SOME OBSERVATIONS ON ELECTRON MICROGRAPHS OF QUARTZ SAND GRAINS[1]

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ABSTRACT

Electron micrographs of sand grains from southern Piedmont saprolites, temperate and polar glacial deposits, and the St. Peter Sandstone are presented. Sand-grain surface features of saprolite grains are described for the first time and from these some concept of the initial surface of a quartz sand grain is obtained. Micrographs of the sand grains from glacial deposits whose erosional history was limited to ice action uniformly show strongly striated surfaces. Comparison of the features described here with those offered as criteria for a glacial history by previous workers suggests the need for further evaluation of the published criteria. Further study should be made of sand-grain surfaces using sands which have been exposed to a single erosional agent to allow for the determination of more rigorously defined criteria for the interpretation of their geologic history.

INTRODUCTION

Since 1962, electron micrographs of sand grains have been studied with increasing interest and in a variety of problems. Porter (1962) described a number of surface textures of sand grains from the Winchell Formation of Pennsylvanian age from Texas and presented a descriptive system for classifying the various surface morphologies. He compared micrographs of sand grains from the Winchell with those of grains from the St. Peter Sandstone of Ottawa, Illinois, and also with those of grains from a modern beach and river deposit. Most of his illustrations are of Winchell sand grains, by means of which he also attempted to relate the types of surface morphology to grain size. His discussion of how to clean sand grains is particularly helpful to one attempting to make sand-grain micrographs for the first time.

The nature and distribution of fine particles are of particular interest in applied problems. Biederman (1962), in studying sands from New Jersey shorelines, used micrographs of sand grains to identify surface features caused by solution—etch-pits aligned crystallographically—and by eolian abrasion—"impact pits". In his paper he discusses the formation of fine silica dust, the formation of a soluble outer layer on quartz grains, and the importance of these factors in geologic processes involving the availability of silica as cement in such sediments.

The most extensive use of electron micrographs has been that of Krinsley and his associates. Krinsley and Takahashi (1962a) compared electron micrographs of crushed quartz grains abraded by air jet, ball mill, and shaking table with grains from modern beach and dune deposits to demonstrate the possibility of interpreting the transport history of the grains from their surface morphology. The same authors (1926b) described in some detail their apparatus for simulating various agents of transport to develop distinctive sand-grain surfaces, and included micrographs of glacial sands, formed both in the laboratory and under natural conditions. Sands from dunes, beaches, and tills are illustrated and compared. One aspect of the study deals with the density of surface marks as a measure of distance traveled. Criteria for identifying the agent of transport are applied to the interpretation of surfaces of grains from cores from off the coast of Argentina. This paper offers some of the best reproductions available of sand-grain micrographs. In 1962(c), Krinsley and Takahashi reported on crushed quartz grains compressed in an ice-filled piston, and compared the resulting sur-

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THE OHIO JOURNAL OF SCIENCE 71(2): 106, March 1971.

face features with those of sands from Pleistocene tills. From these three studies of electron micrographs of sand grains, the authors proposed criteria for the recognition of surface morphology formed by water, wind, or ice. Krinsley *et al.* (1964), using electron micrographs of sand grains from along the Atlantic shore of Long Island, compared the increasing dominance of wave-derived features over those attributed to glacial origin as a measure of the distance of littoral transport. This paper also has good illustrations, although some had been published previously. In 1965, Krinsley and Fennell reported on a study of Lower and Middle Pleistocene sands of Norfolk, England, in which they interpreted a detailed sequence of transport history, involving several cycles of activity as well as various agents of transport. Illustrations of micrographs in this paper are excellent.

In 1965 Waugh used electron micrographs to study the patterns of secondary growth on sand grains from the Penrith Sandstone of Permian age in England. Comparison of micrographs of grains showing abraded surfaces of eolian origin with those of Penrith sand grains suggests a similar origin for the surfaces of the latter. Secondary growths on Penrith grains are thought to have been formed from the fine silica dust particles abraded by wind action. Wolfe (1967) used electron micrographs to demonstrate the effect of solution on sand grains from Cretaceous chalk from Ireland. Grains studied show percussion marks and frosted surfaces covered by a polygonal pattern of pits which reflects the shape of adjacent calcite crystals and, in places, molds of fossils. Distribution of the pits varies in response to different solubilities controlled by crystal orientations.

Recent papers of Krinsley and Newman (1965), Hamilton and Krinsley (1967), and Geitzenauer, Margolis, and Edwards (1968) present sand-grain micrographs with special surface features attributed to glacial origin as evidence for past glacial events; the first and third studies are of grains from deep-sea cores and the second is concerned with samples from Upper Paleozoic rocks from South Africa and Australia.

Southendam (1967) described additional sand-grain surface features characteristic of desert and river environments, and pointed out that desert-environment grains have a more consistent pattern than do those from river environments, which in some examples include features that have been attributed to beach or glacial origin. Southendam demonstrated the use of incident illumination for making micrographs, suggesting that this "simpler," more rapid technique can supplant the electron microscope in some instances. Margolis (1968) studied etch-pits on sand grains from beaches having various intensities of wave energy. He used a ratio of the degree of development of etch features attributed to solution to features attributed to impact as a measure of intensity of wave energy.

Krinsley and Donahue in 1968 summarized the criteria they had developed for recognition of mode of transport, depositional environment, and diagenitic activity from the electron micrographs of sand grains. Little new material is offered in the paper, but the various criteria are identified by aid of annotated plates and listed in tables for easy comparison. Finally, representing the first of several studies in progress is the work of Stieglitz (1969) using the scanning electron microscope, which offers a new mode of representation of sand-grain surfaces. Although its use requires some experience in viewing, the instrument has a greater versatility than does the electron microscope.

