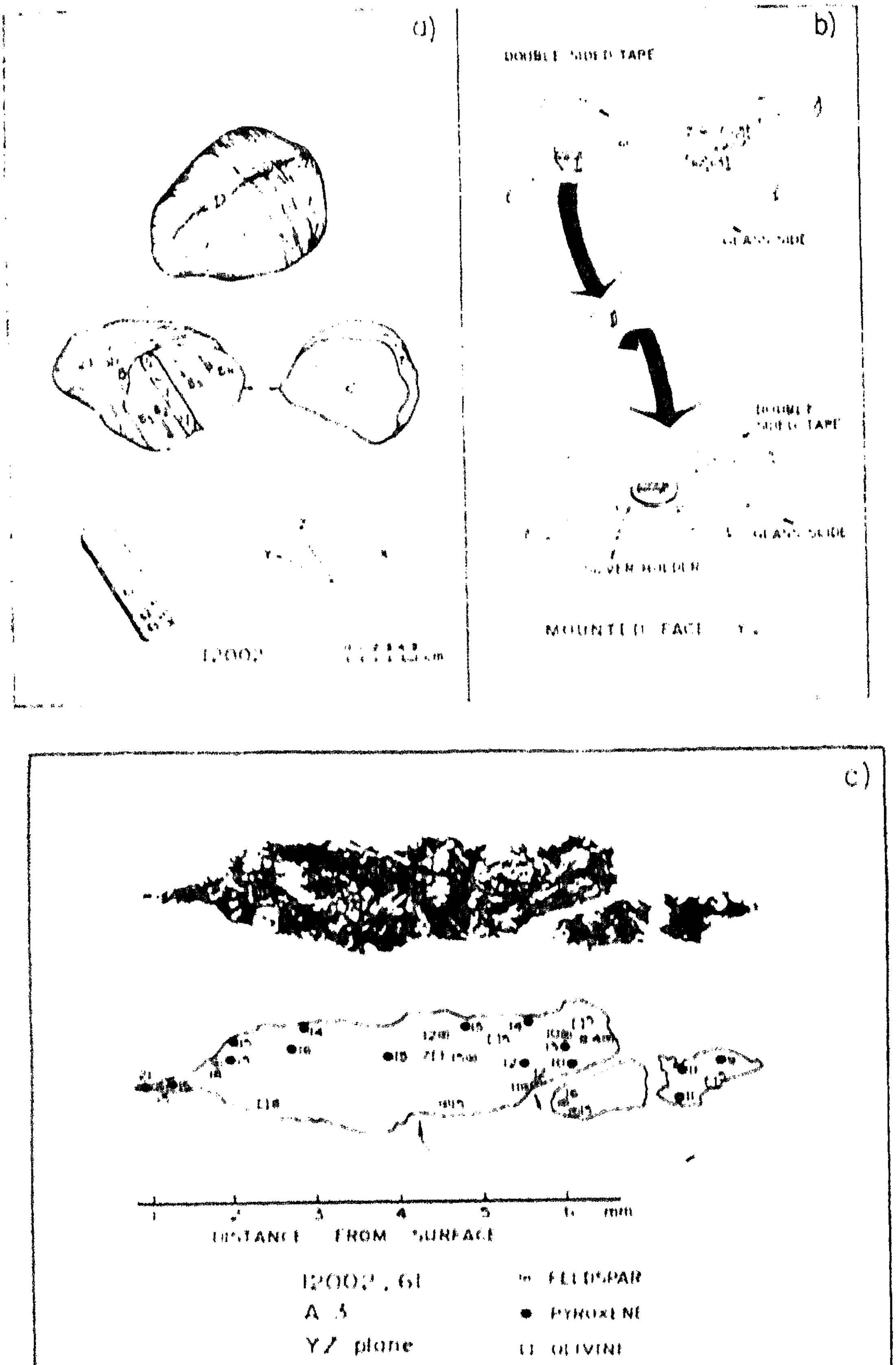


FIG. 4. Track studies in olivine, feldspar and pyroxene grains in Section A3 (YZ plane) from rock 12002. Fig. (*a*) shows the position of slice 12002, 61 in the rock. Fig. (*b*) shows the sectioning and mounting. Observed track densities, along Z, in the three mineral grains are shown in Fig. (*c*). Two chips at the deeper end broke off during mounting; their approximate positions are shown by arrows.

However, the track densities in the near surface regions of lunar rocks and dust are usually much higher due to intense bombardment by low energy solar cosmic rays. For estimating track densities of about 10^8–10^{10} cm^{-2} which cannot be resolved using the optical microscope, we employ the replication procedure (Macdougall *et al.*,[20] 1971) which is an adaptation of the standard two-stage plastic-carbon replicating technique (*cf.*, Brammer and Dewey,[21] 1966). Counting is done on the electron micrographs of palladium shadowed plastic replicas at a magnification of 6,000 to 30,000, depending on the etching time which governs the track size.

In Fig. 5 we have shown various types of replica tracks obtained depending on the experimental parameters: (*a*) etching time, (*b*) angle of shadowing and (*c*) thickness of carbon and palladium coatings.

The small tracks in Figs. 5 (*a*) and (*b*) are due to short etching times, about 25 per cent. of the normal optical etching time for optical measurements. Figures 5 (*c*) and (*d*) show replicas of well developed tracks where the etching time is about 40–50 per cent of the normal optical etching time. In Figs 5 (*b*) and (*d*) and Fig. 6 (*b*) the shadows are almost absent due to large angle shadowing. Figure 5 (*a*) and Fig. 6 (*a*) show examples of optimum shadowing angles, 10°–15°. The thickness of the carbon and palladium coatings affect the contrast and sharpness of the replicated tracks in the final photomicrograph. The dark black tracks (Figs. 5 *a*, 5 *c* and 6 *a*) are due to heavy palladium coatings.

An inter-comparison between optical and electron microscope track densities in the 10^7–10^8 cm.$^{-2}$ region shows that the track density is usually overestimated by upto a factor of 5 in the replicating technique. Furthermore, there is a tendency to progressively overestimate at higher track densities. We are now carrying out systematic measurements to determine the causes of these differences. In the present study we have normalized the replica counts to the optical data at a track density of 5×10^7 cm^{-2}.

In the next section, we discuss results of observations and measurements of fossil tracks in thick sections of 15 lunar rocks using the experimental techniques described above.

