MINERALOGICAL STUDIES OF GONDWANA SEDIMENTS FROM KORBA COALFIELD, MADHYA PRADESH, INDIA. PART II—SCANNING ELECTRON MICROSCOPY OF SAND GRAIN SURFACE-FEATURES

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ABSTRACT

Quartz grain surface textures of the Gondwana sediments from Korba Coalfield, Madhya Pradesh are studied with the help of scanning electron microscope. The results presented in this paper suggest that SEM studies of the quartz grain surface textures can also be successfully used to confirm and identify the depositional environment of this sediment unit, as obtained by other fields of studies, like petrography, mineralogy, palynology, etc.

Sand grains from Talchir stage show marked glacial features, whereas the sand grains from Barakar stage depict fluvial features. The surface features of quartz grains suggest that the change from glacial to fluvial environment, from Talchir to Barakar is a gradual one because the quartz grains from upper part of the Talchir already show some abrasion under fluvial conditions. Diagenetic history of a sediment can be studied with much more precision by scanning electron microscope (SEM) than by other conventional methods. Sand grains from Talchir Stage have escaped diagenetic changes due to protective action of matrix. Sand grains of Barakar Stage have been mild to moderately affected during diagenesis, resulting in secondary overgrowth. The overgrowth was stopped in rather early stages of development, probably in response to the non-availability of silica. The major source of silica has been considered to be the silica released during kaolinitization of felspars, and the dissolved silica in the pore waters.

INTRODUCTION

Mechanism of transport and physico-chemical conditions in the depositional environment modify the surface of the sediment grains. Nature of surface texture is strongly dependent upon the composition of the grains. Quartz is very stable mineral under hydrosphere, and surface features once formed on it have fair chances of being preserved. Moreover, during diagenesis quartz surface may be modified as a result of overgrowth or dissolution, in response to the diagenetic environment of a rock. Study of such features provides information about the diagenetic history of the sediments, that is why, from earlier days, attempts have been made to study the surface texture of the quartz grains. In this paper quartz grains of an otherwise well-studied succession in lower Gondwana sediments have been investigated to obtain information on the depositional environment and diagenesis and its correspondence with lithological, mineralogical, and palynological parameters has been attempted.

HISTORY OF QUARTZ SURFACE STUDY

SORBY (1880) was perhaps the first person to study the quartz surface features in some detail. CAILLEUX (1942) studied quartz grains from various environments and was able to distinguish between quartz grains from glacial, aeolian, and water-worn sediments. He used a binocular microscope for the study of surface features of quartz grains.

More recently, transmission electron microscope (TEM) and scanning electron micro-

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scope (SEM) have been successfully applied in the study of surface features of quartz grains, wherein surface textures can be studied in much more detail. Study by TEM is a tedious process and involves preparation of replicas. Early studies by TEM were made by Krinsley and Takahashi (1962a), Biederman (1962) and Porter (1962).

Application of SEM in the study of quartz grain surface textures have been much more successful than that the TEM, and it has opened an entirely new field of research (Cailleux & Schneider, 1968; Gees, 1969; Krinsley & Margolis, 1969). There are several advantages in studying surface textures with the help of SEM, the important ones are:

(i) Depth of field is great even at relatively high magnifications.
(ii) Preparation of sample is very simple, as no replica preparation is involved and object is observed directly.
(iii) Range of magnification in which sample can be observed, covers the fields of binocular, conventional microscope, and TEM, e.g. from 30 to 5,000 times.
(iv) Specimens can be observed in various orientations by horizontal rotation and vertical tilting.

BOREHOLE PROFILE OF THE KORBA COALFIELD

The samples used in this study are obtained from borehole no. NCKB-19 penetrating through the Lower Gondwana succession. The lower most 20 m of the succession shows glacial characteristics and belongs to Talchir Stage, whereas the rest of the succession is a deposit of fluvial environment and belongs to Barakar Stage (see Singh & Sharma, 1973).

Bharadwaj and Srivastava (1973) have studied the mioflora from this sequence and made six subzones, each with a characteristic miofloral assemblage and climatic condition. General lithology and mineralogy of the profile have been discussed by Singh and Sharma (1973). In the present study, it has been attempted to use the quartz grain surface features as environmental indicator and to study the effect of diagenesis on the quartz grains of this succession. For this purpose quartz grains of 12 samples from different subzones were studied (see Table 1).

Table 1: Details of the samples from which quartz grains were separated and studied under scanning electron microscope.

Sample No.	Core Depth	Palynological Zone	Lithology
1	18.28 m	III B	Coarse-grained sandstone
14	117.50 m	III B	Coarse-grained sandstone
28	189.80 m	III B	Shaly coal
55	316.00 m	III A	Shaly sandstone
77	413.70 m	III A	Medium-grained sandstone
95	474.90 m	II B	Medium-grained sandstone
107	523.39 m	II A	Grey shale
117	548.50 m	II A	Coarse-grained sandstone
132	666.15 m	I B	Sandy shale
136	674.55 m	I A	Shaly sandstone
142	685.05 m	I A	Sandstone with pebbles
144	688.00 m	I A	Sandstone with pebbles

METHOD OF STUDY

The samples were disintegrated for the separation of sand, silt, and clay fractions. Sand fraction was further sieved into various size-fractions. For surface texture studies fraction 0.315—1.0 mm. was chosen. The grains were observed under a binocular microscope, and random clean quartz grains were picked. On an average they were 0.5 mm. in size. The grains were carefully washed to remove the surface impurities. Washed and dried quartz grains (8-10 in number) from each sample were mounted on mounting stubs with the help of stick-tape. Mounting stubs were, then, placed in a vacuum coating unit and coated with gold-palladium alloy. This produces a thin (few Å thick) coat on the grain making its surface electrically conductive. The grains were observed by a Cambridge SEM. Each grain was studied at various magnifications and characteristic features were photographed for further studies. The grains studied were more or less of the same size, this was done to reduce the bias effect of grain size on surface feature development.

SURFACE TEXTURES OF QUARTZ GRAINS

The surface of quartz grains can be put into two broad categories:

(i) *Primary features*—produced as a result of interaction of various forces during deposition. Such features are significant in the interpretation of environmental history.

(ii) *Secondary or diagenetic features*—These features are superimposed on the primary features in response to diagenetic processes, like dissolution or overgrowth on the surface. Study of diagenetic features provides insight in a post-depositional history of a rock. Waugh (1970) and Pittman (1972) have made important contributions in this direction.

PRIMARY FEATURES

Many workers have been able to give a number of criteria which are diagnostic of various environments, e.g. glacial, aeolian, and beach. Krinsley and Donahue (1968a) and Krinsley and Margolis (1969) give a useful summary of surface textures of quartz grains which are diagnostic of various environments. Other papers dealing with the primary environmental sensitive parameters are those by Krinsley and Takahashi (1962b), Biederman (1962), Krinsley and Funnell (1965), Southendam (1967), Margolis and Kennett (1971), Margolis and Krinsley (1971). As mentioned before, the Gondwana sediments studied here belong to two depositional environments, glacial and fluvial. The characteristic surface textures developed on the quartz grains of these two environments are summarized below.

Diagnostic features of quartz grains from fluvial environment

It has been possible to list a number of diagnostic surface features for some of the environments, e.g. aeolian, glacial etc. While most of the workers have failed to register diagnostic features on the quartz grains from fluvial environment (cf. Krinsley & Donahue, 1968b), fluvial action does produce rounding of the grains, and reduction in relief as a result of wear and tear during transport, but the inherent features dominate the picture. This is because the fluvial activity generally is not strong enough to impose new diagnostic features, as in the case of desert or beach environments. Evidently, the diagnostic features of fluvial quartz grains are, rounded to subrounded outline, moderate to low relief, irregular surface and prominent traces of inherent features. Such inherent features depend upon the source of material. If derived from glacial material, fracture surfaces, breakage blocks, striations, conchoidal fracture are visible in parts. If derived from a sedimentary source with diagenetic effects, quartz surface retains in part the diagenetic features. This type of inherited features are mostly better and longer preserved in the recessed areas of the grain, while on the raised portions older features are obliterated and new ones are formed rather quickly.

DIAGNOSTIC FEATURES OF QUARTZ GRAINS FROM GLACIAL ENVIRONMENT

Sand grains from glacial environment have been extensively studied and they have yielded rather encouraging results. Diagnostic glacial features have been summarized by KRINSLEY AND FUNNELL (1965), KRINSLEY AND DONAHUE (1968a) and MARGOLIS AND KENNETT (1971). According to KRINSLEY AND DONAHUE (1968a), the characteristic surface features of quartz grains in glacial environment are the following:

I—Large variation in size of conchoidal breakage patterns: probably related to the large variation in the size of particles in glacial sediments.
II—Very high relief: probably related to the relatively large size of particles and the large amount of energy available for grinding.
III—Semi-parallel steps: probably caused by shear stress.
IV—Arc-shaped steps: probably representing percussion fractures.
V—Parallel striations of varying length; probably caused by the movement of sharp edges against the grains involved.
VI—Imbricated breakage blocks, which look like a series of steeply dipping hogback ridges.
VII—Irregular small-scale indentations, which are commonly associated with conchoidal breakage patterns: probably caused by grinding.
VIII—Prismatic patterns, consisting of a series of elongated prisms and including a very fine-grained background: probably indicating recrystallization.

The criteria for recognition of glacial quartz grains as suggested by MARGOLIS AND KENNETT (1971) while studying the surface features of quartz grains in the deep-sea cores from Subantarctic region are: large breakage blocks, large conchoidal fractures, randomly oriented striations, semi-parallel step-like fractures, meandering ridges, sharp angular outline, high relief, smooth featureless planes.

Quartz grains of some other environments, e.g. aeolian, and beach also possess diagnostic features; however, these features have not been observed in the samples studied from Gondwana sediments. The characteristic features on the quartz grains of beach environment are: small V-shaped pits, straight or slightly curved grooves, blocky conchoidal pattern, chatter marks, rounded outline, moderate relief. The characteristic features on the quartz grains of aeolian environment are: meandering ridges, graded arcs, upturned fracture plates, fine pitted appearance, minute chemical etching as anastomosing lines, rounded outline, moderate relief. There are some features which develop in more than one environment, e.g. conchoidal fracture, upturned fracture plates. These features have diagnostic value only in combination with other more specific features. For example, upturned fracture plates together with rounded grain outline is diagnostic of aeolian environment; whereas when combined with sharp, angular outline it is characteristic of glacial environment (see MAROGLIS & KRINSLEY, 1971). At the end it may be pointed out that no single feature can be used to identify the origin of a quartz grain. It is the combination of certain features that has high diagnostic value.

DIAGENETIC FEATURES

The term diagenesis incorporates all the processes, physical and chemical, which affect the sediment after deposition and up to the beginning of metamorphism (*cf.* Pettijohn *et al.*, 1972). Recognition of diagenetic features on a quartz grain and its differentiation from primary features is of prime importance, as only the primary features reflect depositional environment.

Diagenesis causes many changes in the sediments, e.g. compaction, mineral formation, and solution etc. Important diagenetic processes in the present context are: quartz overgrowth, dissolution and chemical etching, and kaolinitization. All these processes are closely interconnected particularly the last two processes provide the silica for quartz overgrowth.

Diagenetic features on a quartz grain surface are mostly silica-overgrowth in the shape of small projections over a detrital grain. Solution effects are equally important which may be due to pressure solution or chemical etching. Solution features appear as series of pits connected together with intersecting anastomosing lines, solution pits and crevasses, ridges and snubs, smooth areas. The intensity and degree of expression of diagenetic features is controlled by factors like chemical composition of circulating pore water, pH, porosity and permeability of sediments.

SYNTAXIAL OVERGROWTH OF THE QUARTZ

Formation of new minerals during diagenesis is in response to the new set of physico-chemical conditions, produced due to changing composition of moving pore waters, increased temperature and pressure. Interaction between solid mineral grains and pore fluids often results in precipitation of a mineral cement on the surface of a detrital mineral grain. This process takes place in a few micron thin film of fluid immediately adjacent to the mineral grain surface. One of the most widespread new mineral formation is precipitation of silica on the detrital quartz grains, mostly in the form of syntaxial growth—precipitation deposited in optical continuity with the detrital grain, and the crystal lattice of the two are interconnected.

In pore waters silica is present in true solution in the form of $Si(OH)_4$. Experiments on the solubility of silica have shown that the solubility of amorphous silica is much higher in relation to the solubility of crystalline silica. Thus, a solution undersaturated with respect to amorphous silica, is supersaturated with respect of crystalline silica. During quartz overgrowth minute crystals growing on a grian are supplied the amorphous silica from solution, and is transformed into crystalline form and the crystals grow.

Degree of quartz overgrowth and silica cementation in general is controlled by the continuous supply of supersaturated pore fluids over long time period. Mostly, after a definite stage of silica cementation has been reached, it stops due to non-availability of more silica or other associated factors. Thus, most of the sediments show only partial cementation.

The process of crystal growth of quartz has been studied by several workers, i.e. Van der Merwe (1949), Buckley (1951), Ernst and Blatt (1964), Heald (1950), Renton *et al.* (1969). Waugh (1970) and Pittman (1972) have studied crystal growth by SEM. For the initiation of a syntaxial overgrowth a basic layer of regular atomic pattern is formed whose structure is that of the surface of growth. Once a baisc layer is formed further growth takes place on the top of it. Such growth is initiated at several points of a detrital grain independently and simultaneously.

In the initial stages overgrowth appears as blobs, blebs, projections, minute scales where crystal faces are only poorly defined. With continued growth these small features grow and join each other to cover a part of the grain surface. When these projections become bigger, they exhibit prismatic and rhombohedral faces. Various growth stages are present side by side.

The driving force behind the growth of small crystals with same crystallographic orientation into larger crystals is the minimum in the Gibb's free Energy in the larger crystals:

$$\mathrm{G}\ \mathit{total} = \mathrm{G}\ \mathit{mass} + \Sigma\ \mathit{Gi\ interface}$$

When several small crystals grow into a single larger crystal *Gi* factor is reduced due to decrease in total area of interface of crystals.

Even at this initial stage crystalline projections begin to coalesce, overlap, and merge into each other, and form larger crystalline projections with smooth crystalline faces. Their orientation is controlled by the crystallographic orientation of the detrital grain. Growth in C-axis direction is especially rapid, with the result rhomb faces near the apex of a detrital grain grow much rapidly than the prism faces. Growth rates in various crystallographic directions have been determined by BALLMAN AND LAUDISE (1963):

Basal plane	>minor rhombohedral	>major rhombohedral >	prism
(0001)	$(01\bar{1}1)$	$(1\bar{1}01)$	$(1\bar{0}10)$

The larger crystal projections grow into tight fit, merging into each other to produce larger crystal faces with recognizable forms, ultimately the contact between merging subunits is obliterated. The overgrowths near the middle part of a detrital grain show better developed prism faces, whereas those near the apex show better developed rhombohedral faces, which coalesce together to produce pyramid faces. At this stage holes in the crystal faces may be visible due to insufficient supply of silica. In later stages these holes may be infilled. Even at this stage smooth crystallographic faces are present side by side with areas where small blebs and projections are growing.

PITTMAN (1972) pointed out that the contact between overgrowth and nucleus is remarkably open, where in small voids and cavities liquid or dust may be trapped during overgrowth or introduced later. In thin sections this contact is the boundary between detrital grain and overgrowth. At the final stage, almost perfect bipyramidal crystals may be produced, if physico-chemical conditions, space, and time permits. However, in the sedi ments it is seldom achieved because of lack of space required for the free growth, moreover, if supply of silica is exhausted, an overgrowth may stop at any stage of development.

SOURCE OF SILICA FOR QUARTZ OVERGROWTH

A major problem connected with the quartz overgrowth is the source of silica. Usually, following sources of silica are considered to be of major importance. Any one of these sources may play a major role as silica suppliant during diagnesis.

(i) Pore water supersaturated with silica.

(ii) Siliceous tests of organisms, amorphous silica, and siliceous shales are dissolved and taken into pore fluids.

(iii) Quartz dissolved during pressure solution.

(iv) Excess silica released during alteration of felspars into kaolinite.

As shall be discussed later, the process of kaolinitization has been the major process to provide silica for secondary overgrowth in Gondwana sediments.