PURPOSE OF STUDY

Micrography of sand-grain surfaces was undertaken with two objectives: to determine the nature of the surface topography of the grain, the presence of impurities, and the effects of beneficiation on sands known to be useful as molding sands. The results of this aspect of the study were reported in a paper by Williams, Powell, and Fitzpatrick (1967). The second objective, reported here, was the description of sand grains selected to show as nearly as possible the initial surface of the grain. A further aspect of this objective was to test some of the published criteria used in the interpretation of the geologic history of sand grains having a history involving a single agent of erosion (e.g. ice). For contrast, surfaces of grains from southern Piedmont saprolites and from glacial deposits are compared with those of grains from the St. Peter Sandstone of known complex, multicycled history. Although the number of grains studied is too limited for establishing general criteria, the features shown are consistent for the grains from each environment and, if further tested, may prove of general value.

ACKNOWLEDGMENTS

The laboratory work for this study was performed by Fitzpatrick under the guidance of Prof. G. W. Powell, and the study of the molding-sand properties was made under the guidance of Prof. D. C. Williams, both of the Department of Metallurgy, The Ohio State University. Samples of the saprolites from the southern Appalachian Piedmont were obtained from Mr. Thomas O. Crawford of the Georgia Geological Survey and from Prof. Charles B. Hunt of The Johns Hopkins University. Samples of glacial sands were obtained from Mr. Gerald Holdsworth of the Geological Survey of Canada. The St. Peter Sandstone samples came from commercial sources involved in the study of molding sands.

TECHNIQUE

A Philips model EM 100 B electron microscope was used (for detailed description, see Magnan, 1961). The instrument was equipped with an internal camera in which Eastman Kodak fine-grained positive bulk film P651–1 was used. A number of descriptions of techniques for replicating sand-grain surfaces have been published. The method used here is essentially that described by Bradley (1965). Steps in the replicating process are diagrammed in Krinsley and Takahashi (1964); these diagrams are particularly helpful to one learning to interpret the micrographs.

All samples subsequently consisted of disaggregated sands, which were gently washed and sized, and from which grains of 0.25 to 2.0 mm diameter were set aside for replication. At least ten grains from each sample were replicated and photographed.

LOCATIONS OF SAMPLES

Micrographs were made of sand grains from three geologically different environments: saprolites from the southern Piedmont, deposits of modern temperate-climate and polar glaciers, and the St. Peter Sandstone.

Saprolites are designated SA. Samples SA–1 and SA–2 are from a saprolite overlying a granite on State Route 30 south of Concord, North Carolina. Sample SA–1 (Hunt's No. 66–65A1) is from a three-foot massive deep-red saprolite within which are scattered quartz grains. SA–2 (Hunt's No. 66–65A3) is from a foot-thick argillized layer in a structural saprolite under a pod of fresh granite. The saprolite is deep red and contains some feldspar and free quartz grains. Sample SA–3 (Hunt's No. 64–226AC2) is from a saprolite over an argillized arkosic quartzite, located at the intersection of Houks Mill Road and Maryland Route 146 in Hartford County, Maryland. Samples SA–4 and SA–5 (collected by T. O. Crawford) are from a saprolite over a coarse-grained muscovite-biotite granite from a locality seven miles due south of Warrenton, Warren County, Georgia. Sample SA–4 is from a saprolite overlain by Tertiary sediments, and sample SA–5 is from a saprolite on exposed and actively eroded granite a few hundred yards from Sample SA–4.

Glacial samples (collected by G. Holdsworth) are designated GL. GL–1 is from the base of a tunnel in the Casement Glacier, Glacier Bay National Monument, Alaska, a temperate-climate glacier. GL–2 is from the base of the ice of the Meserve Glacier, Wright Valley, Antarctica, a polar glacier.

St. Peter Sandstone samples are designated SP. The St. Peter sand grains used in the study of the molding-sand properties came from the Wedron Silica Company quarry near the town of Wedron, LaSalle County, Illinois. Samples vary in degree of processing, but are all from the same locality. Sample SP–1, a "grab" sample from the sump, has been hydraulically mined from the friable sandstone of the quarry face. Sample SP–2 has been washed and agitated and dried in the standard process for commercial use. Samples SP–3 through SP–5 also came from this quarry, but in addition, have been processed through an air jet, set at various rates, for removing clay and other fine material. SP–3 was processed at a rate of 2000 lb/hr, SP–4 at 1000 lb/hr, and SP–5 at 500 lb/hr.

DESCRIPTION OF SAND-GRAIN MICROGRAPHS

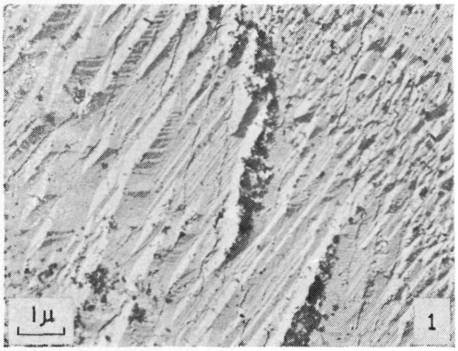
Selected micrographs of sand grains from saprolites from Georgia, North and South Carolina, and Maryland are shown in Figure 3, 1–14. Additional illustrations by the author are given in Williams, Powell, and Fitzpatrick (1967) and in Fitzpatrick (1967). Sand grains from a saprolite over a primary crystalline source-rock would be expected to show surface form resulting from the characteristics of the growth of the crystal faces, the imprint of molding by the exterior of any earlier developed crystal, and the effects of solution as weathering freed the grain from the source rock. It is possible that some mechanical action resulting from frost may have affected the grains, although the lack of confining pressures in the regolith would make such stress of limited effect. With present knowledge, it is not possible to separate the morphological features of crystal growth from the effects of molding by exterior crystals. A further complication exists in that some distortion of the initial grain faces may have been caused by later metamorphism.