RESULTS OF COSMIC RAY AND FISSION TRACK STUDIES IN THICK SECTIONS OF LUNAR ROCKS

(i) *General Observations of Fossil Tracks in Sections*

The present techniques permit detailed measurements of nuclear tracks in rocks in a manner analogous to studies of nuclear emulsions. Although diameter $\geqslant$ 100 microns. Even with this precaution, in the spot sample method it is not always possible to completely eliminate a fission contribution since the exact position of the grain boundary is not preserved. Also in the spot sample method it is not possible to distinguish between track density variations due to difference in orientation (β), those due to variations of fissioning elements, or those due to cosmic ray tracks in irradiated crystals in breccias. In the thick section method both the difficulties are avoided. Grain boundaries are well preserved making it possible to limit measurements to the interior regions of crystals, and since a given section has the same orientation, crystal to crystal track density variations due to differing β angles are eliminated.

(iii) *Cosmic Ray Track Profiles in Lunar Rocks*

The rock samples allotted to us by NASA have all come from rocks of roughly 5–20 cm. diameter. The type of sample differs from rock to rock, and we have received *through slices*, which are complete slabs extending from one side of a rock to the other; *part slices* which extend only part way through the rock; and *surface* or *interior chips* which are usually irregularly shaped rock pieces cut or broken from the rock surface or rock interior respectively. In case of the first Apollo sample studies by us, rock 10017, we analyzed mainly spot samples from surface fragments allotted by NASA to Prof. J. Arnold and Prof. G. Arrhenius at University of California, San Diego. Details of the sample type for each rock studied by us are given in Table I.

TABLE I

Relevant details on sampling of different Apollo rocks

Type of sample	Rock number(s)
Through slice ..	12002, 12018, 14303
Part slice ..	14310, 14321
Surface and interior chips	12020, 12038
Surface chips ..	12004, 12008, 12022, 12063 14310, 14311, 14321
Interior chips ..	14305, 14068
Spot samples from surface	10017

Perhaps the most important advantage in studying thick sections is that this is the only way to obtain accurate track density gradients, and to make proper deductions about the energy spectrum of the track forming cosmic rays and about lunar erosion rates or ablation of meteorites. In Fig. 8, we show thick sections from two rocks we have measured, which illustrate the advantages of the technique quite dramatically. In Fig. 8 (*a*) the section is from a rock surface and contains a steep track density gradient. Figure 8 (*b*) shows a section from the interior of the same rock. Here the track densities vary little throughout the section, the small differences being most likely due to statistical counting errors and variations in uranium content from mineral to mineral. Sections like these are ideal for intercomparison of track densities among different mineral species. Figure 8 (*c*) shows a section which extends f om 3·1 to 4·2 cm. inside rock 12018, 20. Even at this depth, a track density gradient, although slight, is detectable in a section in a radial plane. Such a gradient would be impossible to detect simply by measuring spot samples from various positions along the slice since variations in β would produce differences in track density greater than the change along the section.

In Fig. 9, we have illustrated the way in which track density profiles are measured in a thick section. Selected areas of Fig. 9 are shown at high magnification to illustrate the characteristic appearance of track densities of various magnitudes. Usually a scaled " map " of the thick section being studied is made, and measurements are taken at carefully located positions and recorded on the map. From these raw data the track density profile is constructed.

In the very high density areas, as can be seen from Fig. 9, individual tracks cannot be resolved with the optical microscope; in these cases we use the electron microscope replica technique (Fig. 10).

The observed track density (cm.$^{-2}$) profiles in the 15 rocks studied are given in Figs. 11 and 12 for sections along various planes and for different mineral species. The track density profiles show that rocks 12018 and 12038 represent the simplest exposure history among all the rocks, as has been pointed out elsewhere (Bhandari *et al.*,[16] 1971). The following observations can be made about the rocks studied:

In the case of rock 12018.

1. The track density distribution is centro-symmetric, with a minimum near the centre and increasing steeply at the two ends of the slice.

2. Near the two ends, track densities change by a factor of five within a millimetre of the surface and by more than an order of magnitude over the first centimeter. Between 1 mm. and 1 cm., this rock and 10017 have the steepest gradient found among all the Apollo rocks studied.

3. The track densities in the β_0 plane are usually higher than densities in the β_{90} plane close to the surface but tend to be equal near the center of the rock.

4. The track densities in feldspars are higher than in pyroxenes and those in pyroxenes are higher than olivine at almost all depths, the difference becoming more prominent in regions of lower track density.

Rock 12,038 bears a burial mark and its orientation on the moon is known. The main characteristics of the track profile are:

1. The track density decreases from 5×10^8 cm.$^{-2}$ to 7×10^6 from one end of the rock (, 17) to the other (, 16).

2. Near the "top" surface, this rock exhibits the steepest gradient seen: the density falls off by a factor of 15 in the first millimeter as illustrated in Figs. 8 and 9 where the distribution of track densities in Sections I-2, 11-1 and I-2, 11-2 are shown.

3. Again, there is a tendency for track densities in feldspars to be systematically higher than in pyroxenes.

Results on other rocks studied are discussed in detail elsewhere (Bhandari *et al.*,[16,18] 1971, 1972). Most other rocks show a flatter profile than 12018 and 12038.

(iv) *An Intercomparison of Cosmic Ray Track Densities in Identically Irradiated Minerals*

This study cannot be carried out using the spot sample technique, unless one considers averages based on measurement of a large number of crystals, since the track density at a given depth in a rock depends on the orientation of the crystal. Also, in near-surface regions, the spot sample technique cannot be used because of strong gradients (in track densities) with depth. We have, therefore, carried out studies of track densities in different minerals