KAOLINITIZATION OF FELSPARS

The process of kaolinitization is essentially a process of hydrolysis of felspars by water containing dissolved carbon-dioxide. The kaolinitization produces grains which show outlines of a felspar grain but made up exclusively of aggregates of kaolinite. Following chemical reaction takes place:

$$2KAlSi_3O_8 + 2H^+ + 2HCO_3^- + 9H_2O$$

$$Al_2Si_2O_5\,(OH)_4 + 4H_4SiO_4 + 2K^+ + 2HCO^-_3$$

In terms of thermodynamics this equation can be written as follows:

$$\text{felspar} \rightarrow \text{kaolinite} = \frac{(aK+)^2\ .\ (aH_4SiO)_4}{(aH^+)2}$$

It is evident that if log aK^+/aH^+ value is less than 5 or 6, and H_4SiO_4 concentration is below 10^{-3} moles/liter, K-felspar changes to kaolinite (see PETTIJOHN *et al.*, 1972). In other words, the process of kaolinitization of felspars is affected by pore waters that have low concentration of dissolved material, especially K^+ and H_4SiO_4, and have a relatively low pH controlled by dissolved H_2CO_3. The silica released during kaolinite formation is taken in solution in pore waters. Under suitable conditions this silica is deposited on the detrital quartz grains.

CHEMICAL ETCHING AND SOLUTION FEATURES

Chemical etching and solution of quartz grain surface takes place in response to the changed physico-chemical conditions. Chemical etching is supposed to be initiated and controlled by dislocation planes, impurities, and other crystal defects. Etching produces features like crystallographically oriented etch pits, solution pits and crevasses, widespread breakdown of the grain surface, grooves and striations. From the petrographic studies we know that pressure solution is an important process in the diagenesis of sandstones. The pressure solution process causes solution of quartz at the point of grain contact as a result of stress. Mineral grains under stress have increased solubility. If a grain is stressed unequally the grain is dissolved at stressed points and precipitation may take place on surfaces of lower stress. PITTMAN (1972) has studied the features produced by pressure solution with the help of SEM; such surfaces depict minute grooves and striations. RENTON *et al.* (1969) were able to produce pressure solution and quartz overgrowth experimentally. Important factors controlling the chemical solution of a quartz grain are: quartz solubility, temperature, pressure, grain size, presence of impurities, time available. In general, the presence of a thin film of impurity helps in solution, whereas a thick coating inhibits the diagenetic changes. The available data shows that solubility of silica is more or less independent of pH value below pH=8. Above pH=9 solubility of silica increases tremendously. It is postulated that solution of quartz during diagnesis is result of local pH increase above 9 in the pore fluids.

DESCRIPTION AND INTERPRETATION OF GRAIN SURFACE TEXTURES IN THE SAMPLES

The detailed description of some representative and diagnostic grains from each sample is given. The terminology used is more or less same as suggested by KRINSLEY AND DONAHUE (1968a), AND MARGOLIS AND KENNETT (1971).

SAMPLE No. 144 (Core depth—688.00 m.)—Zone IA:

Grain no. 2195/1—Angular outline, high relief, prominent step-like fracture planes, faint and minute striations and large breakage blocks. Diagenetic features almost absent and only at high magnifications, small etching features as elongated pits, around which some silica precipitation might have taken place are visible on the broad surfaces between two fracture planes. (Figs. 1, 2, 3, 4).

Grain no. 2195/2—Angular outline, high relief, step-like fracture planes, conchoidal fracture, minute striations, washboard feature due to development of upturned fracture plates. Under higher magnifications, concave depressions show extremely smooth inside surfaces similar to 'cirque', minute striations almost parallel, becoming fainter away from the 'cirque' and branching, arc-shaped fracture planes with varied orientations are also developed (Figs. 5, 6).

Grain No. 2195/5—Beside features similar to other grains, the grain exhibits on a featureless fracture plane curvilinear or meandering ridges with sharply broken parts, and fine striations are parallel to such ridges (Fig. 7).

Remarks:—All the sand grains show exclusively features of glacial environment, i.e. high relief, angular outline, fracture planes, fine striations. Diagenetic features are insignificant; except rare traces of chemical etching are visible.

SAMPLE No. 142 (Core depth—685.05 m.)—Zone IA

Grain no. 2196/3—Grain surface slightly modified during diagenesis. Fracture planes are developed. (Fig. 8).

Grain no. 2196/4—Angular outline, high relief, extremely rugged topography fracture planes, breakage blocks and conchoidal fracture. Under higher magnification, meandering ridges are seen within the fracture planes. Curved grooves and ridges, conchoidal fracture and fine striations are also seen (Figs. 9, 10).

Grain no. 2196/5—Angular outline, high relief, featureless curved fracture planes, very sharp edges, step-like fractures well developed. Surface have undergone minor diagenetic modifications leading to a slight blurring of the primary features (Fig. 11).

Remarks:—All the grains show features diagnostic of glacial environment i.e. angular outline, high relief, curved parallel ridges, featureless curved fracture planes. Diagenesis has only slightly affected the quartz grains.

SAMPLE No. 136 (Core depth—674.55 m.)—Zone IA

Grain no. 2197/2—Grain shows rugged topography, high relief, subangular outline, and fracture planes. Surface has been slightly modified during diagenesis obliterating the primary features. At higher magnification incepient quartz overgrowth in the form of minute scales and plates is visible. Scales are developed in an overlapping fashion, growing into larger plates (Figs. 12, 13).

Grain no. 2197/3—Grain with subangular outline, high relief, sharp corners and edges, fracture plane development. Surface has been modified by silica overgrowth during diagenesis. Overgrowth has developed in patches. In one of the cavities, elongated needle like crystal bundle is visible. They are most probably minute quartz crystals growing as if in a geode. At other places quartz over-growth is in the form of minute scales. (Figs. 14, 15, 16).

Remarks—All the grains show glacial features which have been slightly modified by fluvial action, but the glacial features predominate. Diagenesis has modified the quartz grain surfaces in the form of patchy over-growth of overlapping scales.

SAMPLE No. 132 (Core-depth—666.15 m.)-Zone IB

Grain no. 2198/2—Grain shows rather rugged topography, angular outline, high relief. In spite of the moderate surface modification during diagenesis, fracture planes breakage blocks visible. At higher magnifications quartz overgrowth is visible in the form, of overlapping and coalescing scales and plates. (Figs. 17, 18).

Grain no. 2198/4—Angular outline, high relief, surface moderately to strongly modified during diagenesis masking the primary features. Breakage blocks, fracture planes visible. At high magnification, diagenetic features, both dissolution and overgrowth distinct. Chemical etching has resulted into development of solution pits and crevasses. At some points, it looks as if secondary silica has been deposited in the form of minute scales and blebs. (Figs. 19, 20).

Grain no. 2198/7—Angular outline, high relief, featureless fracture planes, conchoidal fracture, step-like fracture, breakage blocks. Almost no effect of diagenesis. At higher magnification, randomly orientated striations are seen. In some parts secondary overgrowth is visible as minute knob-like features. In one part, fracture planes are arranged in the shape of petals of a flower. On the petals conchoidal fracture and striations are present; few crevasses are also visible (Figs. 21, 22, 23).

Grain no. 2198/8—Subangular outline, high relief, subrounded edges, breakage blocks and fracture planes. The grain suggests that it has been modified slightly by fluvial action. Diagenetic effects evident (Fig. 24).

Grain no. 2198/6—At high magnification overlapping scales, minute blebs, and plates are seen, in some of these, crystal faces are developing (Fig. 25).

Grain no. 2198/9—Subangular outline, high relief, one face of the grain shows features of a freshly broken surface: smooth featureless fracture plane, arc-shaped fractures, step-like fractures, breakage blocks.

Other surface shows diagenetic features. Most probably the diagenetic features are inherited. The diagenetically affected surface shows signs of chemical etching. The etching took place in the provenance before the sand grain was fractured during glacial transport. At high magnification breakage blocks, parallel grooves and ridges are well seen. On the fracture planes ridges are developed like flute structures, broad near the major fracture surface and tapering towards the other end. (Figs. 26, 27, 2 , 29).

Grain no. 2198/10—Angular outline, high relief, breakage blocks, conchoidal fracture, meandering ridges, striations, step-like fractures, arc-shaped fractures. The grain looks like a *stone implement.* At high magnification extremely rugged topography becomes very evident. Depressed areas show conchoidal fracture and striations in various directions (figs. 30, 31, 32).

Remarks—Most of the grains show mainly diagnostic features of glacial environment: angular outline, high relief, breakage blocks, fractures, striations. Few of the grains suggest that they have been partly affected by fluvial processes and some grains have been modified during diagenesis.

SAMPLE NO. 117 (Core depth—549.59 m.)—Zone IIA

Grain no. 2199/1—Subrounded outline, moderate relief. Traces of fracture planes are visible. Diagenesis has moderately modified the grain surface and has resulted into quartz overgrowth. At few points even crystal faces are visible. At high magnification, grain surface is covered with minute scales and projections, which grow together in the process of enlargement. As soon as projections become large enough, smooth crystal faces are developed. At still higher magnifications, even the featureless minute scales also exhibit crystal faces. (Figs. 33, 34, 35, 36).

Grain no. 2199/3—Subrounded outline, moderate relief, fracture planes mostly obliterated. Diagenesis has modified the surface. Part of the grain is already covered with smooth crystal faces. Most of the grain is covered with minute scale-like projections. At high magnification, it is evident that several stages and several types of overgrowth are present side by side. On elevated parts tiny scales and plates are developing. In some of the depressed areas very peculiar features are seen (however, traces of conchoidal fractures are still visible), perhaps by the growth of quartz crystals producing smooth crystal faces out of fracture planes, and the crystal faces have been developed due to the growth of vertical and steeply inclined, very closely-spaced books of lamellae, which after achieving a definite height coalesce together and are roofed by the smooth crystal face. This is probably the most significant mechanism responsible for filling of depressions during quartz overgrowth. (Figs. 37, 39, 40).

Grain no. 2199/6—Subrounded outline, moderate relief, fracture planes mostly modified during diagenesis. Most of the grains covered by tiny scales; in some parts smooth crystal faces are developed. In one part, a dislocation plane or a lineage boundary is seen. Quartz overgrowth is discontinuous along this line.

At high magnification various stages of overgrowth become still more evident, and the lineage boundary becomes very distinct. In the cavities overgrowth is in the form of vertically or steeply inclined plates and laminae, which at various heights coalesce and are roofed by a smooth plane growing on their top. Contact between closely growing subunits is seen as a dislocation plane, which on further growth may disappear. At few points it looks as if a new phase of minute scale growth has been initiated after some crystal faces had developed (Fig. 43).

In the laws governing crystallization, it is a known fact that any later solution, instead of developing an independent crystal only adds to the already existing crystal form, therefore, the development of these second phase minute scales under the present state of knowledge is not understandable. (Figs. 41, 42, 43).

Remarks—All the grains have subrounded outline, moderate relief, and only a few traces of fractures. This suggests a fluvial environment.

Diagenesis is moderately developed, all the quartz grains have been subjecetd to varying degree of quartz overgrowth. Main type of overgrowth is by development of tiny scales which grow and coalesce with each other. In strongly recessed areas quartz overgrowth takes place due to growth of steeply inclined laminae or plates which coalesce together and ultimately capped by smooth crystal faces. In one of the grains it looks as if a new phase of silica overgrowth was initiated on the partially developed smooth crystal faces.

SAMPLE NO. 107 (Core depth—523.39 m.)—Zone IIA

Grain no. 2200/2—Subrounded outline, moderate relief, minute primary features obliterated. Surface diagenetically modified (Fig. 44).

Grain no. 2200/7—Subrounded grain, moderate relief, fracture planes partly visible. Diagenesis slightly modified the grain. At high magnification overgrowth appears in the form of scales pasted one above the other. In some parts smooth planes are emerging out. (Fig. 45).

Remarks—The grains show subrounded outline, moderate relief, and few inherent features. This suggests fluvial environment. Diagenesis is slightly developed. Overgrowth is in the form of broad scales growing on each other.

SAMPLE No. 95 (Core depth—474.90 m.)—Zone IIB

Grain no. 2201/6—Subrounded outline, smooth to subrounded corners and edges, moderate relief, primary features obliterated. Diagenesis has modified the grain surface. In some parts smooth crystal faces are developed. At high magnification, rugged surface becomes apparent. Minute overgrowth in the shape of scales and plates is very clear. It looks as if grain surface has also suffered some chemical etching resulting in parallel-running minute drainage channels (Figs. 46, 47).

Grain no. 2201/1—Subangular outline, high relief. Few featureless fracture planes still prominent. On these planes minute primary features, e.g. striations etc. are visible. Some parts of the grain show diagenetic changes. At high magnification scaly overgrowth, and crystal faces are visible. (Figs. 48, 49).

Grain no. 2201/5—Grain shows a very smooth surface adjacent to the very rugged surfaces. On the rugged surface overgrowth has been initiated and few minute smooth crystal faces have developed. (Fig. 50).

Remarks—Quartz grains show features of fluvial environment: subrounded outline, moderate relief, some inherent primary features. Diagenesis has only slightly affected the quartz grains.

SAMPLE No. 77 (Core depth—413.70 m.)—Zone IIIA

Grain no. 2202/2—Subrounded outline, moderate relief, few traces of fracture surfaces. Diagenesis has moderately modified the sand grain. C-axis is well marked as is evident from the smooth crystal faces meeting in the form of sharp edges. (Fig. 51).

Grain no. 2202/6—Subrounded outline, moderate relief, primary features mostly obliterated. Diagenesis has sufficiently modified the grain. C-axis well marked near the apex, pointed pyramidal faces have been initiated. At high magnification a smooth crystal face shows small and large holes and depressions. These depressions have been left because of deficiency of silica during diagenesis. In the case of further growth these holes would have been infilled. (Figs. 52, 53).

Remarks—Grains possess subrounded outline and moderate relief suggesting a fluvial environment of deposition. Diagenesis was strong enough to have led to the formation of large smooth crystal faces.

SAMPLE No. 55 (Core depth—316.00)—Zone IIIA

Grain no. 2203/4—Subangular outline, high relief, fracture planes moderately developed. Diagenetic effects are only minor. In some parts dissolution has taken place. At high magnification areas of dissolution and insignificant coating of silica seen more clearly. (Figs. 54, 55).

Grain no. 2203/5—Subrounded outline, high relief, perhaps a composite grain. Diagenesis has affected the grain surface. Both quartz overgrowth and dissolution features present. (Fig. 56).

Remarks—Fluvial environment of deposition is quite evident by the subangular outline i.e. obliteration of primary features. Diagenesis has mainly produced chemically etched dissolved surfaces; quartz overgrowth is of minor significance.

SAMPLE No. 28 (Core depth—189.80 m.)—Zone IIIB

Grain no. 2184/1—Rounded to subrounded outline, moderate relief, traces of fracture planes still visible. Surface of fracture planes still visible. Surface diagenetically modified At high magnification overgrowth is evident, and in general has taken place in the form of haphazardly growing, partly imbricated minute scales and plates. Minute smooth crystal faces are also seen (Figs. 57, 58).

Grain no. 2184/7—Subangular outline, corners and edges are only slightly smoothened, moderate relief. Diagenesis moderately affects the surface. At high magnification growing scales with some smooth crystal faces are clear. In some of the minutely depressed parts inherent primary features, e..g striations, fracture planes are still present. (Figs. 59, 60, 61).

Remarks—All the grains show subrounded outline, moderate relief, subangular to rounded edges, and inherent primary features in depressed areas. These features point to a fluvial environment of deposition.

Diagenesis has feebly affected the grains as suggested by deposition of only a thin coating of silica. The overgrowth looks like overlapping fish-scales or roof tiles. At high magnification minute scales are seen to possess crystal faces.

SAMPLE No. 14 (Core depth—117.50 m.)—Zone IIIB

Grain no. 2190/5—Subrounded outline, moderate relief, inherent primary features almost obliterated. Diagenesis moderately high, modifying the surface, producing smooth crystal faces. C-axis well marked. Growth of crystals at the apex very prominent.

At high magnification overgrowth is very well seen. Even in depressed areas small projections with crystal faces are seen growing and coalescing with each other. Only in a few small depressed areas, primary inherent features, e.g. striations, conchoidal fracture are visible. (Figs. 62, 63, 64).

Grain no. 2190/6—Subrounded outline, moderate relief, Primary inherent features almost obliterated. Diagenetic effects evident. Near the apex small crystals with well-developed faces prominent.

At high magnification features of quartz overgrowth are well seen. The secondary growth is in the form of minute overlapping scales. (Figs. 65, 66).