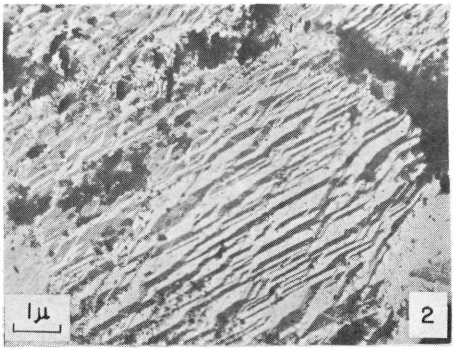
Surfaces of grains that show sharply ribbed and faceted surfaces in parallel geometric patterns (fig. 1 and 2), reflecting crystal growth, are similar to surfaces of freely grown crystals, and are described as "striated faces." (Unfortunately, in mineralogy, the parallel ridges of mineral faces are described by the term "striations", and in sand-grain morphology some abrasion marks attributed to ice are similarly named. One has to determine from the context which definition is meant.) It is not possible to distinguish the morphology that may be controlled by the growth of the quartz from that which may result from molding by confining grains, probably of feldspar. For our purposes, surfaces of either origin will be referred to as crystal-controlled surfaces (representing either growth or molding sculpture).

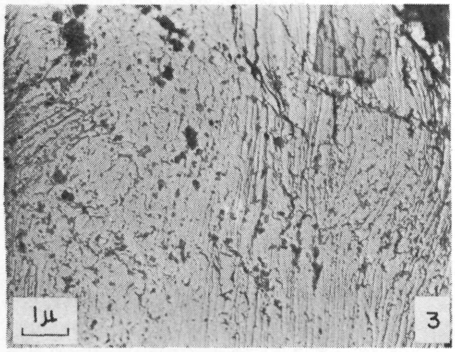
In Figures 3 and 4 the initial crystal-controlled surface shows two patterns of amount of relief, both surfaces having subdued, somewhat rounded ridges that are finely pitted or corroded. Because neither grain has been transported, the rounding may possibly be a molding effect, but it is more likely related to chemical weathering, for both grains come from a sample described by Hunt (personal communication) as "argillized." Excluding the surface pitting, the relief and general morphology shown in Figure 4 are quite similar to those of the micrographs reproduced in Krinsley and Takahashi (1969 Fig. 2A) which are attributed to glacial origin.

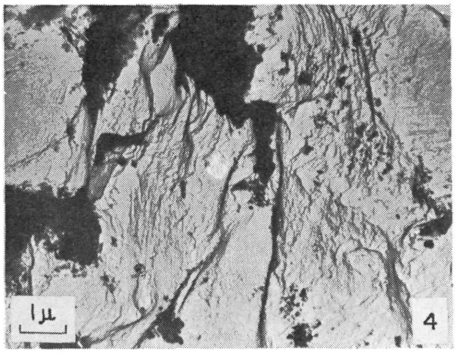
Figures 5 and 6 show a coarser pattern of striations on initial quartz grain surfaces. Both are from weathered granite and without indication of transport. In each, outlines of more than one controlling surface are apparent. The spacing of the generally parallel ridges is wider than that in Figures 1 and 2 and is less regular. In places the appearance of the surface suggests a conchoidal pattern. The pattern of the left half of Figure 6 is almost identical to that described by Waugh (1965, Pl. 6, fig. 1) as "parallel striations characteristic of prism faces of quartz crystals."

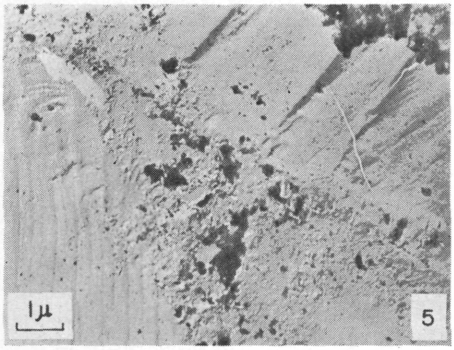
Complicating the surface morphology of quartz grains are twinning and polycrystalline boundaries. In Figures 7 and 8 are examples of boundaries that may