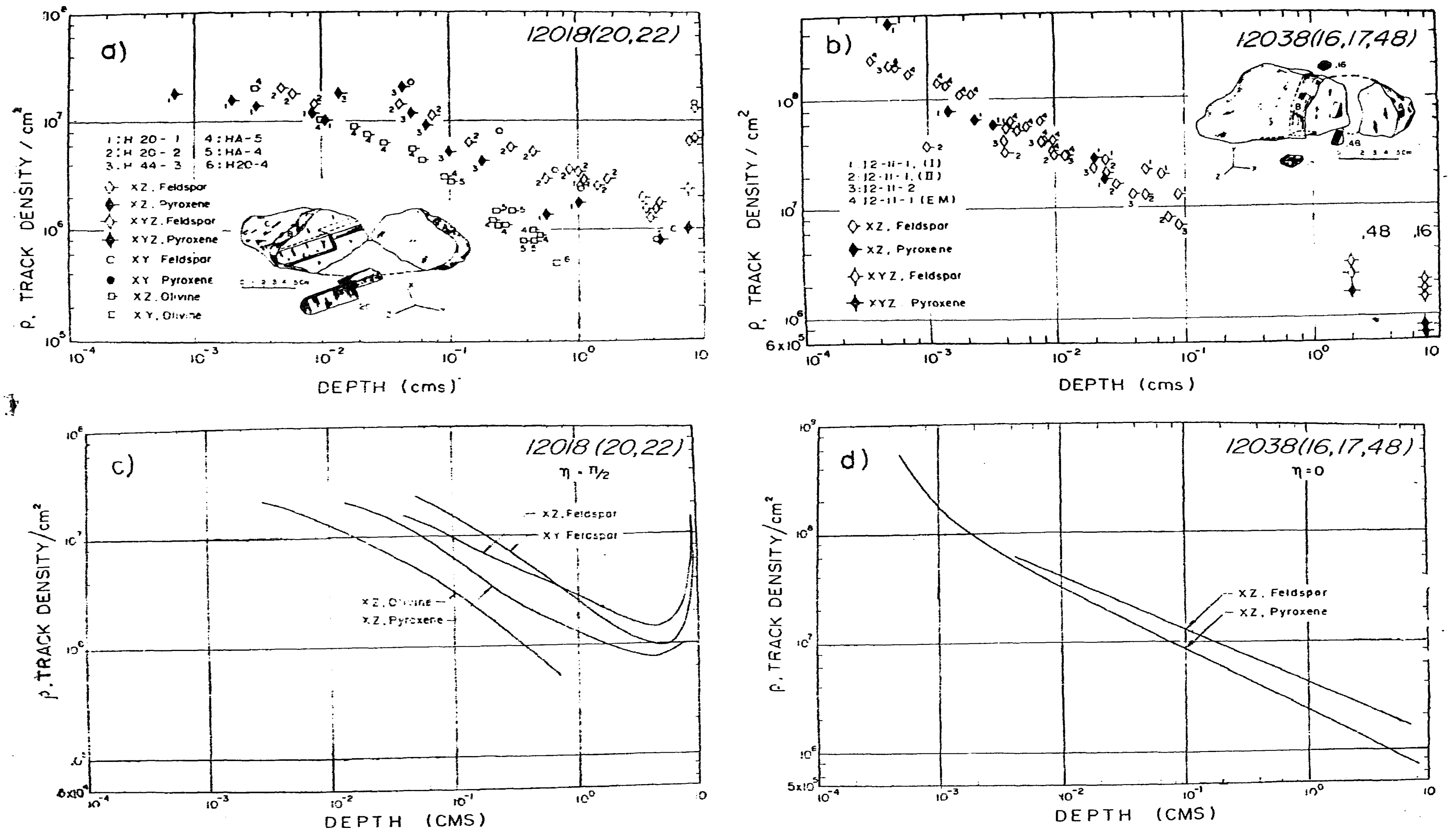


FIG. 11. Representative illustrations of track data obtained by the use of thick section technique. (*a*) and (*b*) show the original position of slices/chips in the rock from which thick sections were cut. The legend in Figs. (*a*) and (*b*) gives the code of the thick section (by a number), the orientation, and a symbol identifying the mineral studied (diamond, circle, and square). The best fit track profiles for the different minerals and thick section orientations are shown in Figs. (*c*) and (*d*). On the basis of track data, the orientation of the rock surfaces on the moon is deduced to be $\eta = \pi/2$ for 12018 and $\eta = 0$ for 12038.

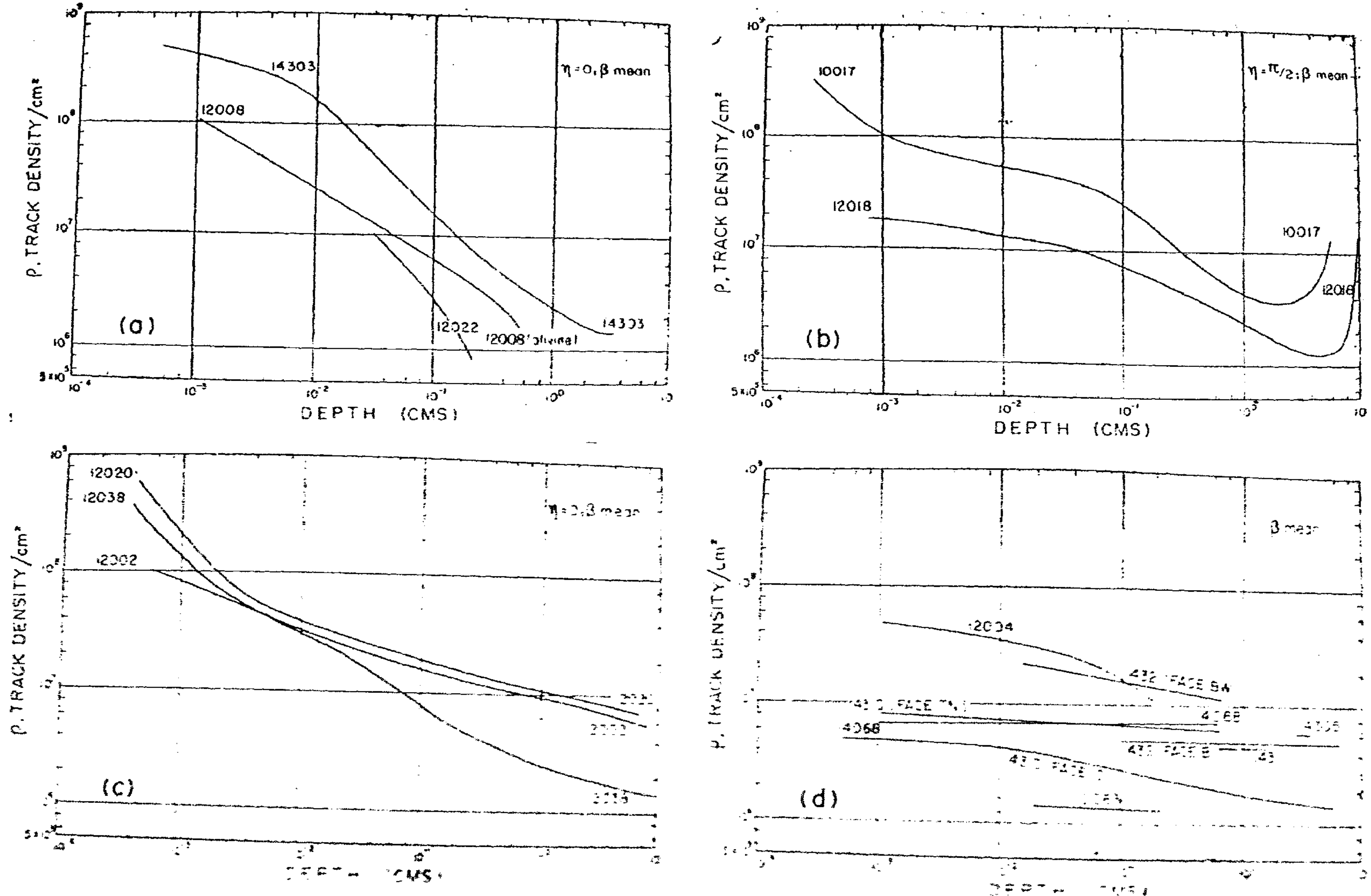


FIG. 12. The best fit track profiles in fifteen Apollo 11, 12 and 14 rocks based on track data in thick sections. Figs. [illegible] and [illegible] represent cases where rock surfaces have been exposed unshielded whereas in the case of Fig. 12(d), the rock faces studied are defined [illegible] have been shielded during exposure, as judged from the flat track profiles. In all cases, the track densities are mean values for thick sections of different orientations. Rock 12[illegible] data were measured in [illegible]; all other profiles are based on measurements in feldspar or pyroxene.