Remarks—The sand grains have subrounded outline, moderate relief, and the primary inherent features are obliterated. The features indicate deposition in a fluvial environment. Diagenesis is moderate, overlapping scale-like overgrowths are well developed. In the apical part of the grains, small crystals with smooth faces prominent.

SAMPLE No. 1 (Core depth—18.28 m.)—Zone IIIB

Grain no. 2191/3—Subrounded outline, edges and corners well-rounded, moderate relief, traces of fracture planes well seen. Diagenetic effects present. At high magnification diagenetic features become evident. A thin coat of secondary silica has developed, which appears like a grass-land. Overgrowth is in the form of minute projections and blebs projecting from the surface. Larger projections show prism and rhomb faces, on further growth crystal projections coalesce together to produce smooth wall like feautres. All the growth stages are present even in a small area. (Figs. 67, 68, 69).

Grain no. 2191/4—Subrounded outline, moderate relief, traces of fracture planes visible. Surface diagenetically modified.

At high magnification quartz overgrowth becomes apparent. A very thin layer of secondary silica has developed, appearing as minute scales and projections coalescing together. (Figs. 70, 71).

Remarks—Subrounded outline, moderate relief and presence of traces of primary fracture planes suggest deposition in fluvial environment.

Diagenesis has slightly affected the grains by producing a thin layer of secondary silica. Overgrowth is in the form of small projections and blebs, a feature not developed in sand grains of other samples where it is mainly in the form of minute overlapping scales.

DISCUSSION

INTERPRETATION OF ENVIRONMENT

Study of primary textures of the quartz grain surface reveals that only two environments are present, glacial and fluvial. Glacial characteristics are very prominent in the grains from lower part of the Talchir (sample nos. 144 and 142). Samples 136 and 132 also show abundance of grains showing glacial features, together with some fluvial features. Most of the glacial features on the grain surface are variants of mechanical breaking under temperature stresses to which quartz grains are exposed within the ice during glacial transport.

Most of the studies of the quartz grain surface features from glacial environment are on the Recent and Quaternary sediments, for example, KRINSLEY AND FUNNELL (1965), MARGOLIS AND KENNETT (1971). HAMILTON AND KRINSLEY (1967) have reported definite glacial features on the quartz grains in the Permo-carboniferous tillites from Africa. Almost all the features, which have been described as diagnotstic for glacial environment in previous studies were found on the quartz grains of the lower part of the succession (Sample nos. 144, 142, 136, 132). Some of the features observed during this study which have not been reported earlier are:

(i) The whole grain surface covered with step-like fracture planes (Fig. 1).

(ii) 'Cirque' like depression, with fanning and branching striations on the surrounding flat surfaces. (Fig. 6).

(iii) Featureless fracture plane showing curvilinear ridges with sharply broken parts (Fig. 7).

(iv) Fracture surface on which smaller 'tongue' or petal shaped fracture planes are arranged like petals of a flower (Fig. 23).

(v) Fracture plane with flute-like ridges, broad near the major fracture surface and tapering towards the other end (Fig. 29).

(vi) The quartz grain is broken to look like a *stone-implement* (Fig. 30).

The quartz grains of sample nos. 117, 107, 95, 77, 55, 28, 14 and 1 assigned to fluvial environment, show pronounced effect of fluvial abrasion leading to varying degree of rounding and reduction in relief. The characteristic features being subrounded outline, moderate relief, and only traces of primary fracture planes.

Quartz grains from the samples of the lower part of the Zone IA i.e. Talchir (sample nos. 144 and 142) exhibit almost exclusively glacial features. These samples have yielded statistically insignificant number of pollens and spores; and partly fresh plogioclases and alkali felspars. (BHARADWAJ & SRIVASTAVA 1973; SINGH & SHARMA, 1973). These facts support an extremely cold glacial climatic condition.

Quartz grains from samples of the upper part of the Zone IA (Talchir) and lowermost part of Zone IB (Barakar) (Sample nos. 136 & 132) show features both of glacial and fluvial environments. Thus, a glacio-fluvial environment can be assigned to these samples. Glacial features predominate; fluvial action has been rather mild and has resulted only in slight rounding of sharp edges and corners. Lithological and palynological results point to a glacial environment to sample no. 136; and fluvial environment in cold temperate climate to sample no. 132 (BHARADWAJ & SRIVASTAVA, 1973; SINGH & SHARMA, 1973). It is suggested that during deposition of these sediments, material was derived from glacial environment, and was deposited under fluvial conditions only after slight reworking.

Samples from rest of the sequence show almost exclusively the fluvial features. Degree of rounding of edges and corners is variable even in the grains of the same sample. There is no systematic increase or decrease in rounding characteristics from lower to upper part of the investigated profile. In the fluvial succession part of this the grain surface has been moderately modified during diagenesis; thus delicate primary surface textures have been obliterated.

DIAGENETIC CHARACTERISTICS

Diagenesis modifies the quartz surface and obliterates the delicate primary features. In the sequence studied effect of diagenesis is very variable. Not all the samples have undergone same degree of diagenetic changes; moreover quartz grains of some samples have escaped diagenesis altogether. In general, quartz grains of the lowest part of the succession (those belonging to glacial environment) show almost no effect of diagenesis, quartz grains of the samples belonging to glacio-fluvial environment show little to negligible effect of diagenesis, and the quartz grains of the rest of the succession (those of the fluvial environment) show moderate effects of diagenesis.

Main reason for the lack of diagenetic effects in glacial and fluvio-glacial sediments seems to be the presence of high content of clay matrix. The quartz grains are embedded in a clayey matrix, which serves as impervious layer to the pore fluids. As quartz grains do not come in contact with pore fluids, dissolution and overgrowth cannot take place. Only a few grains which were exposed to pore fluids have been diagenetically modified.

On the contrary, better development of diagenetic features in sediments of fluvial environment is due to lack of matrix as protecting layer. With the result, most of the quartz grains have been modified by circulating pore waters. In short, degree and type of diagenetic changes on the quartz grains in the samples of various environments are as follows: samples from glacial environments (sample nos. 144, 142) exhibit very little diagenetic effects. It is shown by the development of minute etched pits and development of thin skin of secondary quartz on the grain surface.

In some of the quartz grains from glacio-fluvial environment (sample nos. 136, 132) quartz overgrowth is developed. The overgrowth is in the form of minute scales, overlapping and coalescing each other.

Almost all the quartz grains from the samples of fluvial environment show a thin layer of secondary silica deposited on them. Only in exceptional cases minor chemical etching has taken place.

Following are the major features produced during secondray overgrowth:

(i) In the beginning a very thin skin like coating develops on the detrital grain surface. This coating does not show any differentiaiton into smaller features (Figs. 11, 54).

(ii) The above stage is followed by the development of minute scales on the surface, which grows to produce 'roof-tiles' like pattern, the most common type of overgrowth recorded during this study (Figs. 12, 35, 66).

(iii) In some samples early stage of growth is not in the form of scales; instead small 'blob' like projections are formed (Fig. 68).

(iv) Scale-like features or blob-like projections coalesce together to produce bigger plates and walls with smooth crystal faces (Figs. 25, 34, 49, 69).

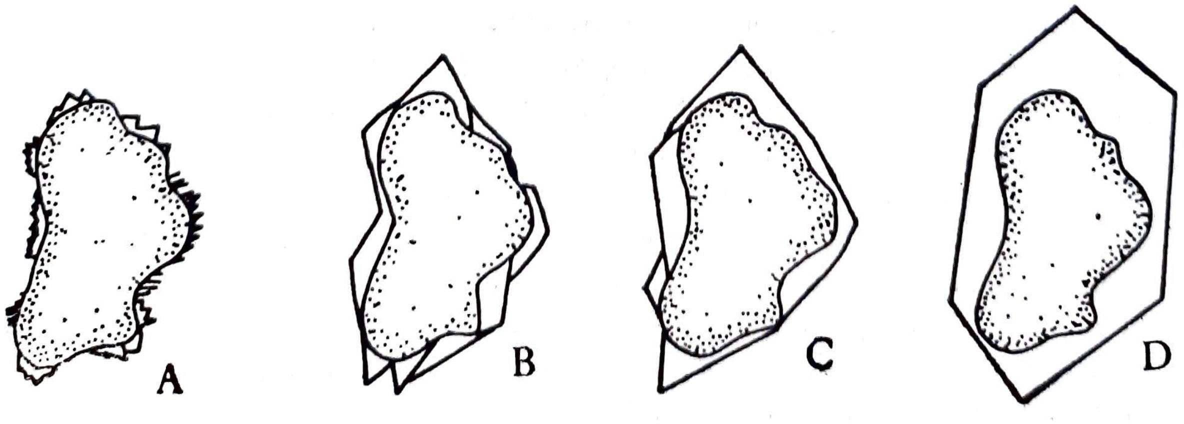
(v) In the quartz grains with more advance stages of growth, major part of the grain surface becomes covered with smooth crystal surfaces. At this stage C-axis of the grain becomes apparent (Figs. 51, 62).

(vi) Near the apex crystal growth is more rapid and many crystals with well developed crystal faces grow together. They start welding together to initiate development of pyramid faces (Figs. 52, 62, 65).

(vii) In some cavities crystals of accicular habit are seen to grow together in a bunch (Figs. 15, 16). Such crystal habits suggest sudden growth. It is postulated that sudden availability of supersaturated silica solution in the cavity led to the quick growth of the crystals. This feature has been recodred for the first time.

(viii) The quartz overgrowth in the depressed areas of the grain surface sometimes takes place as follows: In the areas first vertical or steeply inclined thin laminae start growing upwards. During growth these laminae coalesce together to produce plates (Fig. 43). After the plates have attained a certain height, overgrowth starts horizontally to cover them (Figs. 40, 43). Plates are welded together, and lastly covered by a smooth crystal face (Figs. 39, 40, 43). Several smaller units join together to produce larger crystal surfaces. During welding of crystal units, space may be left which appear as narrow pits on an otherwise smooth crystal face (Fig. 40). This type of growth has not been reported earlier.

It may be pointed out that the studies by WAUGH (1970) and PITTMANN (1972) demonstrated that in the initial stages of quartz overgrowth small blobs and projections develop. However, in the Gondwana sediments, initial growth stage is predominantly developed as scale-like features, not projecting outwards but growing in a 'tiled roof' pattern. Text-fig. 1 depicts various stages of secondary overgrowth of quartz.



Text-fig. 1

The dissolution of quartz surface is almost absent; only in a few cases, minor dissolution features produced due to chemical etching have been observed (Figs. 47, 55, 20). For the accomplishment of the diagenetic phenomena of quartz overgrowth extra silica is required to be deposited on the detrital quartz surface. In most cases pressure solution has taken as the main process providing extra silica for quartz overgrowth (see PITTMAN, 1972), but the petrographic and SEM studies of the Gondwana sediments from Korba Coalfield demonstrate that pressure solution is almost absent. Therefore, for the development of overgrowth the following two sources have been envisaged.

(i) *Silica available in the original pore fluids entrapped in the sediment during deposition.* In all the samples of the Gondwana sediments kaolinite is an important clay mineral. During weathering and pedogenesis kaolinite is formed by hydrolysis of felspars and mica, and extra silica is released and taken away in solution. Thus, waters coming from a terrain undergoing kaolinite development are ought to be rich in dissolved silica. These waters entrapped during deposition would provide silica for quartz overgrowth. However, solubility of silica is very low, so only a limited amount of silica can be supplied from original pore waters which is insufficient to account for all the quartz overgrowth in the samples studied.

(ii) *Extra silica released during kaolinitization of felspars during diagenesis.*

Study of thin sections of the sediments show that kaolinitization of felspars has been an effective process during diagenesis. This process has produced kaolinitized felspars; i.e. felspars altered to aggregate of kaolinite. The silica released during kaolinitization is present in solution as $Si(OH)_4$. Under favourable conditions, the silica may get deposited on the mineral grains in the form of overgrowth.

For the present study it seems that silica released during kaolinitization is the major source, together with original dissolved silica in pore fluids.

The content of silica available controls the degree and extent of quartz overgrowth. In the present case silica content in turn is controlled by degree of kaolinitiztation and original content of felspars available for kaolinitization. Other important factor controlling the quartz overgrowth are grain size and permeability. Coarser grained sediments are usually more permeable, pore fluids can easily circulate producing overgrowth more efficiently. Moreover, more pore space is available for development of crystal projections into pore spaces. On the other hand, in finer-grained sediments permeability is low and pore space chocked. This leads to the fact that quartz overgrowth can not grow efficiently and freely due to lack of space for growth, and lack of supply of silica from circulating fluids.

This lithological and textural control on the quartz overgrowth is well marked in the Korba Coalfield samples. Sample nos. 117, 95, 77, 14 and 1 are medium-to-coarse-grained sandstones. Quartz overgrowth of these samples show better developed crystal faces and crystalline projections. On the contrary, sample nos. 107, 55, and 28 are fine-grained shaly sediments. Here quartz overgrowth is developed only in the form of a thin layer of overlapping scales. Well defined smooth crystal faces are not formed.

CONCLUSIONS

QUARTZ GRAIN SURFACE FEATURES AS ENVIRONMENTAL INDICATOR

If one tries to summarize the information about the primary features obtained

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Text-fig. 1. Schematic representation of various stages in secondary quartz overgrowth. In the Gondwana samples only the stages A-C are present.

by the study of quartz grains of the Gondwana sediments from Korba Coalfield, following generalizations can be made:

(1) SEM study of quartz grain surface features can also be successfully and independently used to confirm and interpret the environmental history of the sediments because the results so obtained conform well with those of palynological, mineralogical and geological studies.

(2) Quartz grains of glacial environments develop very diagnostic features, and all can be easily identified. Some features observed here have not been reported earlier, e.g. curvilinear ridges, 'cirque' like depressions, fracture planes arranged like petals of a flower, fracture planes with 'flute' like ridges.

(3) Quartz grains of fluvial environment are characterized by rounded edges and corners, and moderate relief. Degree up to which inherited features are retained, i.e. fracture planes and breakage blocks, if derived from glacial, depends upon the abrasion history. Nevertheless, mostly inherited features are moderately to poorly preserved.

DIAGENETIC SURFACE FEATURES OF THE QUARTZ GRAINS

The diagenetic features can be summed up as follows:

(1) Sand grains of glacial deposits show negligible effects of diagenesis; primary features are well preserved. This has been interpreted as a result of shielding effect of fine-grained matrix in which these grains are embedded.

(2) Sand grains of fluvial deposits have been significantly modified during diagenesis. This is a result of lack of protecting matrix. Diagenesis leads to destruction of inherited and primary features. However, invariably enough primary features are retained so as to allow a safe interpretation of depositional environment.

(3) Diagenesis gives rise to the development of quartz overgrowth on the detrital grains. Effects of chemical etching are insignificant.

(4) Quartz overgrowth takes place in stages, starting with the development of scale-like or blob-like projections which coalesce together to produce crystal faces. Overgrowth in the depressed areas may show development of needle-like crystals in a bunch, or growth of vertical laminae and plates.

(5) Quartz overgrowth is controlled by lithology and texture of the sediments. In coarser sediments, smooth crystal faces of the quartz overgrowth are better developed than in the finer-grained sediments.

(6) Main source of silica seems to be extra silica released during kaolinitization of felspars, together with original content of silica in pore waters.

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EXPLANATION OF PLATES

PLATE I

1. Sample no. 144, grain no. 2195/1. Glacial environment. Angular quartz grain with sharp edges and corners, high relief. Step-like fracture planes are developed on most of the surface. ×48.
2. Same grain as in fig. 1. A closer view of the quartz grain surface showing fracture planes, and striations. × 147.
3. Same grain as in fig. 1 at higher magnification. Along the striations elongated pits and crevasses are developed. Around the opening of the crevasses some recrystallization and silica precipitation has taken place. ×733.
4. Same grain as in fig. 1 at very high magnification. Minute pits and crevasses are seen. ×3667.
5. Sample no. 144, grain no. 2195/2. Glacial environment. The grain shows high relief, step-like fracture planes, upturned fracture plates. ×67.
6. Same grain as in fig. 5. The surface shows a concave 'cirque' like depression with smooth inner surface, minute striations fanning and branching outwards, imbricated breakage blocks. ×667.