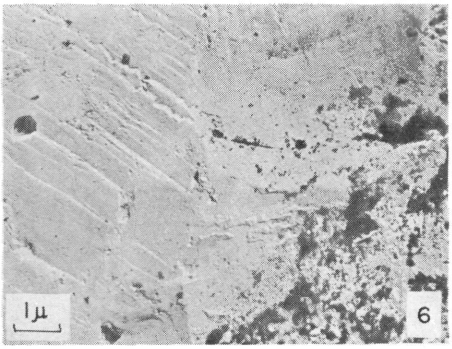






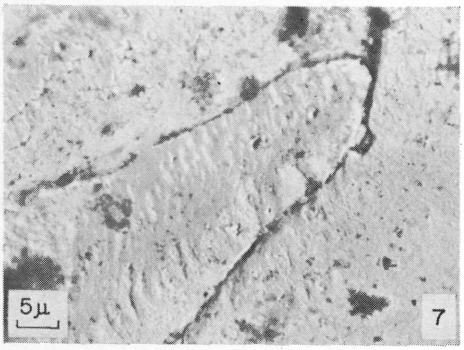


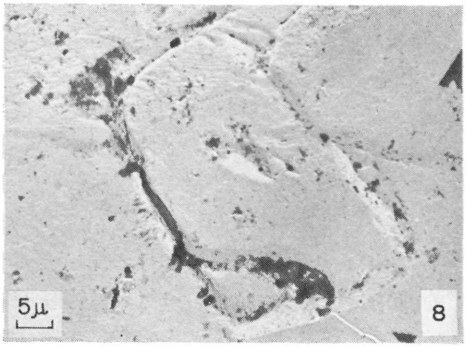


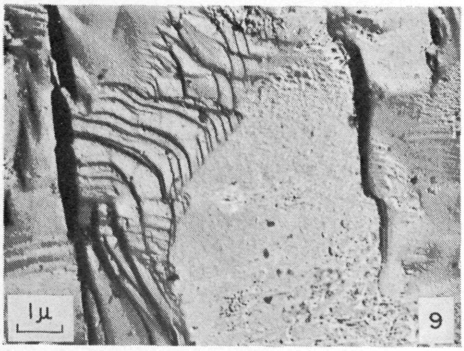


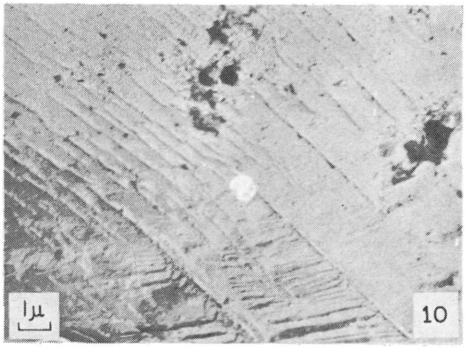
All figures are electron micrographs of quartz-grain surfaces and are oriented with the source of the electron beam from the left or above. Magnifications range from about 1,200 x to 10,500 x (fig. 14) and the scale is indicated by a bar scale in microns. Locations of sources of grains can be determined from the identifying letter in the sample number.

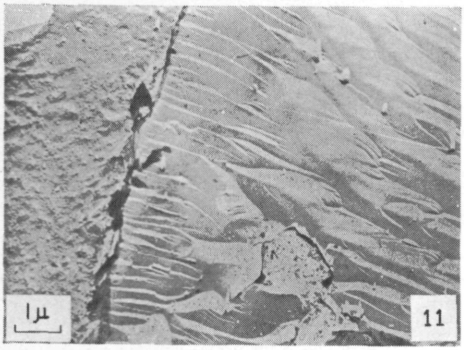
All figures beginning with the letters "SA" are of quartz grains from saprolites. FIGURES 1 and 2. Sample SA–5. Surface of quartz grain showing faceted geometric patterns of a crystal-controlled surface. FIGURE 3. Sample SA–2. Surface of quartz grain showing crystal-controlled pattern with rounded apexes on the ridges. Pitting and rounding are probably the result of weathering. FIGURE 4. Sample SA–2. Surface of quartz grain showing coarse relief comparable to that attributed by others to glacial origin. FIGURES 5 and 6. Sample SA–1. Quartz-grain surfaces showing parallel ridges that are probably crystal controlled, but closely resemble conchoidal fractures.











FIGURES 7–12 are of quartz grains from saprolites. FIGURE 7. Sample SA–5. Quartz-grain surface showing polycrystalline contacts, possibly of Dauphine twins, and a crystal-controlled surface with faint striations.

FIGURE 8. Sample SA–5. Quartz-grain surface showing smooth pattern comparable to that formed by the combination of abrasion, polycrystalline contacts, and fine striations, in the upper left of the photograph, on a crystal-controlled surface.

FIGURE 9. Samples SA–1. Quartz-grain surface showing parallel ridges and a finely pitted area on a crystal-controlled surface.

FIGURE 10. Sample SA–1. Quartz-grain surface showing underlying grid of ridges and fine striations on conchoidal fracture or crystal-controlled surface with rounded, lightly pitted surface, probably resulting from solution.

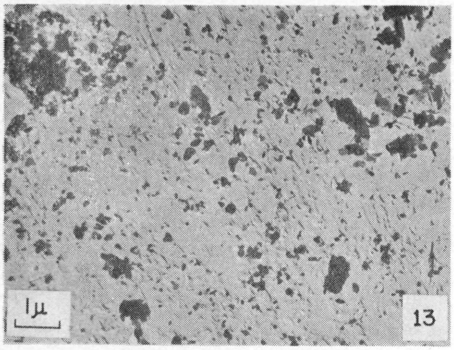
FIGURES 11 and 12. Sample SA–5. Quartz-grain surfaces showing combination of a probable conchoidal fracture and a finely pitted pattern. The pitting is probably due to grain contact with modification by solution. The junction of the two patterns in Figure 11 may be emphasized because of a polycrystalline contact.