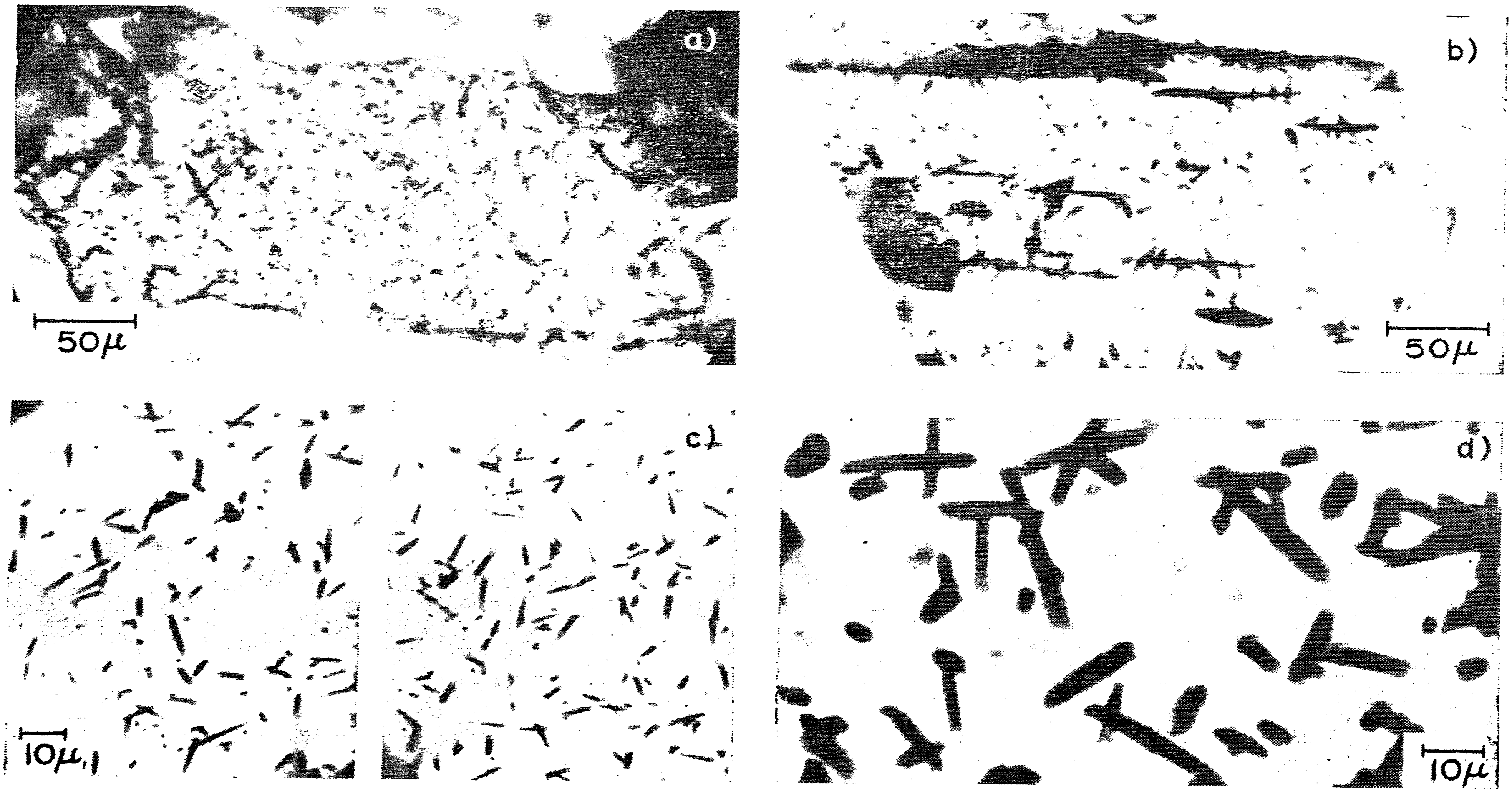
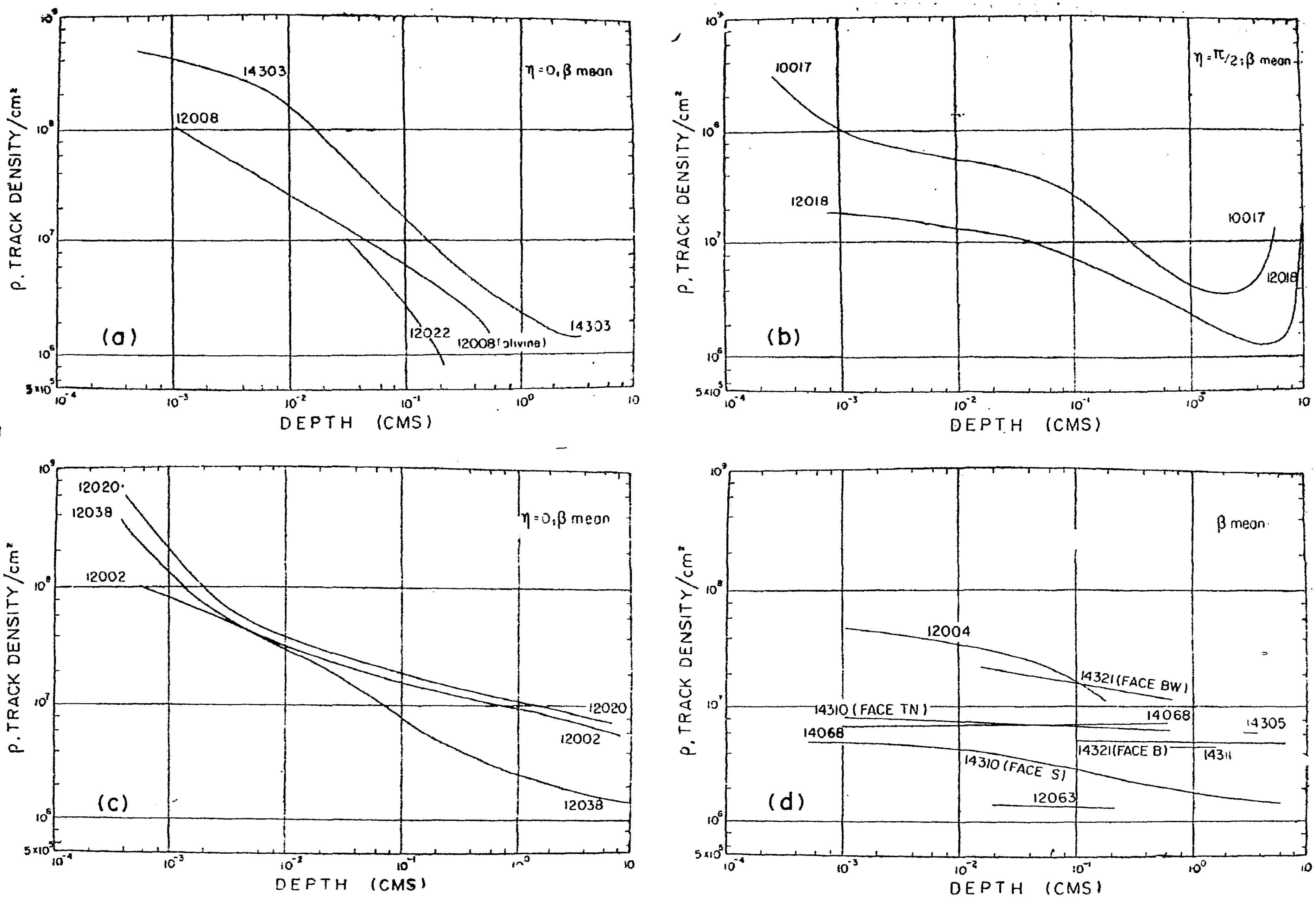