PLATE II

7. Sample no. 144, grain no. 2195/5. Glacial environment. A featureless fracture plane showing curvilinear ridges with sharply broken parts, and fine striations. ×176.
8. Sample no. 142, grain no. 2196/3. Glacial environment. A grain surface slightly modified during diagenesis; minute scales representing quartz overgrowth are seen. ×135.
9. Sample no. 142, grain no. 2196/4. Glacial environment. Quartz grain exhibits sharp, angular outline, high relief, and various kinds of fracture planes. ×43.
10. Same grain as in fig. 9. Grain surface shows meandering ridges, conchoidal fracture, curved grooves and ridges, and fine striations. ×373.
11. Sample no. 142, grain no. 2196/5. Glacial environment. Quartz grain showing angular outline, high relief, featureless fracture planes. In the central part some diagenetic effect are apparent. ×73.
12. Sample no. 136, grain no. 2197/2. Glacio-fluvial environment. Quartz grain shows subangular outline, high relief. Smaller glacial features, e.g. conchoidal fracture, striations have been obliterated due to secondary overgrowth on the surface during diagenesis. ×67.

PLATE III

13. Same grain as in fig. 12. A closer view of the quartz grain surface showing incepient secondary overgrowth. The growth appears in the form of minute scales overlapping each other. ×333.
14. Sample no. 136, grain no. 2197/3. Glacio-fluvial environment. Quartz grain shows subangular outline, high relief, and various fracture planes. The grain surface has been modified by quartz overgrowth, which has also resulted in blurting of the primary features. ×65.
15. Same grain as in fig. 14. A closer view of the quartz grain surface showing diagenetic features. Scale-like overgrowth is present in patches. In one cavity in the centre a bundle of needle-shaped crystals is growing. ×320.
16. Same grain as in fig. 14. A closer view of the cavity showing needle like crystals growing in a bunch. ×640.
17. Sample no. 132, grain no. 2198/2. Glacio-fluvial environment. Quartz grain shows angular outline, high relief. Primary features have been moderately modified during diagenesis. ×83.

18. Same grain as in fig. 17. Surface showing secondary overgrowth of silica. Minute scales and plates are overlapping and coalescing each other. Development of smooth crystal faces has been initiated. ×320.

PLATE IV

19. Sample no. 132, grain no. 2198/4. Glacio-fluvial environment. Quartz grain shows angular outline, high relief. Surface is strongly modified during diagenesis. Traces of primary features visible. ×83.
20. Same grain as in fig. 19. A closer view of the diagenetically modified quartz grain surface. Some chemical etching has produced minor crevasses and pits. At the same time secondary silica has been deposited in the form of minute scales and blebs. ×640.
21. Sample no. 132, grain no. 2198/7. Glacio-fluvial environment. Quartz grain shows angular outline, high relief, featureless fracture planes, step-like fracture, breakage blocks features diagnostic of glacial environment. Fluvial abrasion not present. ×77.
22. Same grain as in fig. 21. Conchoidal fracture, striations are seen on the grain surface. A part of the quartz grain surface exhibit diagenetic features, which were probably formed prior to glacial action. ×320.
23. Same grain as in fig. 21. A closer view of a fractured surface. Fracture planes are arranged in the shape of petals of a flower. Fine striations are developed. ×1280.
24. Sample no. 132, grain no. 2198/8. Glacio-fluvial environment. Quartz grain shows glacial features which have been partly modified by fluvial action, thus making subangular outline, moderate relief. Diagenesis has slightly modified the grain surface. It is developed as thin layer of secondary silica. ×77.

PLATE V

25. Sample no. 132, grain no. 2198/6. Glacio-fluvial environment. Quartz surface showing quartz overgrowth. The surface is covered with minute scales, and blobs growing into larger plates with crystal faces. ×323.
26. Sample no. 132, grain no. 2198/9. Glacio-fluvial environment. Quartz grain shows subangular outline, high relief. One face of the grain shows freshly broken surface with features like breakage blocks, conchoidal fractures, step-like fractures. The other face shows diagenetic effects in the form of quartz overgrowth. These diagenetic changes most probably took place before the grain was subjected to glacial activity. ×70.
27. Same grain as in fig. 26. A closer view of the grain surface showing breakage blocks, striations of freshly broken surface. On the left side diagenetic surface is present. ×320.
28. Same grain as in fig. 26. A fracture surface showing flute-like ridges broad at one end and tapering at the other end. Conchoidal fractures and striations are also seen. ×633.
29. Same grain as in fig. 26. A closer view showing details of flute-like tapering ridges arranged in a centrifugal way. ×1267.
30. Sample no. 132, grain no. 2198/10. Glacio-fluvial environment. Quartz grain shows angular outline, high relief, sharp edges and corners, featureless fracture planes, conchoidal fracture, step-like fracture. All are diagnostic glacial features. ×91.

PLATE VI

31. Same grain as in fig. 30. A closer view showing high relief, conchoidal fracture in various directions in a depressed area. On part of the surface inherent diagenetic features are seen ×367.
32. Same grain as in fig. 30. Surface showing conchoidal fracture and striations in various directions in a depressed area. In lower part of the grain chemical etching is prominent. ×1333.
33. Sample no. 117, grain no. 2199/1. Fluvial environment. Quartz grain shows subrounded outline, moderate relief. Fracture planes mostly obliterated during diagenetic quartz overgrowth. ×53.
34. Same grain as in fig. 33. Quartz grain surface is seen covered with minute scales, which overlap each other and coalesce to produce larger plates with smooth crystal faces. ×130.
35. Same grain as in fig. 33. A closer view of the quartz surface showing minute scales growing in various directions. In upper right corner traces of primary fracture planes are still seen, ×653.

36. Same grain as in fig. 33. Scale-like overgrowths as seen at high magnification. Scale-like nature of overgrowth is evident. Even in smaller scales crystal faces are developed. ×3267.

PLATE VII

37. Sample no. 117, grain no. 2199/3. Fluvial environment. Quartz grain shows subrounded outline, moderate relief. Diagenesis has obliterated the delicate primary features. Quartz overgrowth is developed as minute scales, in some parts larger smooth crystal faces have been formed. Big-scale differences in the relief are still present. ×53.

38. Same grain as in fig. 37. A closer view of the grain surface showing details of secondary overgrowth of quartz. On the elevated parts minute scales are growing into each other to produce smooth crystal faces. In depressed areas conchoidal fracture is still visible. In depressed areas overgrowth is taking place due to growth of plates of quartz. ×133.

39. Same grain as in fig. 37. A closer view of depressed area depicting growth of laminae and plates. Very closely spaced plates grow upwards at very high angles. The plates are seen growing in different directions. These plates are joined by a horizontally developing plane producing a crystal face. ×333.

40. Same grain as in fig. 37. Surface under very high magnification. Vertically growing plates are seen being joined and covered by a horizontal plane (Central part). On the right hand side few gaps are seen. They are due to incomplete fitting of adjacent units. ×667.

41. Sample no. 117, grain no. 2199/6. Fluvial environment. Quartz grain shows subrounded outline, moderate relief. Grain surface has been modified due to quartz overgrowth. ×55.

42. Same grain as in fig. 41. A closer view of the grain surface. Smooth crystal faces have developed. In other part minute scales are growing. In upper left corner minute scales are seen growing on the newly formed smooth crystal faces. In the upper right corner a lineage boundary is visible. On this line no overgrowth has taken place. ×130.

PLATE VIII

43. Same grain as in fig., 41 , A closer view of the grain surface showing filling of depressed parts Vertical to highly inclined laminae grow upwards and are joined together and capped by a horizontal smooth crystal face . In the right upper corner contact between tightly growing crystals is visible It forms a plane of dislocation ×647

44. Sample no. 107, grain no. 2200/2. Fluvial environment. Subrounded outline, moderate relief. Surface shows effects of quartz overgrowth. ×48.

45. Sample no. 107, grain no. 2200/7. Fluvial environment. A close view of a grain surface with secondary overgrowth. The overgrowth looks as if plates and scales have been pasted on each other. In parts smooth surface have developed. ×733.

46. Sample no. 95, grain no. 2201/6. Fluvial environment. Sand grain shows subrounded outline, moderate relief. Surface shows a thin cover of secondary quartz. It appears in the form of minute scales, and smooth larger crystal faces. ×37.

47. Same grain as in fig. 46. A closer view of the diagenetic surface. Overgrowth is present in the form of minute scales and plates. It seems that surface has also suffered some chemical etching. Minute channels running parallel to each other (from left to right) are seen. ×367.

48. Sample no. 95, grain no. 2201/1. Fluvial environment. Sand grain shows subangular outline, high relief. On one face primary features, e.g. breakage blocks, fracture planes are visible. Rest of the grain shows effects of diagenesis. ×51.

PLATE IX

49. Same grain as in fig. 48. A closer view of the grain surface. Minute scales representing quartz overgrowth are seen, they join together to produce smooth crystal faces. In the left lower corner breakage blocks and striations are visible. ×130.

50. Sample no. 95, grain no. 2201/5. Fluvial environment. Grain surface shows development of smooth crystal surfaces. Even on the corroded lower part such surfaces are seen developing. ×90.

51. Sample no. 77, grain no. 2202/2. Fluvial environment. Sand grain showing subangular outline and moderate relief has been much modified by quartz overgrowth. A considerable part of the elevated portion of the grain shows development of smooth crystal surfaces. C-axis, the axis of elongation is apparent. Smooth crystal faces are seen meeting at angle of prism faces. Near the apex pyramid faces are in its initial stages of formation. ×53.

52. Sample no. 77, grain no. 2202/6. Fluvial environment. Sand grain with subrounded outline and moderate relief. has been much modified during diagenesis. Smooth crystal faces are abundant. C-axis is well marked. Near the apex pyramid faces are seen developing. ×53.

53. Same grain as in fig. 52. A closer view of the grain surface showing newly formed smooth crystal face. Note the extreme smoothness of the surface. In between some pits and depressions are present. These features are due to incomplete infill during joining of the overgrowths because of insufficient supply of silica. ×880.

54. Sample no. 55, grain no. 2203/4. Fluvial environment. Quartz grain shows subangular outline, moderate relief, and traces of fracture planes. Diagenesis has produced a thin skin of secondary silica. ×53.

Plate X

55. Same grain as in fig. 54. A closer view of the grain surface. In the upper part a thin skin of silica has been deposited. In the lower left corner surface seems to have undergone chemical etching. ×350.

56. Sample no. 55, grain no. 2203/5. Fluvial environment. Quartz grain has been diagenetically modified. In the upper part quartz overgrowth in the shape of small crystal projections are visible. In the lower most part chemical etching has taken place. × 72.

57. Sample no. 28, grain no. 2184/1. Fluvial environment. Quartz grain shows subrounded outline, moderate relief, traces of fracture planes. Diagenesis has produced a thin coat of secondary silica on the surface. ×57.

58. Same grain as in fig. 57. A closer view of the quartz grain surface showing overgrowth. The overgrowth is in the form of scales arranged like the tiles of a roof. Few smooth crystal faces are also visible. ×627.

59. Sample no. 28, grain no. 2184/7. Fluvial environment. Quartz grain shows subangular outline, moderate relief. The surface has been modified during diagenesis and is coated by a thin layer of secondary silica. ×67.

60. Same grain as in fig. 59. A closer view of the grain surface. Haphazardly growing minute scales are growing and overlapping each other. In larger scales smooth crystal surfaces are visible. In narrow depressions primary features are still seen. ×767.

Plate XI

61. Same grain as in fig. 59. A highly magnified view of the quartz grain surface. In narrow depressions conchoidal fracture, and step-like fractures are visible. Rest of the surface shows scales of quartz overgrowth in various stages of growth. ×3833.

62. Sample no. 14, grain no. 2190/5. Fluvial environment. Quartz grain shows subrounded outline, moderate relief. Quartz overgrowth is well-developed. Part of the surface is covered by minute scales. The rest of the surface shows development of smooth crystal surfaces. C-axis is apparent Near the apex crystal faces are prominently developing to produce pyramid faces. ×48.

63. Same grain as in fig. 62. A closer view of the grain surface. Development of smooth crystal surfaces is well seen. Even depressed areas are being filled by secondary overgrowth. ×137.

64. Same grain as in fig. 62. Quartz grain surface at high magnification. On the right side smooth crystal faces are developing in the depressed area. On the left side minute striations are seen on the wall of a depression. ×683.

65. Sample no. 14, grain no. 2190/6. Fluvial environment. Quartz grain shows subrounded outline. A thin layer of secondary silica has been deposited on the quartz grain surface. Near the apex of the grain (left hand side) crystal faces are prominent. ×79.

66. Same grain as in fig. 65. A closer view of the surface to show nature of quartz overgrowth. The overgrowth is in the form of minute scales which are overlapping and coalescing each other. ×387.

Plate XII

67. Sample no. 1, grain no. 2191/3. Fluvial environment. Quartz grain shows subrounded outline, moderate relief, traces of fracture planes partly modified during fluvial abrasion. Surface is covered by a thin layer of secondary silica. ×48.

68. Same grain as in fig. 67. A closer view of the grain surface showing details of quartz over-

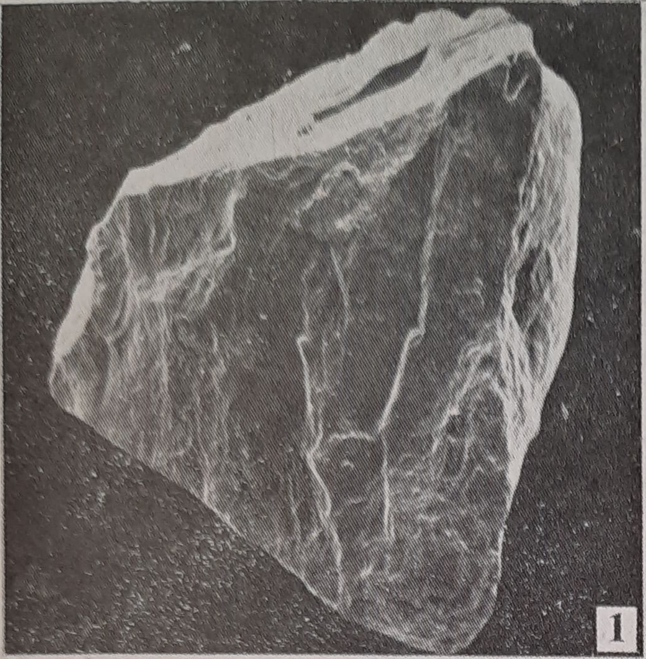
growth. The surface appears like a grass land. Overgrowth is in the form of small projections and blobs. In larger projections prism and rhomb faces are visible. ×367.

69. Same grain as in fig. 67. Surface shows details of quartz overgrowth. Small blob like features dominate the surface. Some what bigger projections exhibit crystal faces. These crystal projections coalesce together to make larger wall like features with smooth surfaces. Various growth stages are present in the same small area. ×733.

70. Sample no. 1, grain no. 2191/4. Fluvial environment. Quartz grain shows subrounded outline, moderate relief, and traces of fracture planes. Surface is seen coated with a thin layer of secondary silica. ×47.