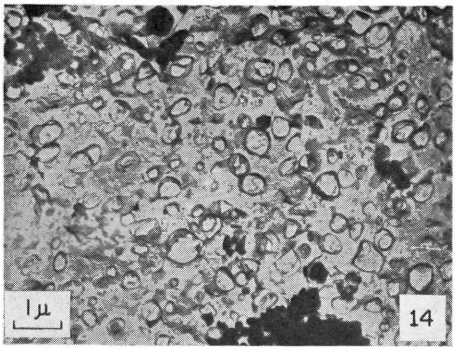
represent polycrystalline grains, or twins. Additional examples are shown in Figures 19, 23, and 24. In Figures 8 and 19, the outlines suggest boundaries of Brazil twins; the outline in Figure 7 appears to be that of a Dauphine twin (twinning habits for quartz are described in detail by Frondel, 1962). Interpretation of the Brazil twins is consistent with the optical properties of the grains. (The magnification jump, random position, and very small area of the micrograph make positive correlation between observations on the two types of microscopes impossible.) The surfaces of the two grains in Figures 7 and 8 are quite different, that of Figure 7 being somewhat pitted and showing a faint parallel striation pattern in the area of the diagonal crystal, and that of Figure 8 being very smooth comparable to some highly abraded surfaces.

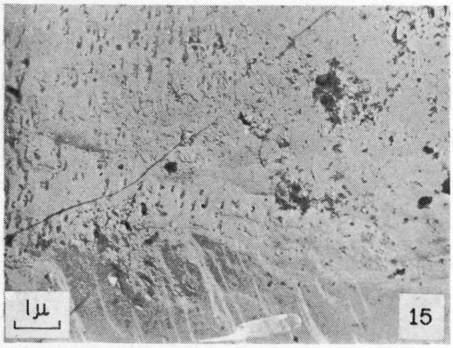
Grain-surface patterns in Figures 9 and 10 show variations that are the result of the influence of a combination of controls. In Figure 9, the stepped surface on the left is probably growth relief of the quartz crystal, and the smooth pitted area on the right is probably the mold of an adjoining grain. In the lower right and central areas, a faint crystal-controlled geometric pattern is present. In Figure 10, the flattened rib pattern trending toward the upper left is probably a subdued conchoidal fracture pattern, flattened by interference with the indistinct cleavage of the underlying quartz grain, which causes the striations at the bottom of the figure. In Figure 11, the sharp boundary between the two different surface morphologies is probably a polycrystalline grain boundary. Assuming that the surface on the right side was not developed subsequent to that on the left, the pitted pattern of the left side is likely to indicate exterior control rather than effects of weathering, because if it were the latter, it should be common to both sides. The right side is anomalous in that the pattern is much closer to that of fracture origin than to that of crystal growth, but the history of the grain allows little if any opportunity for fracturing by transport. Possibly local frost action could have caused the fracture pattern, or it might have been produced by an effect of mechanical expansion in the process of weathering. Although neither of these origins has been offered previously as influencing grain morphology, and no direct evidence is available to support either of them, it is necessary to consider all possibilities. In Figure 12, a further extreme of a fractured surface is present on a grain with a history of no known transport, but the pattern is typically conchoidal, very similar to those interpreted as of glacial origin by previous workers. A small area of pitted-grain surface exists along the right side. Again the sequence of development is important, for if the surface on the right side is the product of weathering, then the fracture surface is younger. (There may also be a small, secondary crystal on the upper surface.)

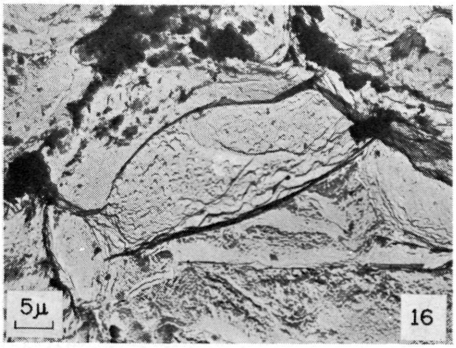
In addition to the effects of crystal growth and exterior forms in shaping the saprolite grains, the activity expected to be most influential would be chemical weathering. Solution and secondary-deposition patterns would be most prominent. Solution pitting, taking place as a part of the weathering history of the grain, has probably altered the surfaces of the grains in Figures 2, 4, 7, and possibly of those in Figures 9 and 11. The triangular pits in Figure 13 are almost identical to those attributed to solution by previous workers. Because this grain is from a saprolite developed over an arkosic quartzite, the generally smooth surface has probably been abraded; at least its history is more complex than that of grains from saprolites derived from granite. In Figure 14, the small grains show secondary growth of quartz on a saprolite grain. This surface is almost identical to that of an example described by Waugh (Pl. 5, fig. 1, 1967) in his study of the authigenic silica in the Penrith Sandstone.

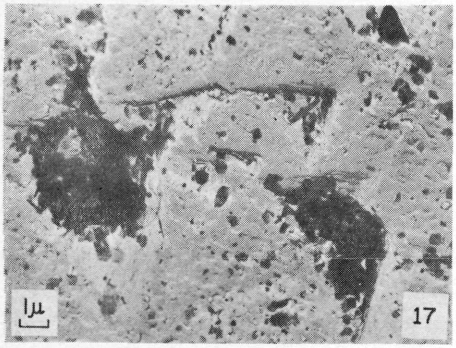
The sand grain from a saprolite in Figure 15 shows a surface with a pattern suggestive of the effects of chemical action, but the limitation of this pattern to the smooth part of the grain makes possible the interpretation that the surface is one of contact origin or simply of different faces on a single crystal. The upper

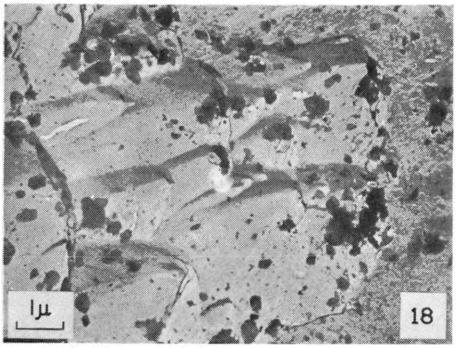












Micrographs of quartz grains from different sources showing solution effects.