FIG. 2. Fossil tracks in feldspar and pyroxene crystals. Figs. (*a*), (*c*) and (*d*) refer to single grains picked from rocks 10017 and 14310 and fines 12025, 28. Fig. (*b*) refers to a feldspar crystal in a thick section from rock 12002, a few microns of surface was grinded off for a clearer view of the TINCLEs: the original areal track density was about 2X higher.



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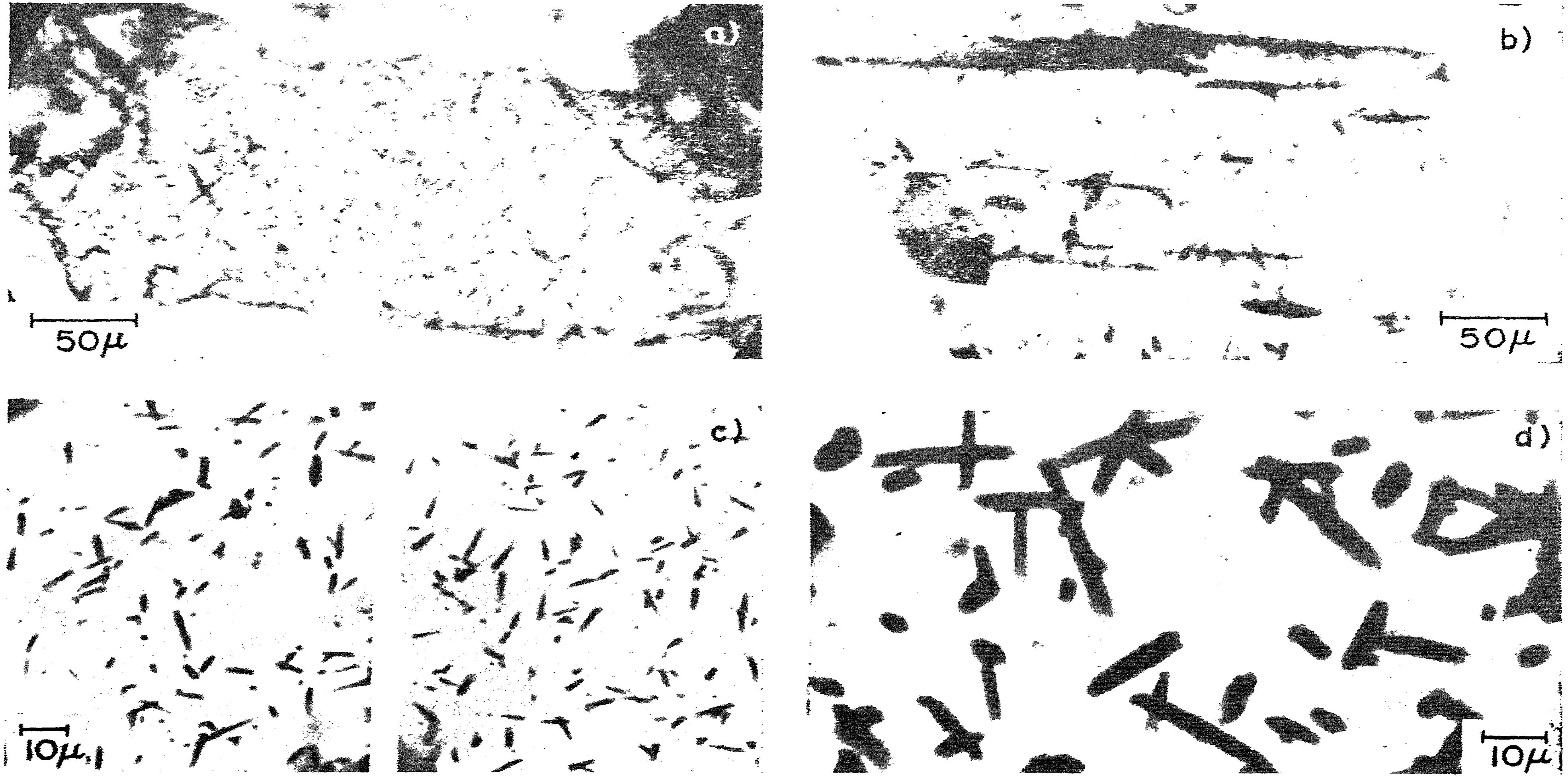