71. Same grain as in fig. 70. Surface is seen coated with extremely minute blobs and scales coalescing together Some inherent primary holes and depressions are also seen ×147

72. Sample no. 28, grain no. 2184/3. Fluvial environment, subrounded outline, moderate relief The surface has been modified during diagenesis and is coated with secondary silica. ×80.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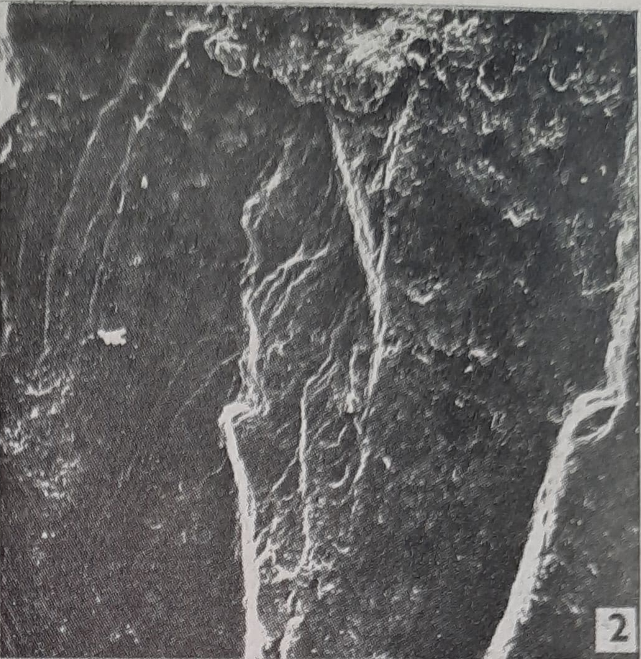
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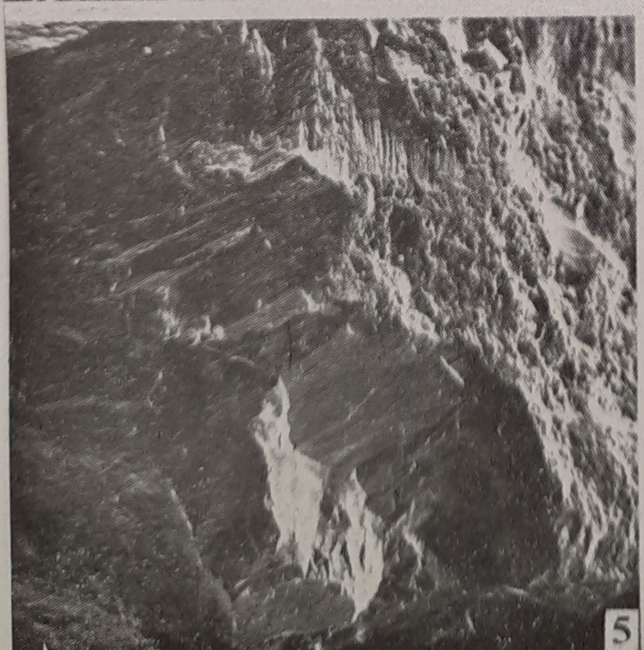
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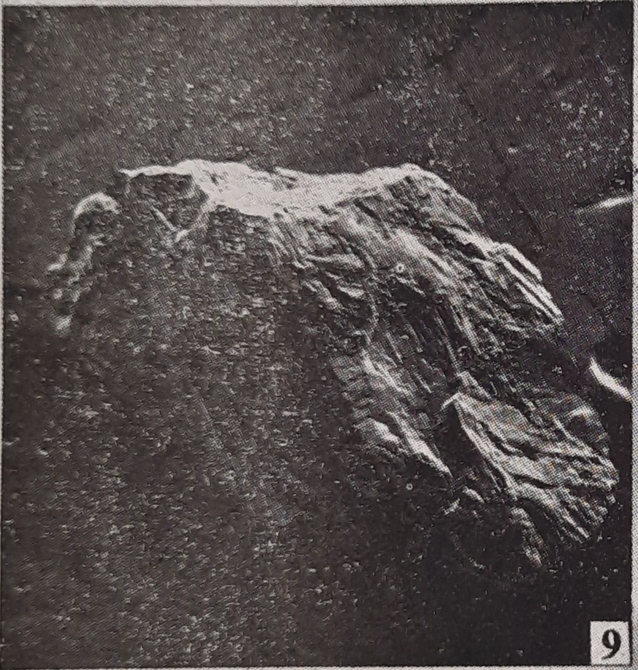
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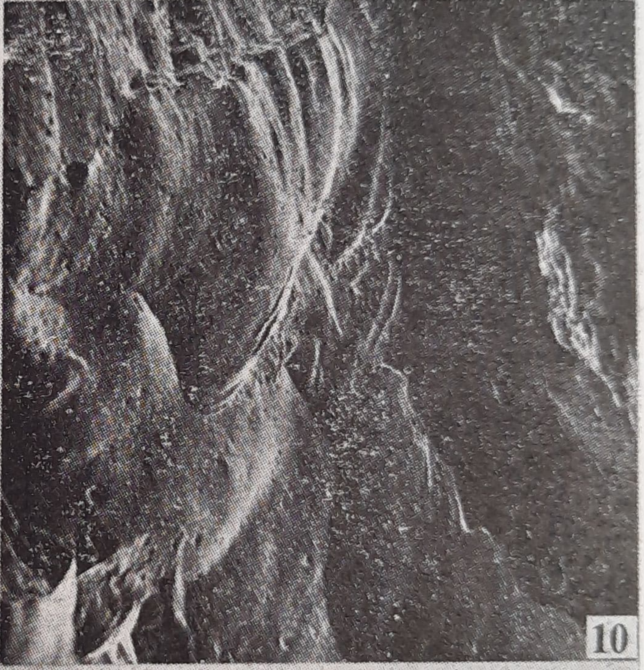
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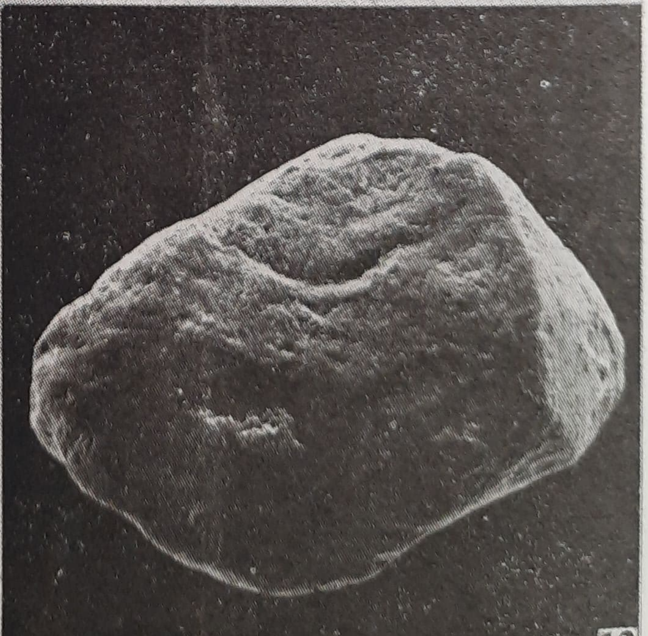
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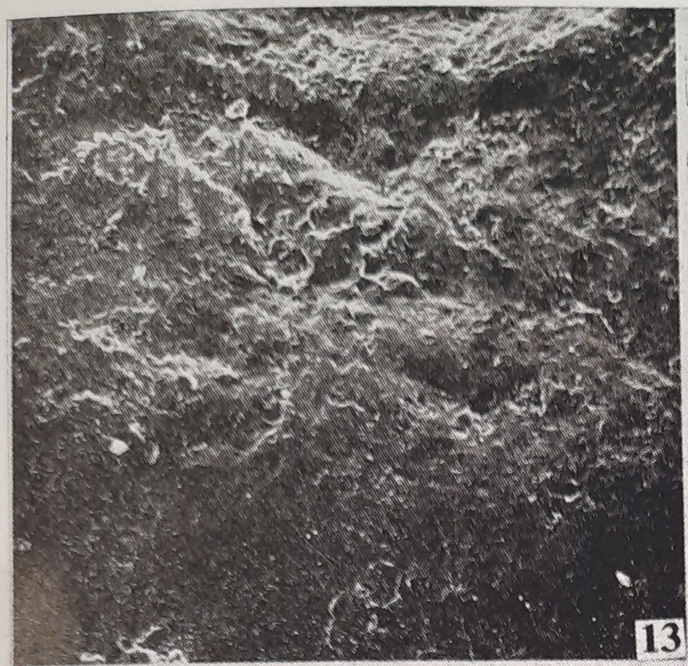
Singh—Plate 2



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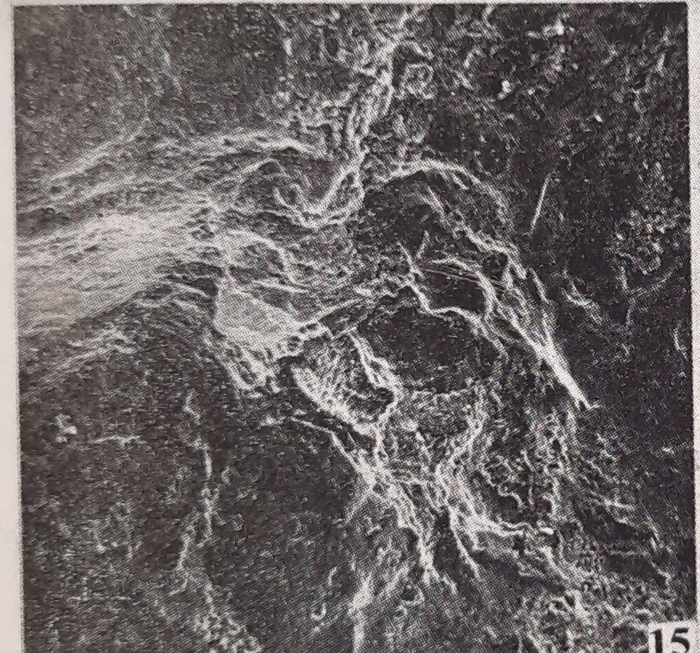

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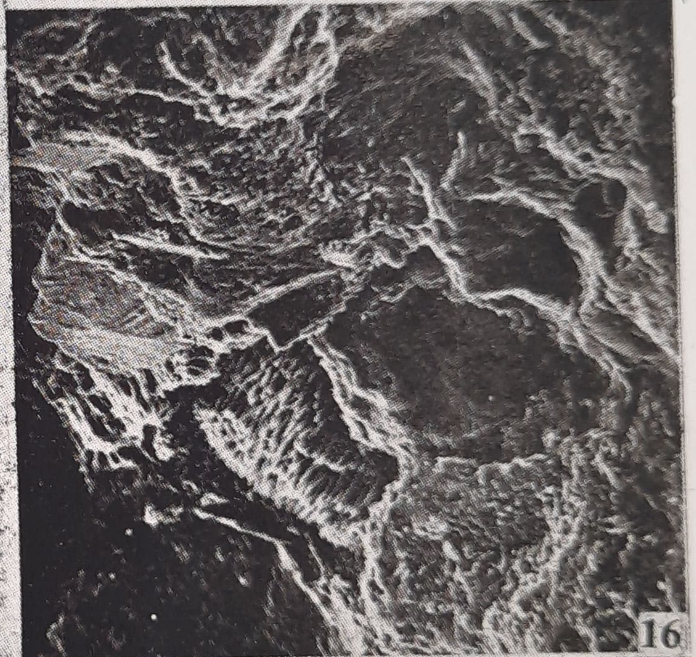

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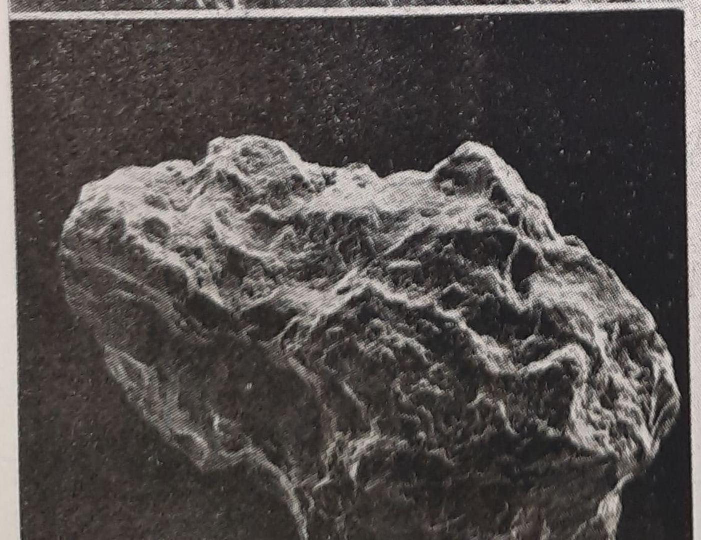

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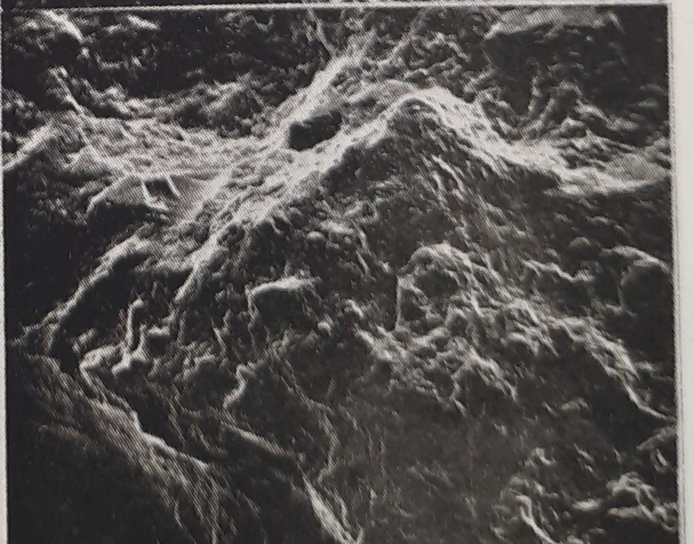

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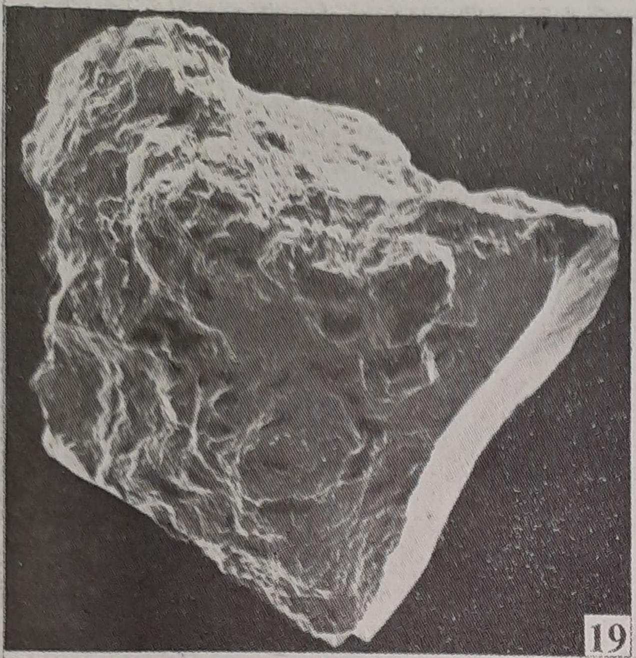

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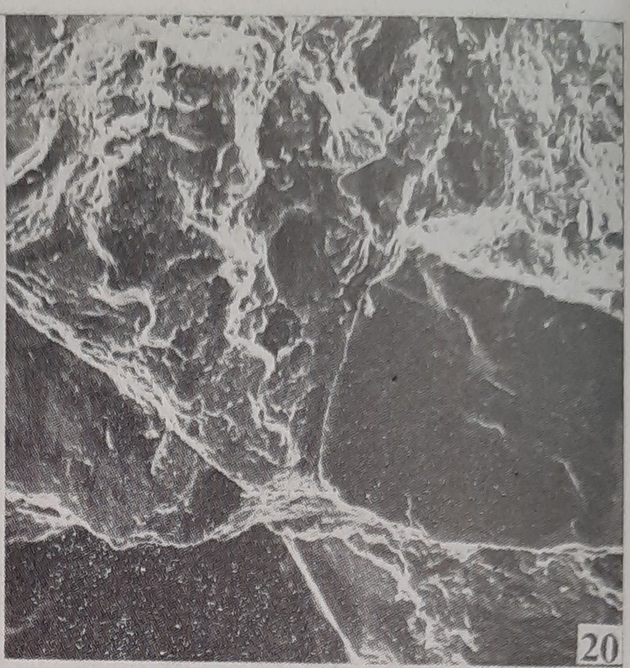

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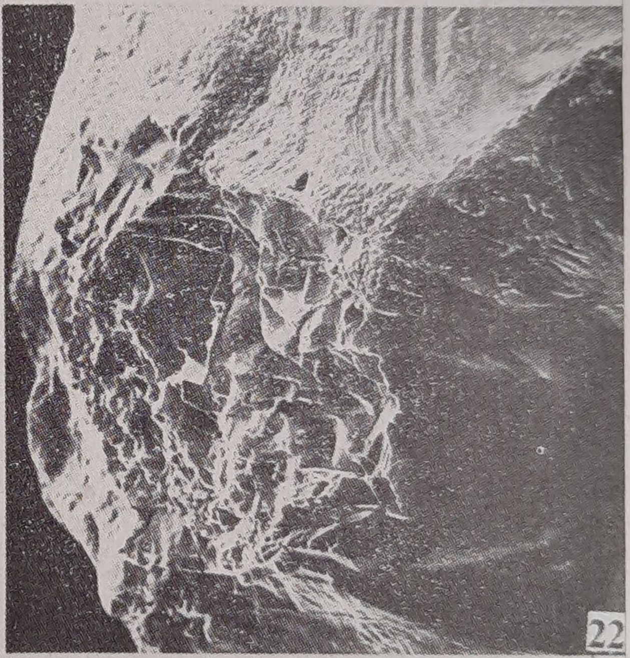