FIGURE 13. Sample SA–4. Quartz-grain surface showing triangular pits formed by solution and a covering of clay particles.

FIGURE 14. Sample SA–5. Quartz-grain surface covered with small crystals of quartz formed by secondary growth.

FIGURE 15. Sample SA–5. Quartz-grain surface showing pitting surface resembling solution pattern, but possibly formed in part by contact with adjoining grain and, in the lower portion, with a different crystal face with parallel striations.

FIGURE 16. Sample GL–1. Surface of quartz grain from a deposit by a temperate-climate glacier, showing well-developed pitting on a surface of high relief.

FIGURES 17 and 18. Sample SP–4. Surfaces of quartz grains from the St. Peter Sandstone, showing etched and abraded surface of multicycle erosion history.

portion of the grain shows elongate, triangular etch-pits suggestive of the impression of a rhombohedral face, and the lower portion shows rounded, parallel edges suggestive of modified growth lines on a prism face.

A sand grain from a temperature glacier is shown in Figure 16. Its corroded surface was presumably dissolved by meltwater. Note the similarity in relief of the grains in Figure 16 and Figure 5. Both are grains of high relief and both have evidence of chemical activity, yet one is from a saprolite and the other is from a glacial deposit.

Figures 17 and 18 show surfaces of grains from the St. Peter Sandstone. The known multicycle history of this deposit is very complex. The relatively smooth surface appears to be the product of both repeated wind and water abrasion, and the triangular patterns are probably solution sculpture.

Sand grains in Figures 19, 20, and 22 are from deposits of a temperate glacier (GL–1), and those in Figures 21 and 23 are from those of a polar glacier (GL–2). The striking feature shown in Figures 19 and 20 is the presence of fine scratches or striations on the surfaces of the grains. No generalizations can be made from so few micrographs, but if these markings prove to be common on deposits of glacial origin, they may be a useful criteron for glacial grains, perhaps less ambiguous than some criteria previously described. The surfaces of the glacially transported grains are generally smooth, but a comparison with Figure 16 shows that relief can be quite variable. The fine pitting on the grains in Figures 19, 20, and 22 may be the effect of limited exposure to meltwater. The grains in both Figures 21 and 23 show very smooth surfaces. The furrows on the grain in Figure 21, because of their striated (crystalline?) sides, are suggestive of beveled initial crystalline surface; however, the curved lines of both furrows and striations suggest a percussion or pressure origin. These may be equivalent to the well-known "lunate" fracture marks on glacially striated quartzite boulders. On the upper surfaces of the grain in Figure 22, fine parallel striations of crystal-controlled origin are present. Superimposed on the higher parts of the surface are randomly oriented striations of glacial origin. The regular spacing and parallel arrangement sets those striations produced by crystal growth apart from those formed by abrasion. Figure 23 is complicated because of the strong contact effects on what is probably a polycrystalline grain. Although all of these grains were collected

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EXPLANATION OF FIGURE

FIGURE 19. Sample GL–1. Surface of quartz grain from deposit of temperate-climate glacier, showing smoothly abraded surface with randomly oriented striations. Crystal boundary crossing grain is probably contact of Brazil twins. Note lines etched in the left crystal which parallel the grain boundary.

FIGURE 20. Sample GL–1. Surface of quartz grain from deposit of temperate-climate glacier, showing abraded surface and details of striations. This figure is a magnified image of the center of the previous figure.

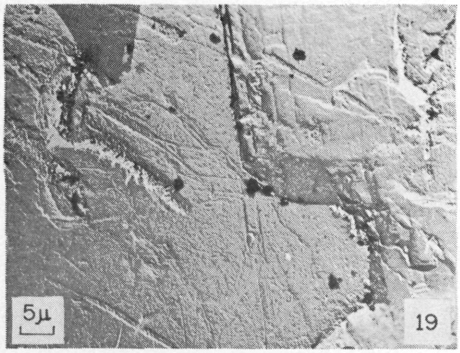
FIGURE 21. Sample GL–2. Surface of quartz grain from deposit made by polar glacier, showing smooth surface with striated furrows. The latter are probably remnants of grain-to-grain contacts, possibly equivalent to "lunate fracture" marks of glacially striated bedrock.

FIGURE 22. Sample GL–1. Surface of quartz grain from deposit of temperate-climate glacier, showing smoothly abraded surface in some areas and moderate relief in others. High magnification shows groupings of fine striations in parallel patterns suggesting crystal-controlled etching by transient solutions rather than glacial origin.

FIGURE 23. Sample GL–2. Surface of quartz grain from deposit made by polar glacier, showing polycrystalline boundaries and a generally smooth surface. Fine parallel striations of upper left quarter and diagonally across lower left are probably remnants of a crystal-controlled pattern.