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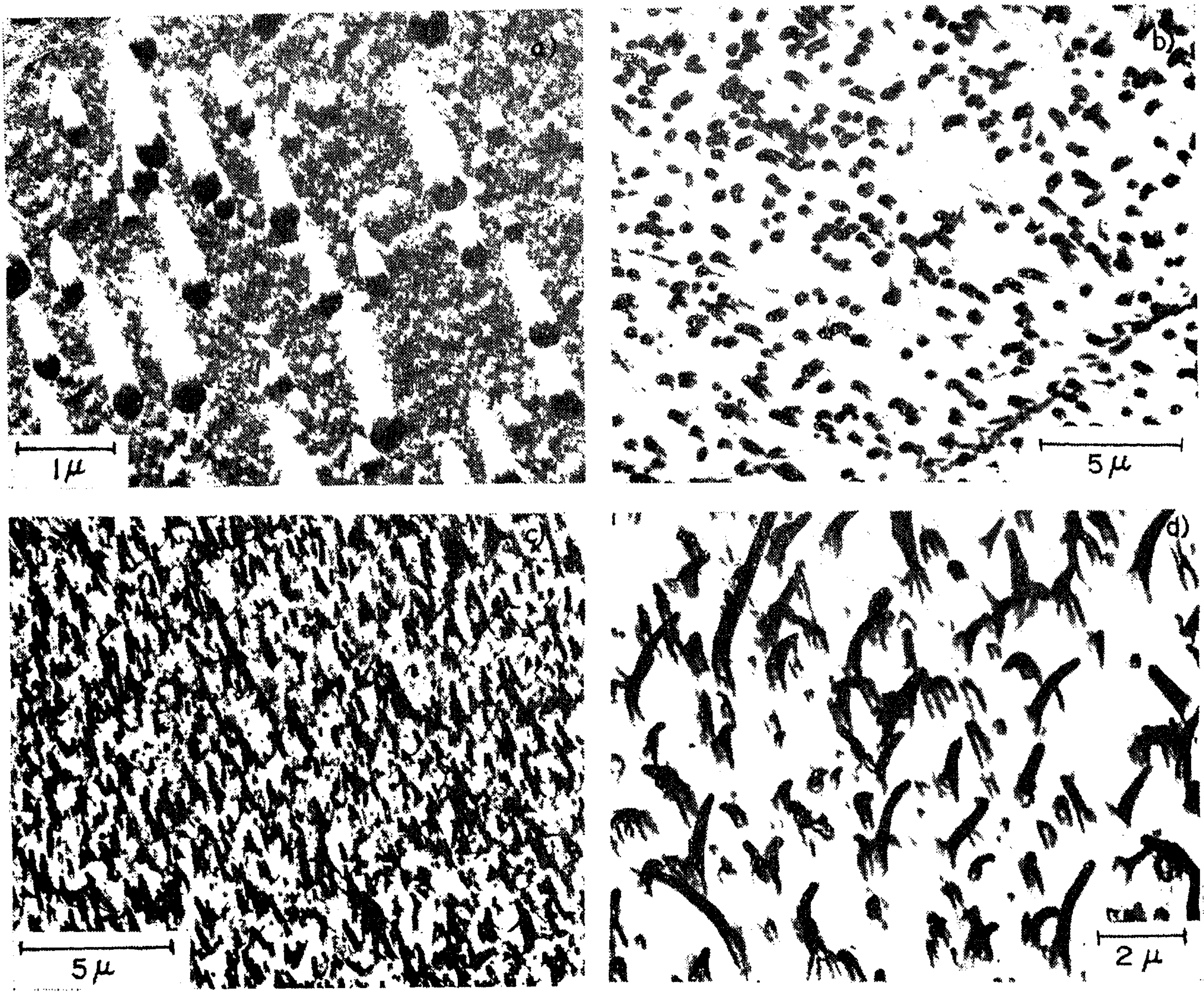

FIG. 5. Electron micrographs of track replicas to illustrate the different track appearances depending on the various experimental parameters, such as time of etching, shadowing angle and amount of carbon/palladium coated; *see* text for discussion. (*a*) Olivine grain from fines 14259 etched in WN for 40 minutes at the boiling point. (*b*) and (*c*) are Feldspar grains in thick sections from rocks 12038 and 14303, respectively; the time of etching in both cases was 20 minutes at the boiling point of 6 gm. NaOH, 12 cc H_2O solution. (*d*) Olivine grain from fines 12037, 57 etched in WN at its boiling point for 40 minutes. In all cases the track density is close to 10^8 $cm.^{-2}$

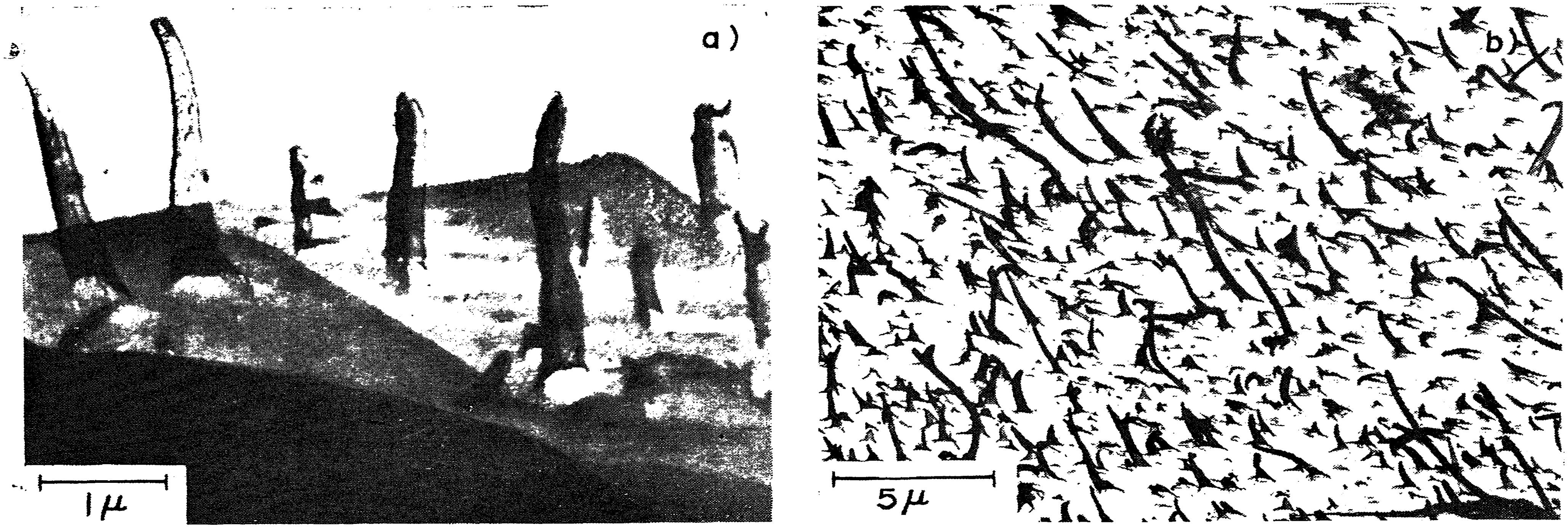

FIG. 6. Electron micrographs of track replicas which are more or less ideal for accurate counting of track, densities. (*a*) Tracks in a feldspar grain from rock 12038. The time of etching was 20 minutes at the boiling point of 6 gm. NaOH, 12 cc H_2O solution; $\rho \approx 10^8$ cm.$^{-2}$ (*b*) Tracks in olivine grain from 12037, 57. The time of etching was 40 minutes at the boiling point of WN solution.