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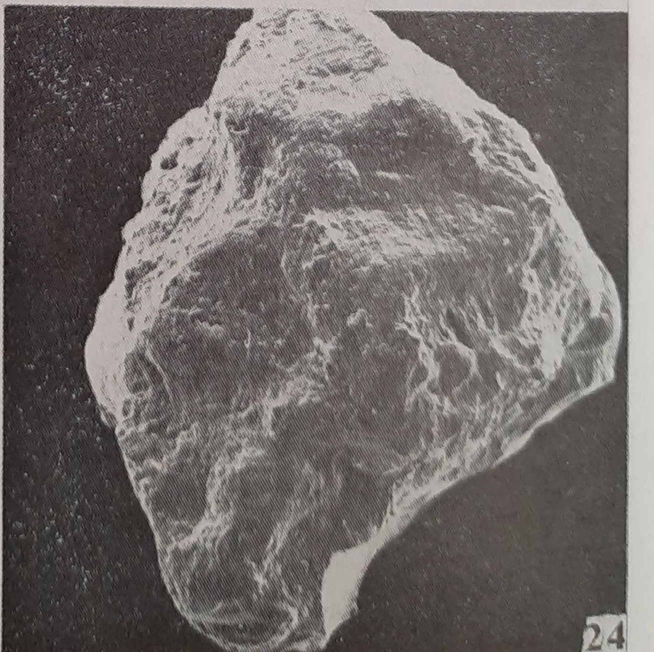

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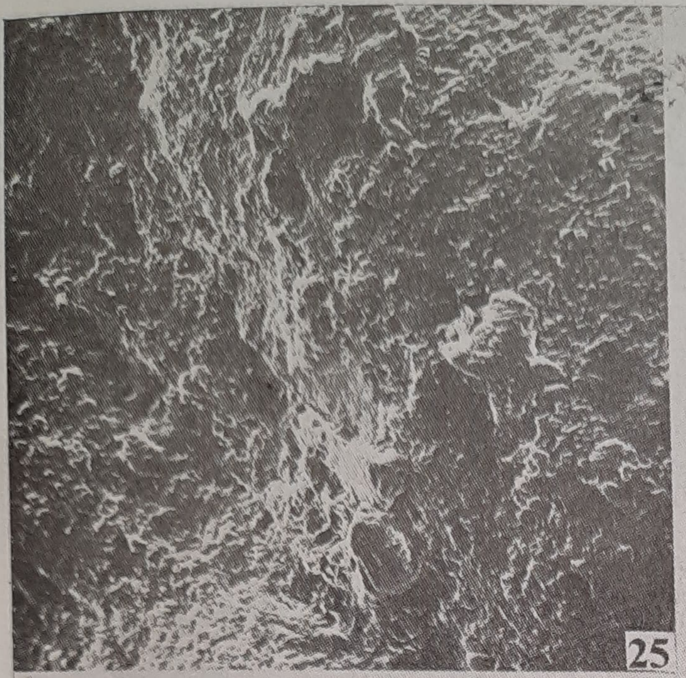
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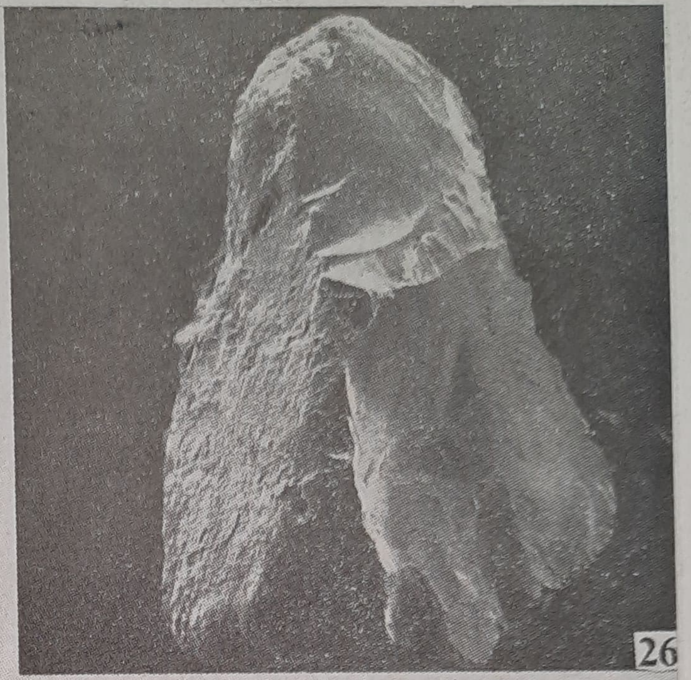
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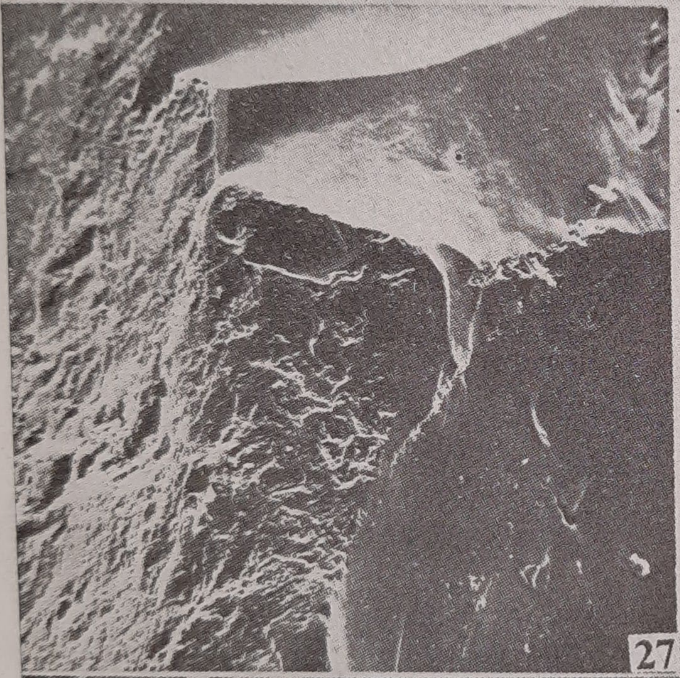
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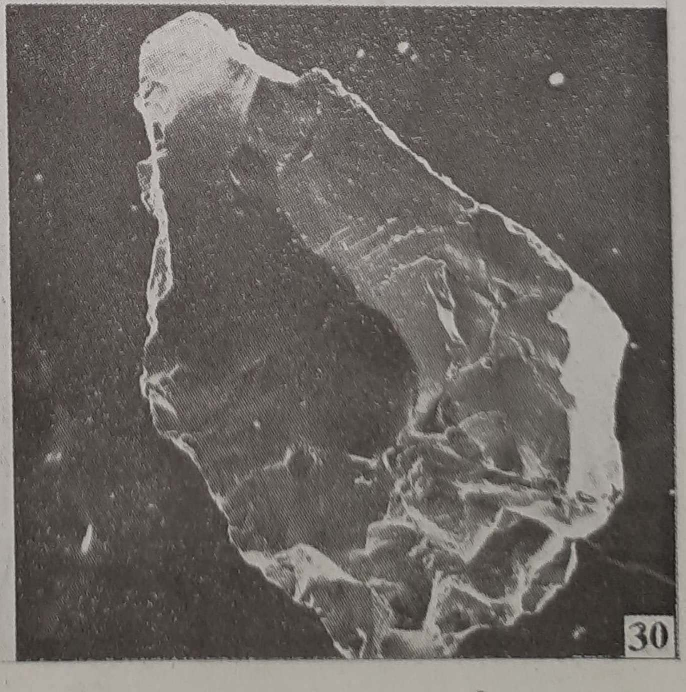
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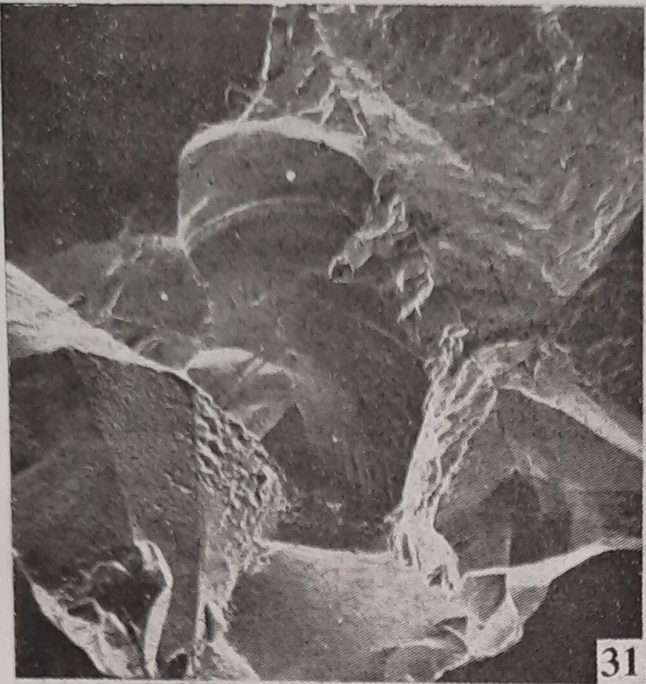
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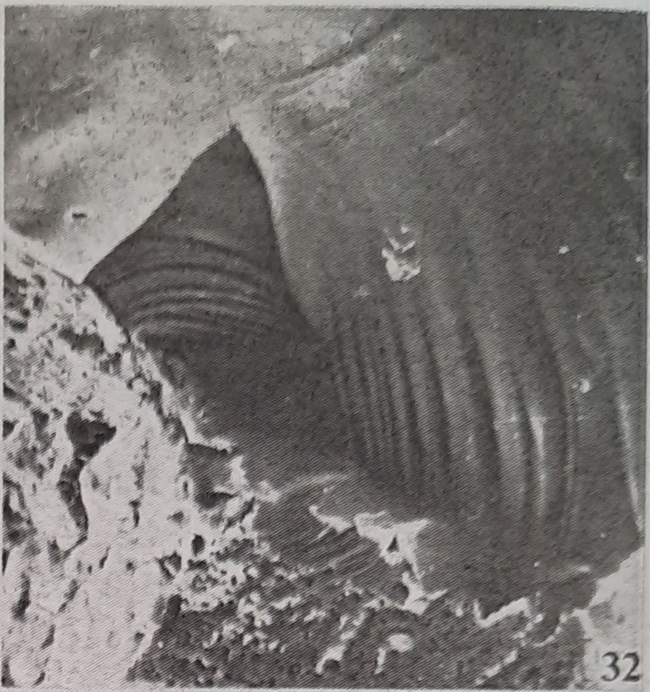
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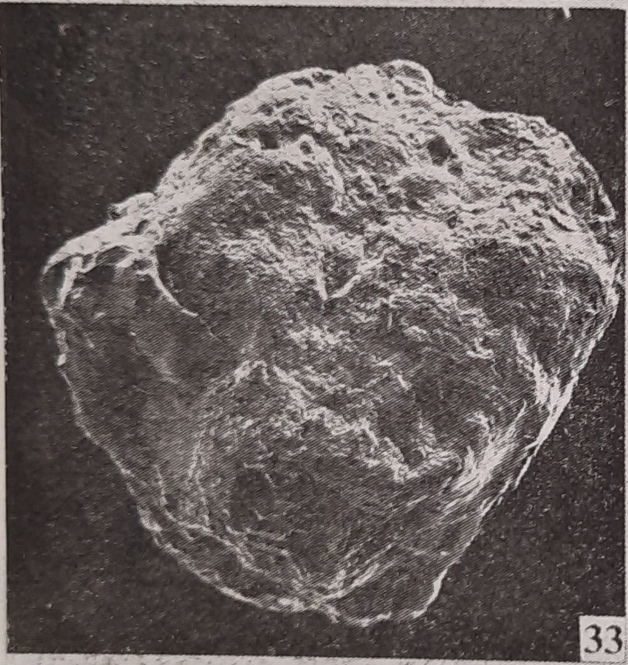
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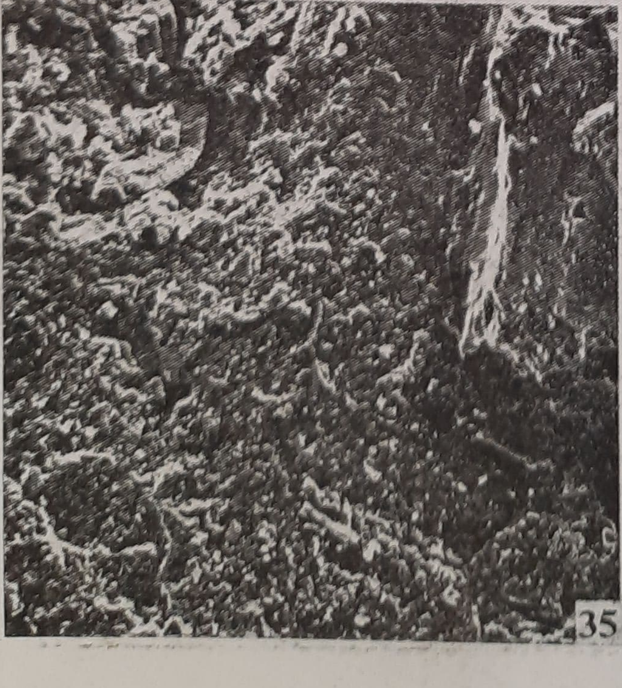
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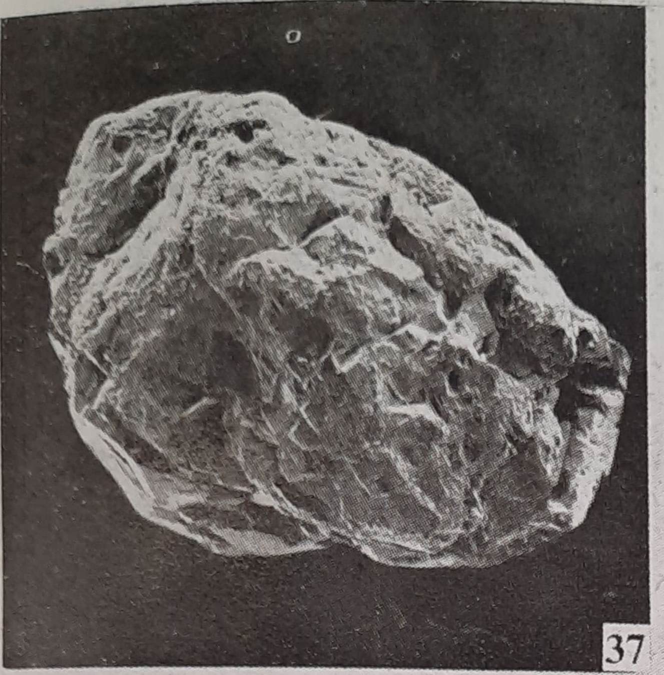
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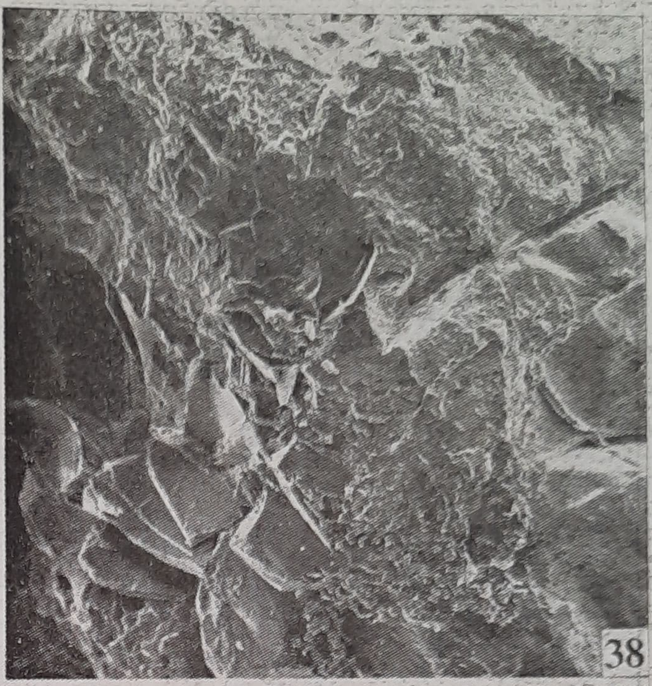
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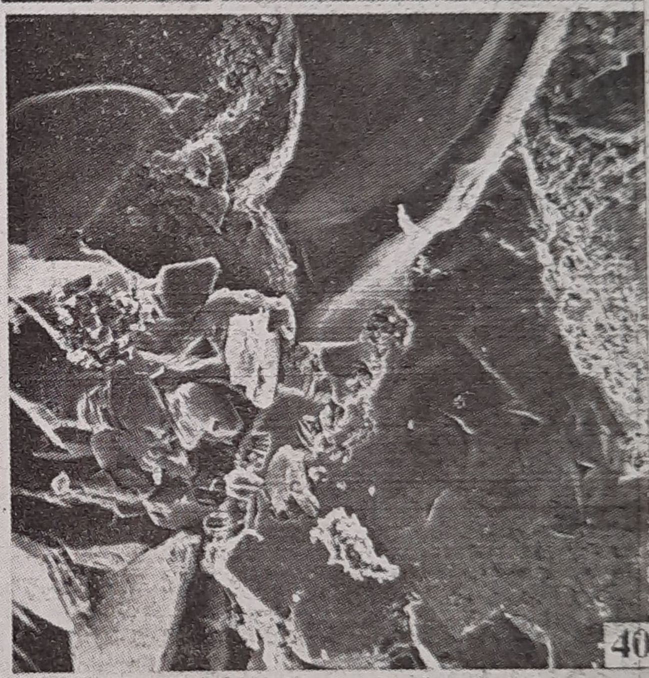
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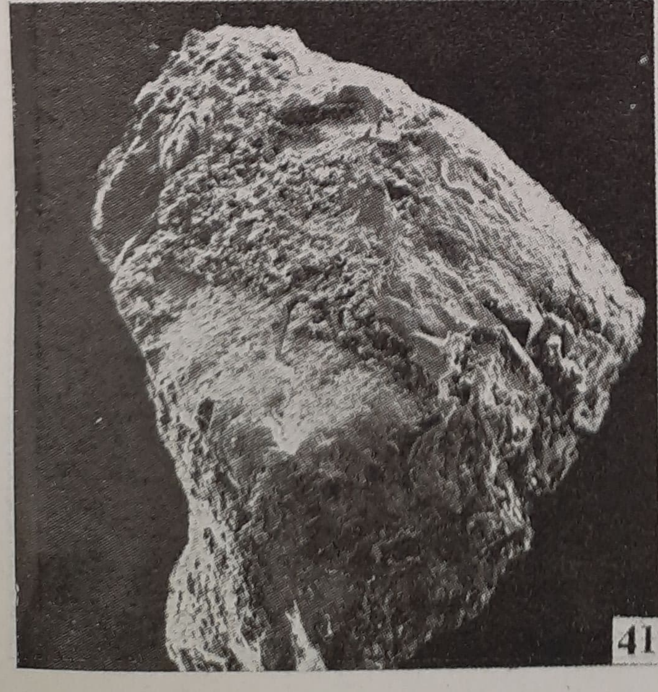
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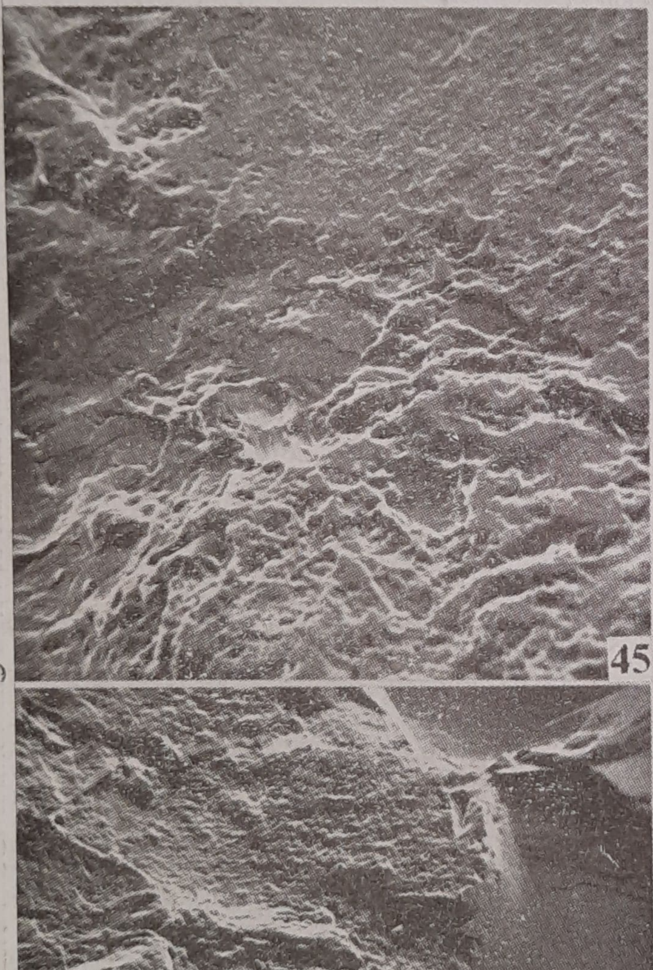