FIGURE 24. Sample SP–2. Surface of quartz grain from St. Peter Sandstone showing strong relief, conchoidal fracture, and a smoothly abraded surface that has rounded the ridges of the fractures. Crystal boundaries of polycrystalline grain contribute to strong relief. Grain has been heated and washed in treatment for commercial purposes.

from glacial environments, none of them exhibits the conchoidal patterns indicated as being diagnostic for glacially derived sand grains by previous authors (Krinsley and Takahashi, 1962c; Krinsley and Donahue, 1968). For comparison, a grain from the St. Peter Sandstone in shown in Figure 24. A limited area of abraded surface shows in the lower left corner; the remainder of the surface of the grain (probably polycrystalline) consists of conchoidal fractures. Much, if not all, of the conchoidal fracturing is the result of beneficiation processes, particularly heating. The rounding of the ridges may have resulted from abrasion in sizing, drying,



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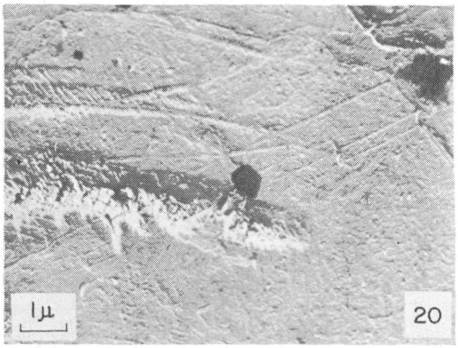

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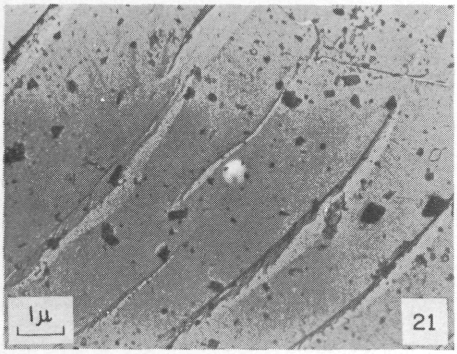

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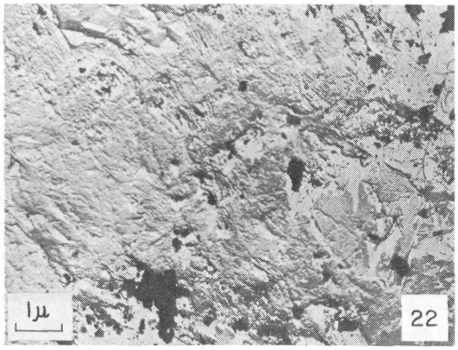
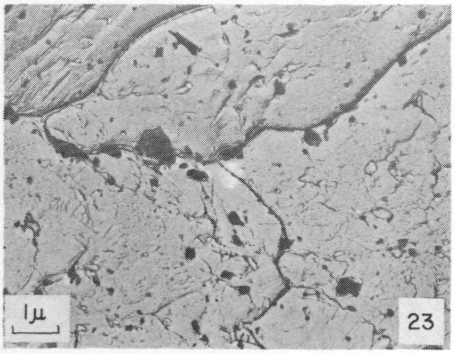


22



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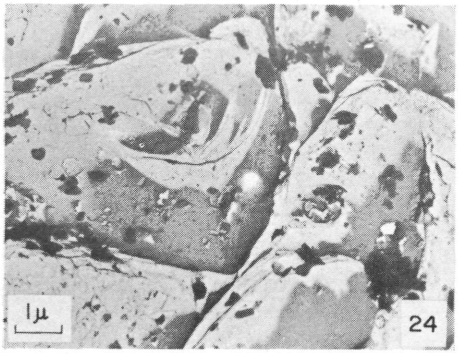

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and the cleaning of fine particles from the grains. Compare the relief of this micrograph with that shown by Krinsley and Takahashi (Fig. 22, 1962c).

DISCUSSION

From the limited experience of the authors and a review of the work of others, the following points seem worthy of comment: 1) the problem of studying electron micrographs, 2) the processes potentially capable of affecting the morphology of sand-grain surfaces, and 3) the evaluation of observations and interpretations that have been made.

Certain problems in the understanding and interpretation of micrographs of sand-grain surfaces stem from the limitations of the electron microscope itself. Aside from the meticulous technique required in replicating the surface of the grain, the gap in range in magnification from that of the optical microscope to that of electron micrographs makes correlation of known properties and structures determined at the two magnifications almost impossible. Because the area of the micrograph is so extremely small, it is almost impossible to duplicate. To our knowledge, there has been no systematic study of the variability present on a single grain to give some basis of judgment concerning the consistency of features for the subjective descriptions and characterization of origins that have been published. The total number of micrographs published and readily available is about 125, of which several are reprinted. These represent grains from a wide variety of environments of deposition and with quite varied geologic histories. The most difficult problem is the lack of any common means of measurement or terminology. Description is a most frustrating task, being comparable to attempting to classify abstract paintings on the basis of form lines. However, there are some consistencies in appearance which may possibly be tied to a standard terminology. Porter (1962) made an attempt to do this, but on very limited data. Our experience is also too limited to do so, but such a classification is needed and, as the number of available examples increases, some systematization should be attempted. Standardization would greatly improve descriptions of micrographs, definitions of criteria for interpretations, and comparison of results.

The scanning electron microscope provides a great improvement over the electron microscope, and reduces the difficulties involved with the control of the magnification mentioned above. The scanning electron microscope requires a less complicated target preparation, allows a greater range of magnification, and is virtually unlimited by problems of depth of field (for a description of the scanning electron microscope, see Sandberg and Hay, 1967). The use of this instrument for study of sand-grain surfaces should give the observational control that is presently lacking, as well as a greatly expanded range of presentation of grain surfaces. Some results are just being published (see Stieglitz, 1969) which suggest a surface configuration that is much more complex than that given by the electron microscope and one that will require a new body of experience for meaningful interpretation. One direction of study should include a careful, stepped sequence of magnification as a guide for interpretation.

Both the versatility of the scanning electron microscope and the ease preparation of micrographs by this instrument have been especially emphasized by Krinsley and Margolis (1969). In this paper, illustrations of sand grains from similar environments made from both the transmission electron microscope and the scanning electron microscope are compared. Such comparisons will be most helpful, as will a series showing the effects of a range in magnification of the same surface. This new instrument greatly increases the future possibilities of interpretating the mode of occurrence of sand grains.