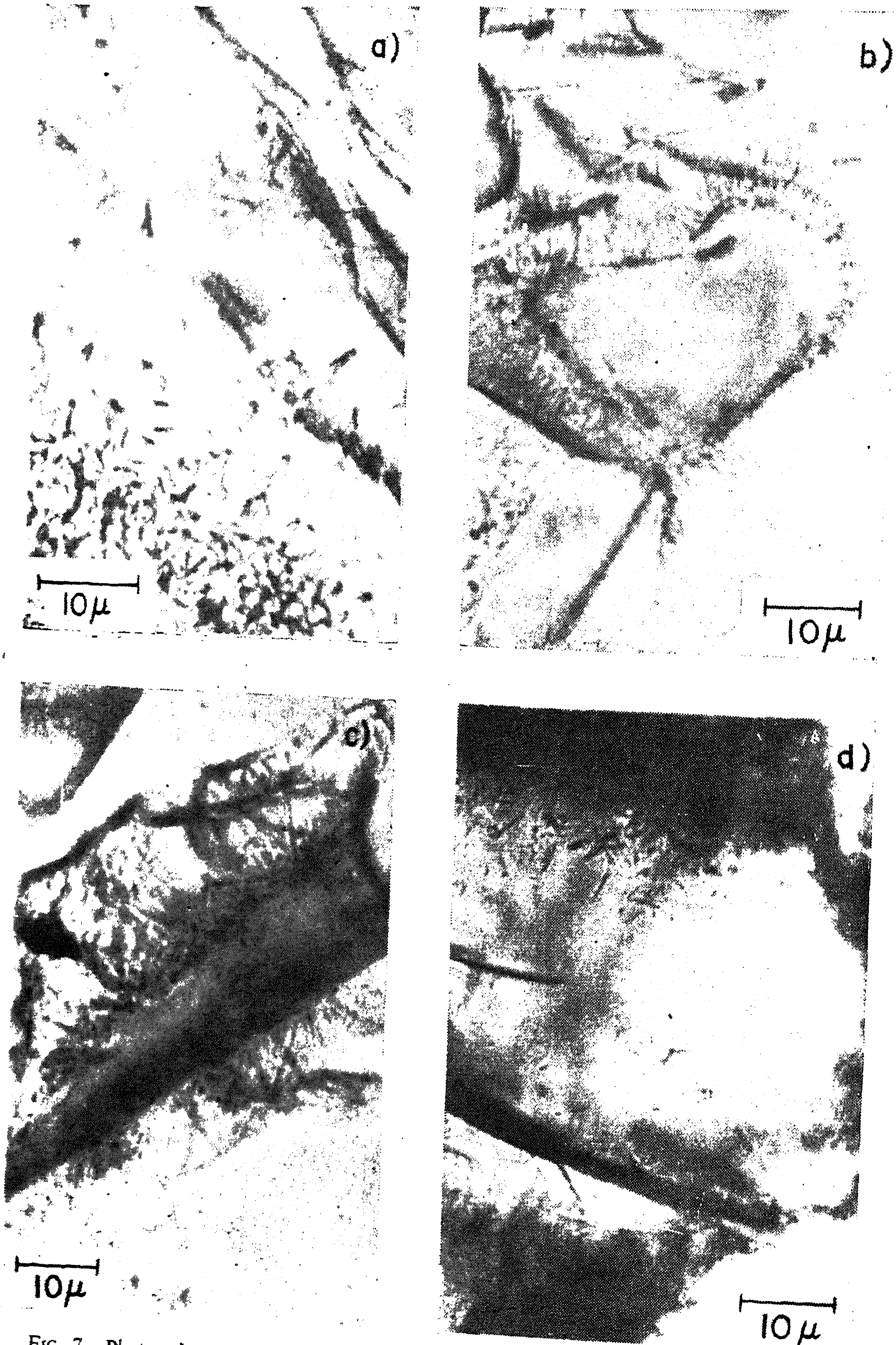

FIG. 7. Photo-micrographs of etched tracks revealed in thick sections of three Apollo rocks showing the localisation of fission tracks along grain boundaries. Figs. (*a*), (*b*) and (*c*) show tracks in feldspar from rocks 14311 and 14310. Fig. (*d*) shows tracks in a pyroxene grain along the grain boundary in rock 12002.