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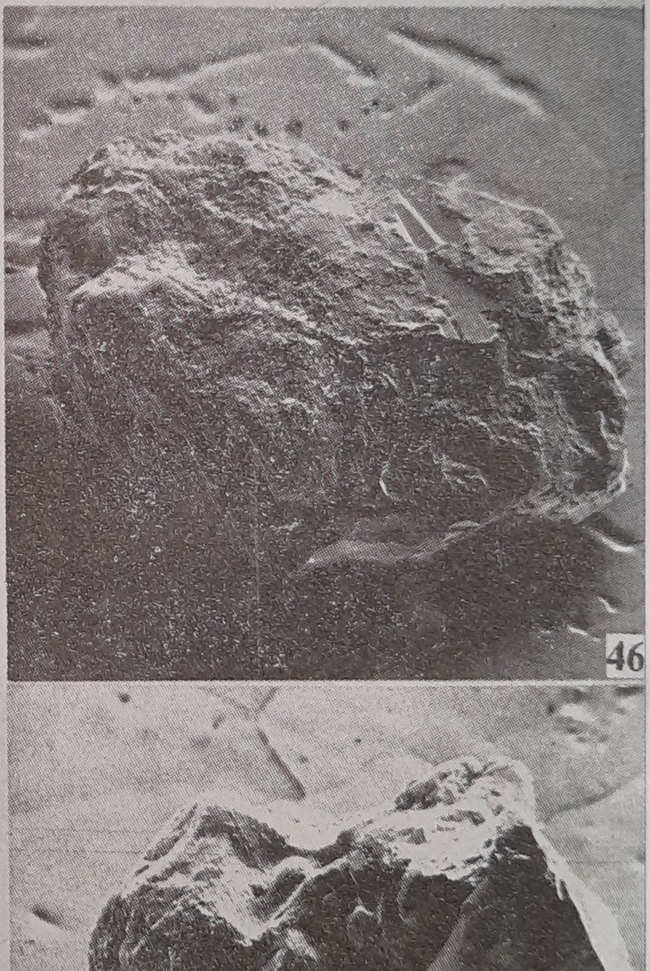

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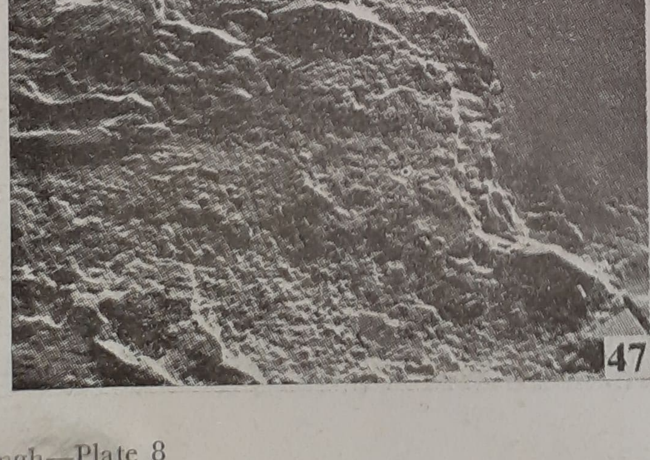

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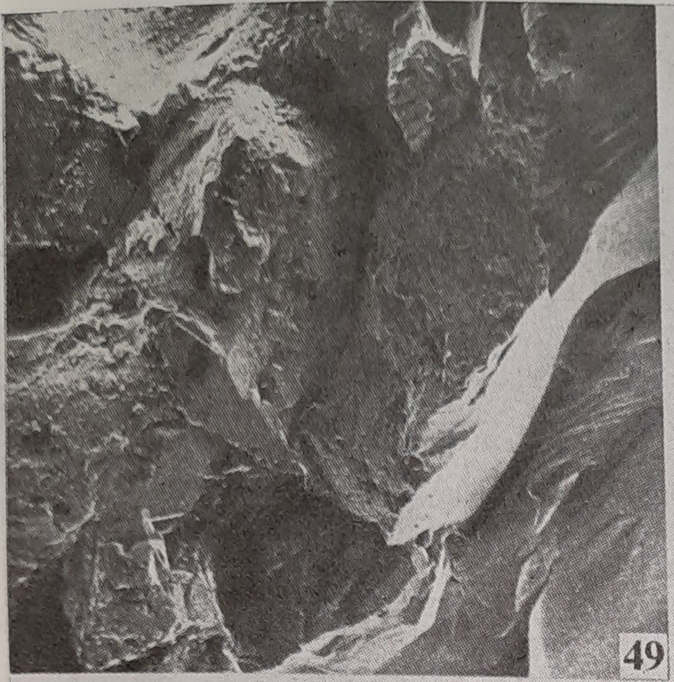

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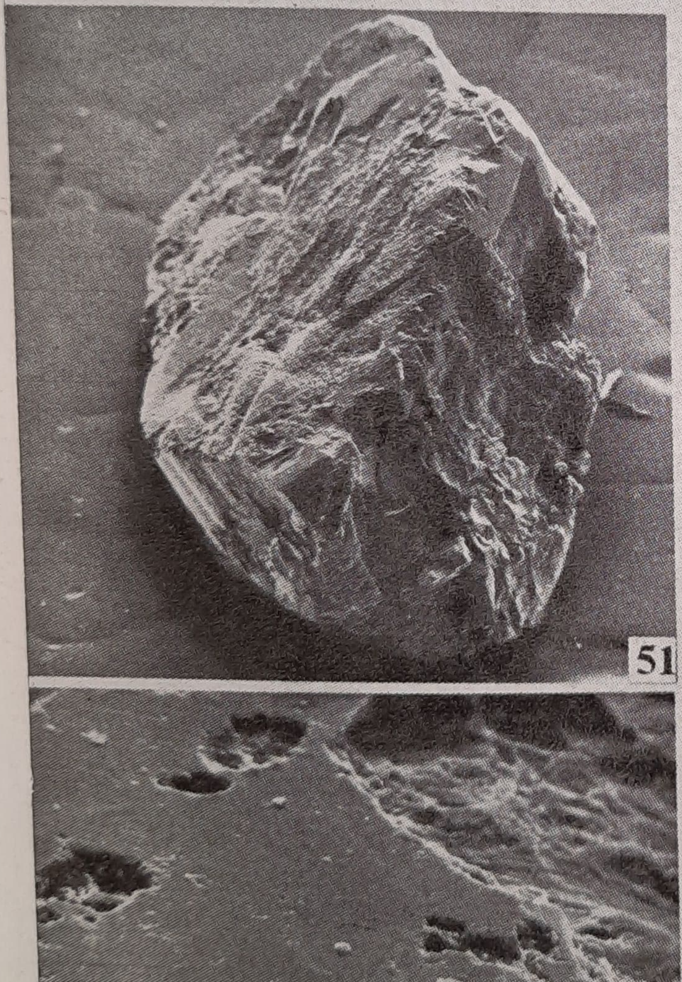

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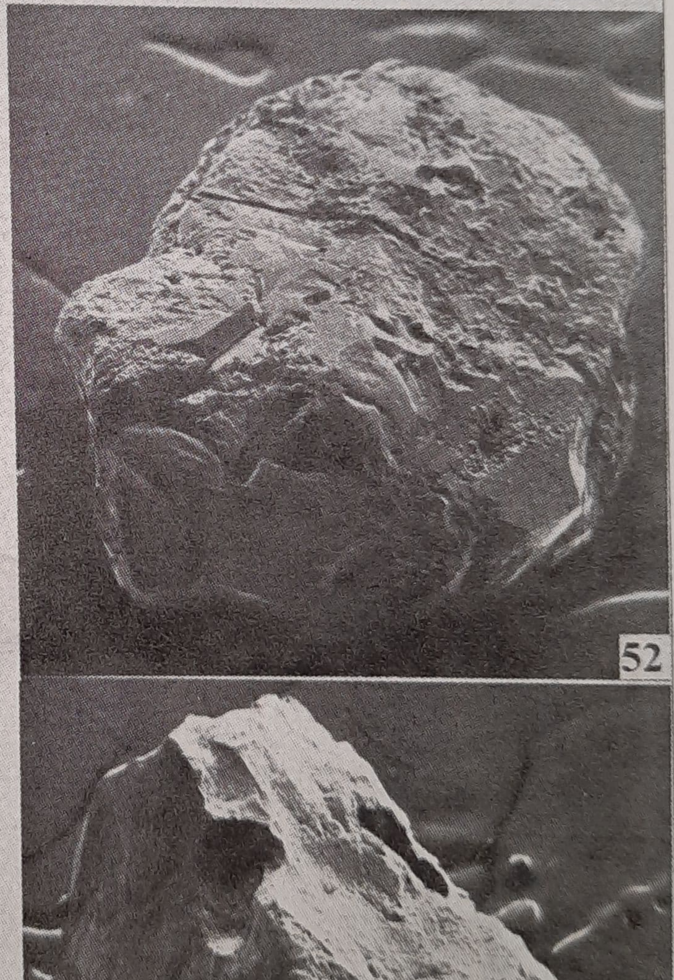

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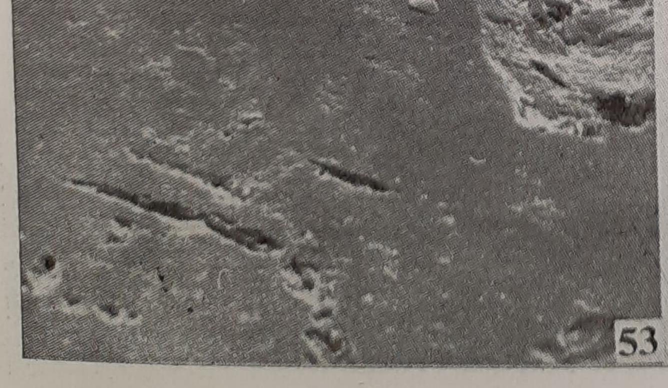