In this attempt to become acquainted with sand-grain surface morphology, we decided to look at grains with surfaces that were as nearly unaltered as could be obtained. For this purpose sand grains were chosen from saprolites, though even these grains may have a history more complex than might be at first realized. The complexities introduced by transport are absent, but there still remain some influences difficult to evaluate. In considering the potential factors affecting the morphology of a grain of quartz in an igneous rock, two basic controls have been considered: the growth characteristic of the quartz crystal, and the shape of the confining space or the surfaces of the bounding crystals of earlier formed minerals. However, the quartz grain, on becoming free through the processes of weathering, is subjected to additional activity that may alter its surface. The chemical activity of the weathering environment is clearly evidenced by etch-pits and secondary quartz crystals on some of the grains. This is obviously a variable, and the degree of activity is dependent on the individual chemical micro-environment; therefore, it will have various expressions even on residual sand grains. The possible mechanical effects of relief of pressure and of frost action also may alter the surface of a grain. Neither of these has been discussed in previous works, but some of the saprolite grains presented here show fractured surfaces and, if the effects of transport are eliminated by the conditions of the grains' occurrence, some other mechanical force is necessary to explain the fracturing.

In previous studies involving transport, the sand grains used have had a complex history of modes of transport and therefore of mechanical actions. In contrast we have attempted to use samples whose erosional histories involved only a single cycle and as simple a transporting process as possible. Of the glacial sand grains, each was collected from the ice at a locality where it had been freed by ice erosion from a bordering crystalline source. By selective collecting, the attempt was made to isolate those effects that were due to ice action. Although the samples used are too small to be definitive, the surfaces obtained are distinctive. However, they appear to lack the criteria previously described as identifying glacial activity. Although only one agent was studied in this manner, the results are so challenging that the approach seems promising for a more precise definition of the characteristics of grain surfaces attributed to each agent of erosion.

In evaluating present knowledge of the description and interpretation of sand-grain surface morphology, the experience recorded here is exploratory for a controlled sampling pattern, as well as a test of previously offered criteria. Very few individuals have worked on the problem, and the methods used have been highly subjective. Reliability and utility can be gained only from repeated results by a number of observers. Of the previous workers, by far the most active have been Krinsley and his various associates. In their earliest work, Krinsley and Takahashi (1962a) started with a most difficult situation and, by laboratory analogy and the process of elimination, sought to separate out the different features found on highly magnified sand grains of very complex origin and sequence. If one examines the comparisons made and conclusions drawn from their study of features attributed to ice origin alone, one can see potential ambiguities in the design of the study. Consider, for example, the strong breakage pattern of conchoidal fractures or percussion marks found on sand grains from tills and duplicated in the laboratory by use of quartz grains in ice under pressure in a movable piston, as reported by Krinsley and Takahashi (1962b and c). This experiment demonstrated the formation of conchoidal fracture patterns on sand grains, but in no way demonstrated the exclusive formation of these features by ice. Could they not also form on a sand grain caught between colliding cobbles? What would be the effects of a change in temperature or of frost action? Since one can strongly suspect the assumption that the features described by Krinsley and Takahashi (1962b) were formed exclusively by ice, it is proper to question the use of these features as criteria for evidence of glaciation in other, more recent papers (Krinsley and Newman, 1965; Hamilton and Krinsley, 1967). Most recently an illustration by Gram (1969, fig. 1), attributed to ice origin, contains a stepped pattern that is far too regular and geometric in outline to suggest a fracture origin; this pattern may well be the result of crystal growth.

Some studies (Krinsley, 1962b, 1964, 1965) have been made of sand grains transported by ice and probably by running water, now found on a beach or in a beach dune. Not knowing which features may have been formed by which agent, or whether some feature may have been produced by more than one agent, the comparison of such features on naturally sculptured grain surfaces with laboratory analogues of known origin is not a completely dependable test. Some patterns are apparently consistent to a degree; e.g., triangular pitting is fairly well established as the result of solution action. However, similar pits may result from irregular growth of a crystal face as well as from solution. Fine, smooth textures are likely to be formed by wind abrasion, but these are not distinctive when compared with some river- or wave-abraded surfaces (note the smooth surface of the grain in Figure 21, which was formed by ice). Considerable promise is suggested by the previous work, particularly by that of Krinsley and his associates, but before sand-grain surfaces are generally used as a key to geologic history, a more rigorous testing of the effect of each erosion agent, singly and in as simple a geologic situation as possible, is needed. In addition, the possibilities of improved instrumentation will allow a much greater control in the making of the micrographs, thereby increasing the reliability of the information for study.

SUMMARY

Sand-grain surface morphology includes a great variety and combination of features. Several workers have begun to describe these features and to interpret their origins, thereby making the ubiquitous sand grain an important source of information for determining the origin of some sedimentary deposits. However, certain limitations are present in our knowledge at this time—difficulties in the use of micrographs made by electron microscopes, lack of a disciplined description of surface features of the grains, and uncertainties concerning the origin of many of the surface patterns. It is possible to improve the interpretation of sand-grain micrographs by use of the electron scanning microscope, by more carefully controlled sampling, and by more thorough study of surface features formed by each geologic agent. Presented here are two examples of geological situations of limited complexity from which a more reliable catalogue of surface features of sand grains and their origin can be made. It is suggested that further study be made on carefully sampled grains with a known history involving a single agent of erosion, and that other studies be made both of uneroded grain surfaces and of the various features on the surface of a single grain.

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