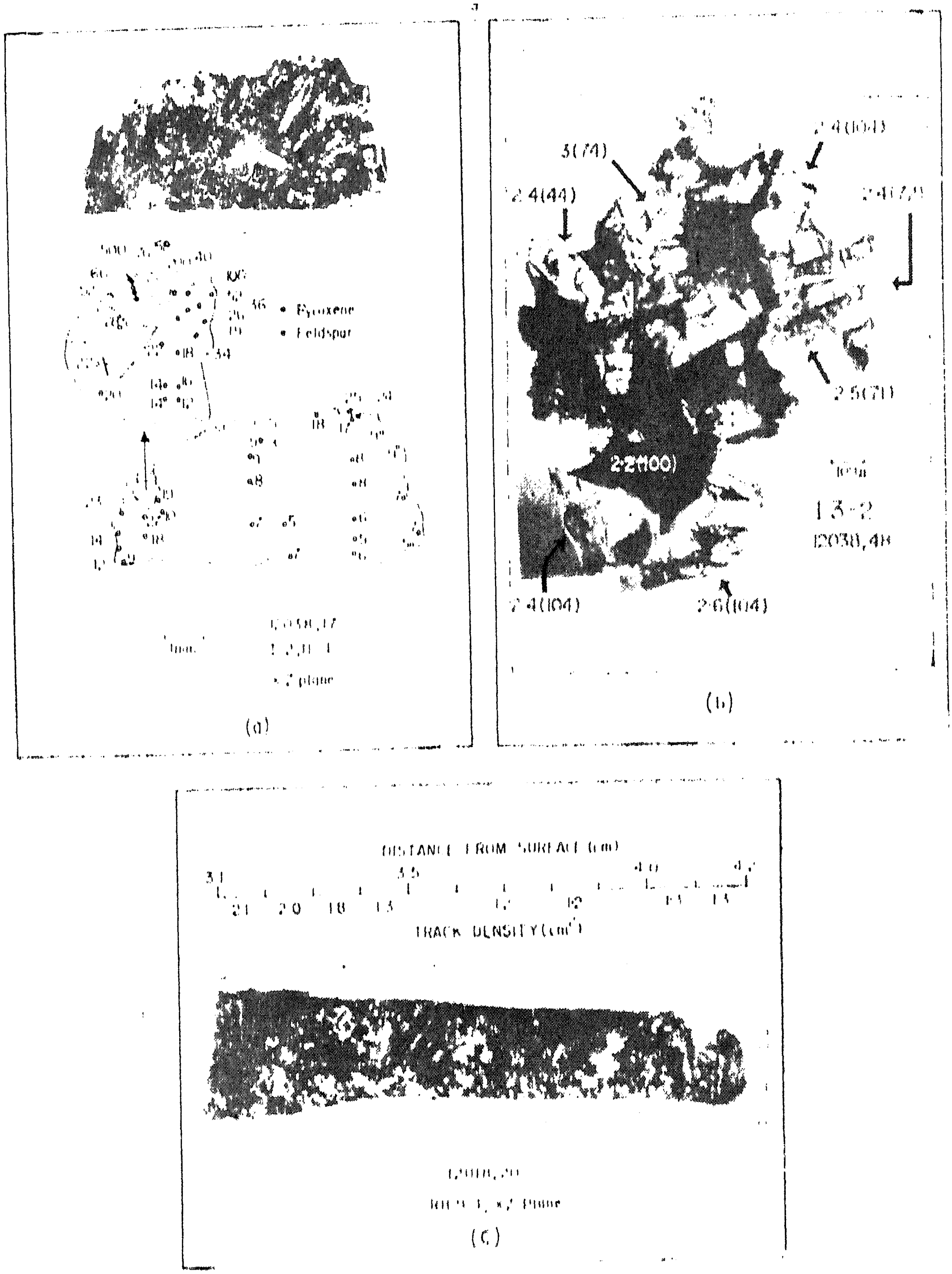

FIG. 8. Typical examples of variations of track densities measured using the thick section studies. Track densities measured in transparent crystals are shown in units of 10^6 tracks cm^{-2}. In (*a*), the measured track densities are shown in the fascimile accompanying the thick section photograph. This section was made from a surface chip and shows a steep gradient from the upper left corner (this area is shown in more detail). In case of the interior chip, (*b*) track densities are nearly the same throughout the section. Fig. (*c*) demonstrates that small gradients can be measured fairly accurately using the thick section technique. The track density decreases from $2 \cdot 1 \times 10^6$ to $1 \cdot 3 \times 10^6 cm^{-2}$ over a distance of ~ 1 cm.

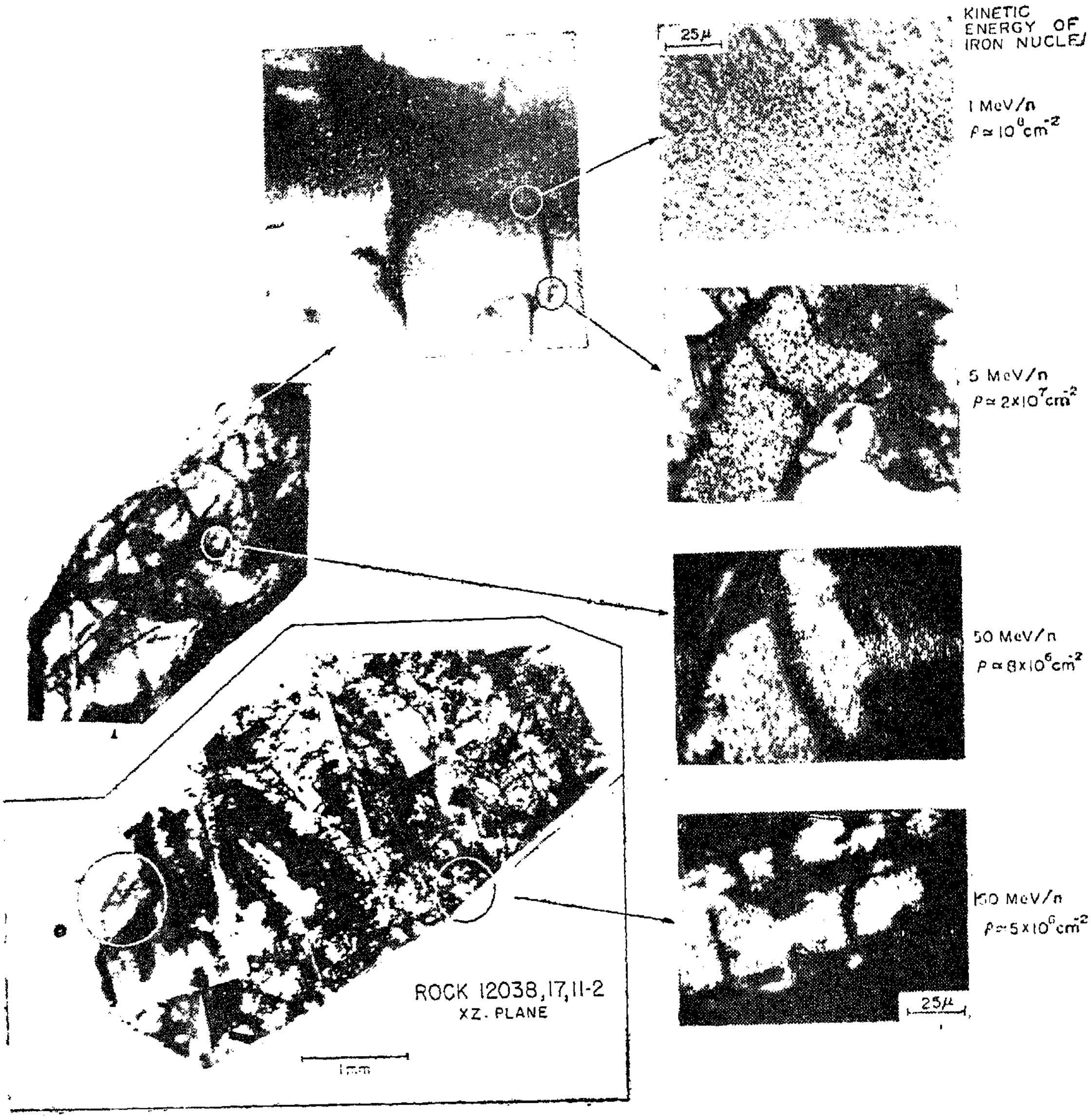

FIG. 9. The *solar cosmic ray imprints* of fossil tracks in a surface section of rock 12038. The photomicrograph near the bottom of this figure shows the whole section. High magnification photograph of selected areas of the section etched for revealing tracks in feldspars are shown to illustrate the appearance of region having different track densities. Based on the measured depth from the rock surface, approximate effective energies of the track forming nuclei are indicated with each photograph.