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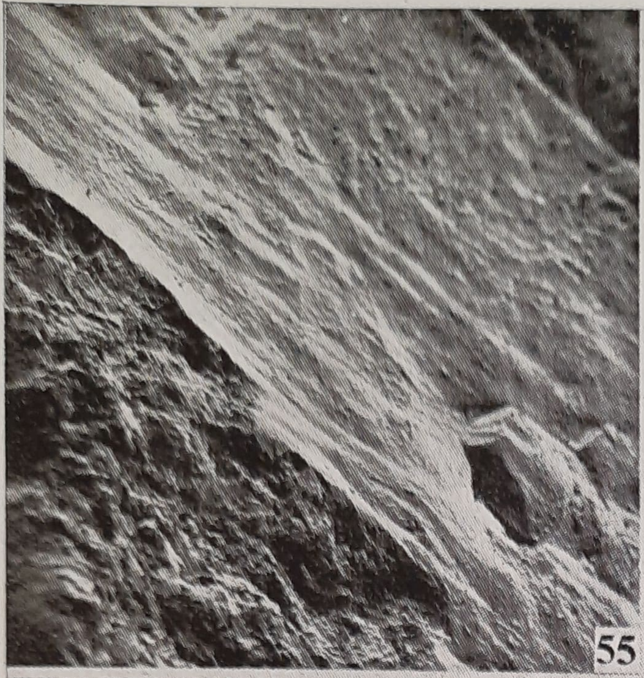
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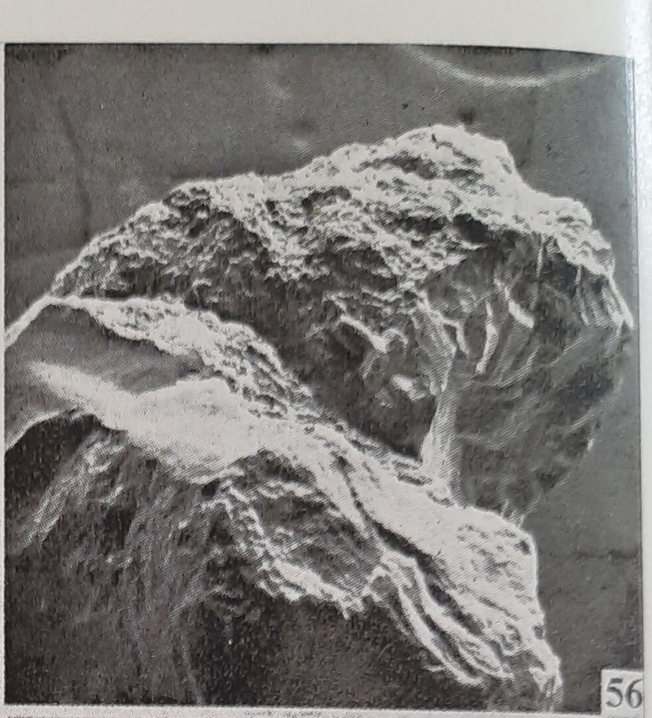
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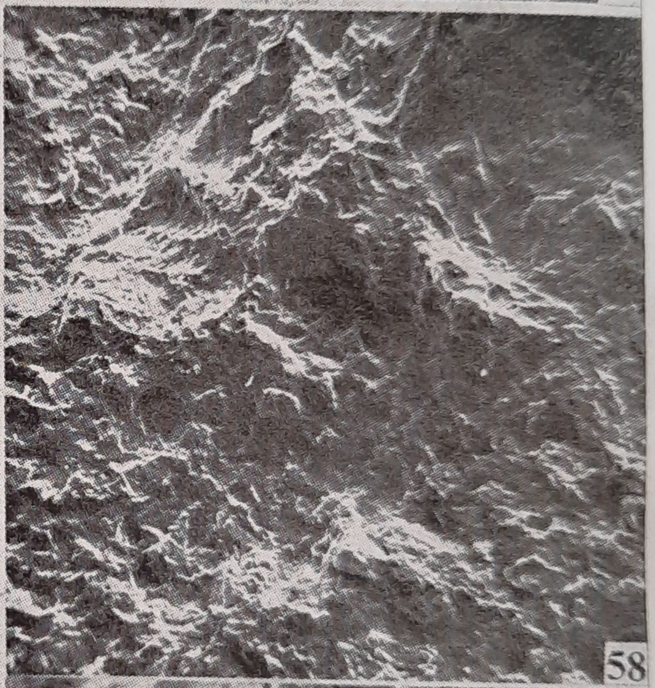
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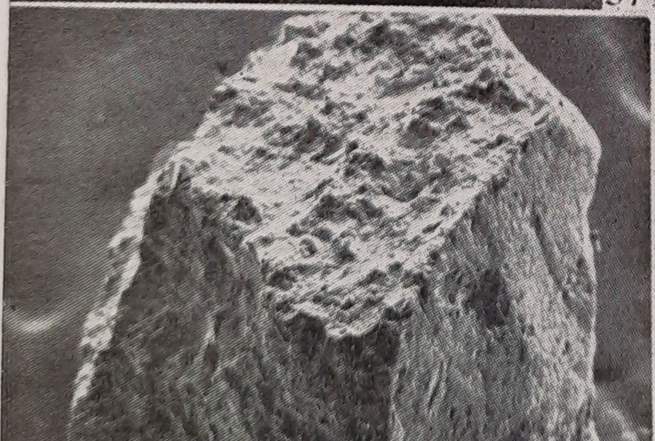
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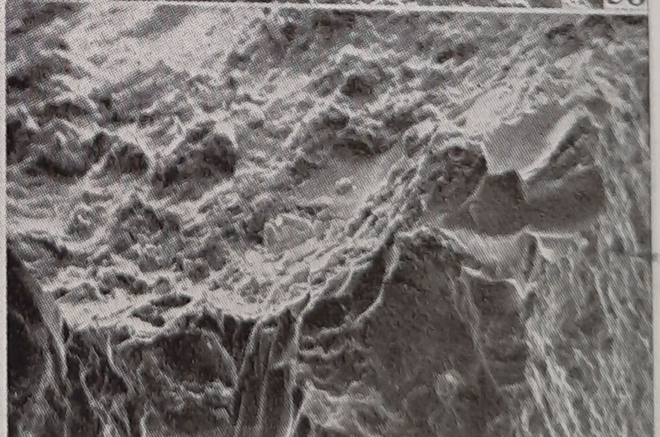
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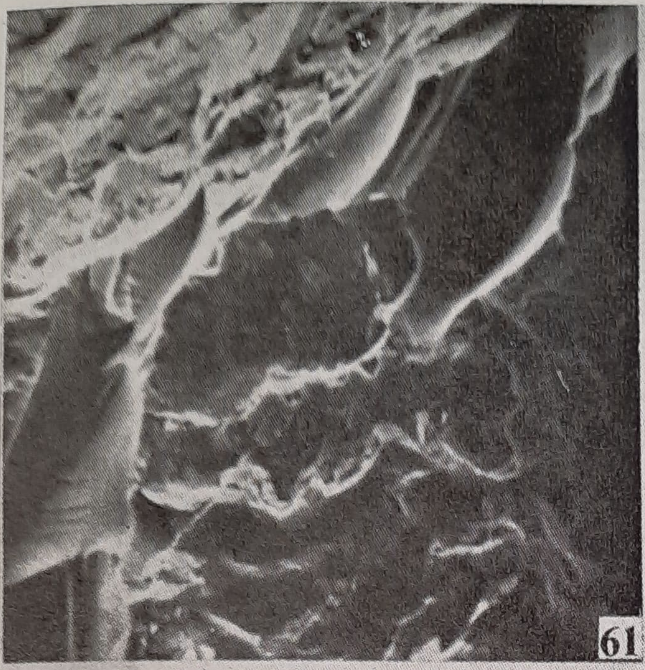
Singh—Plate 10



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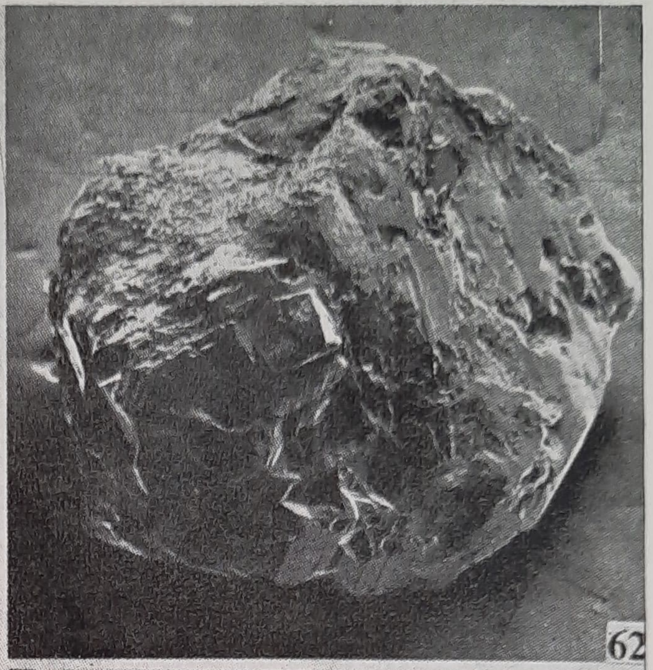

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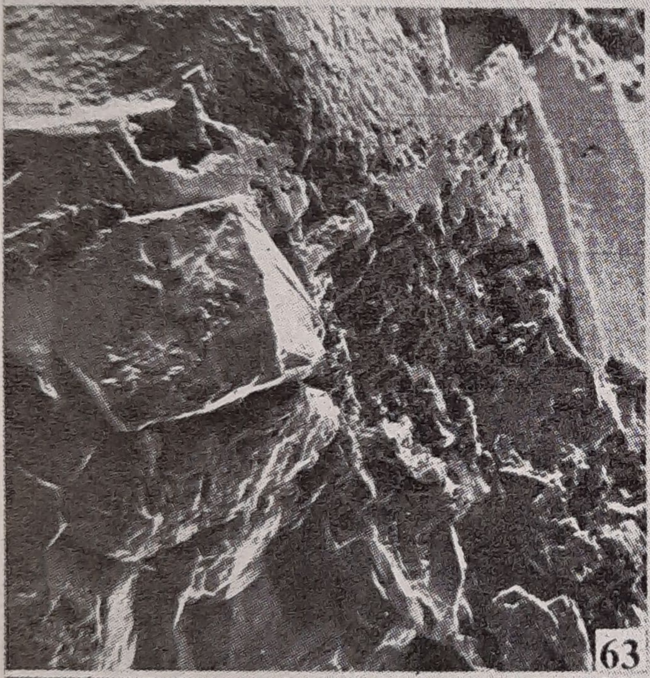

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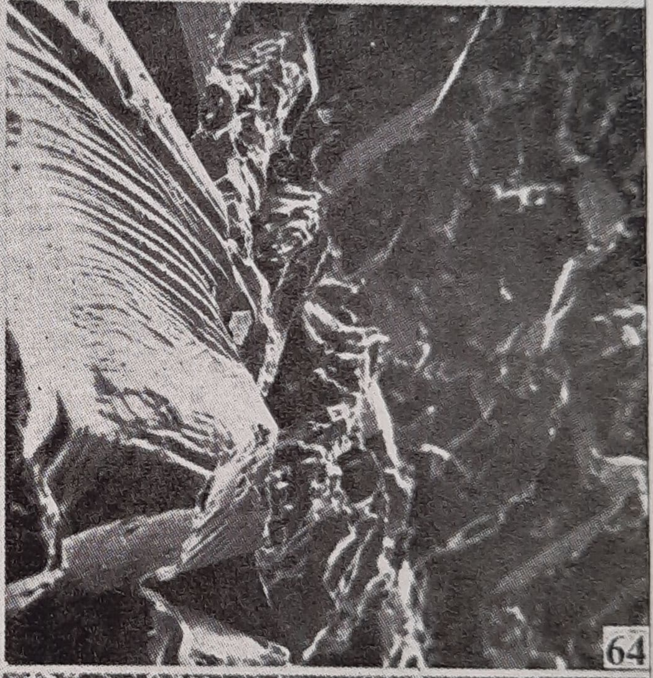

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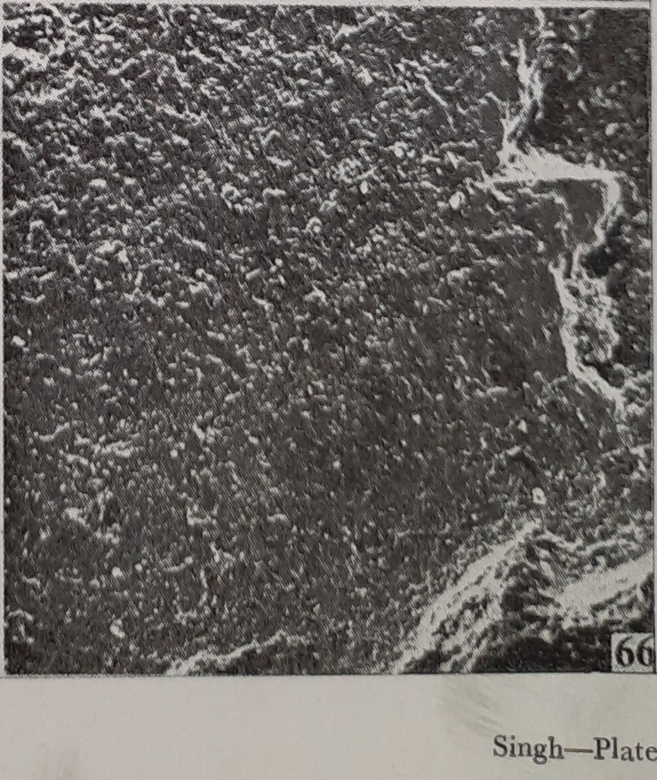

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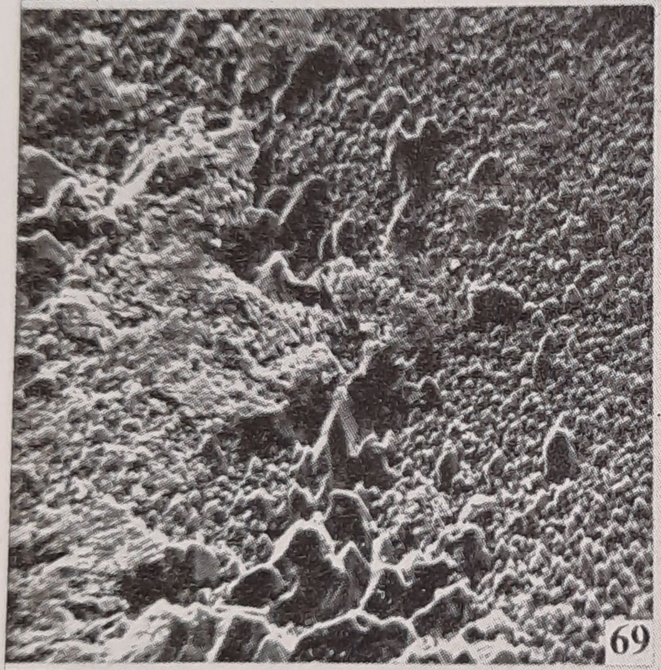

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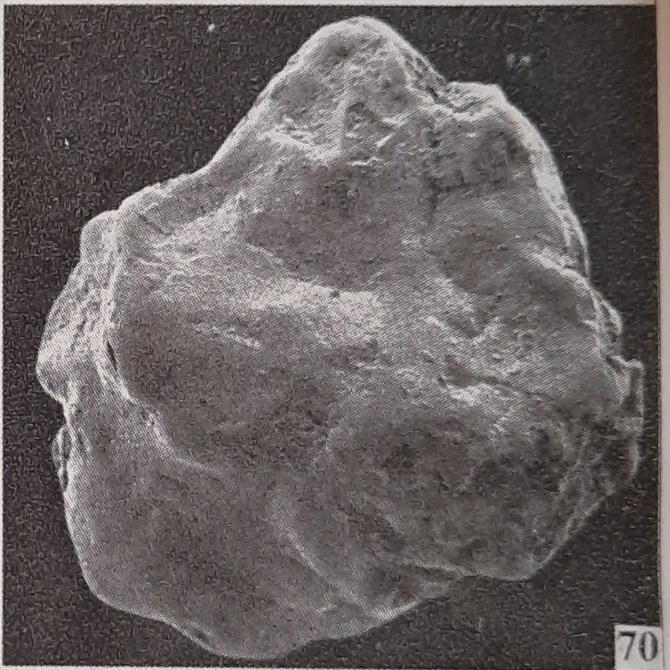

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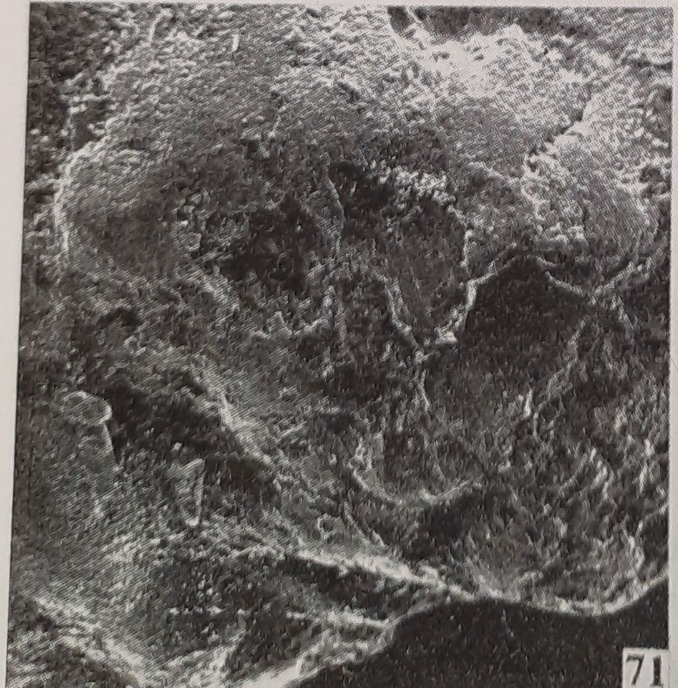

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