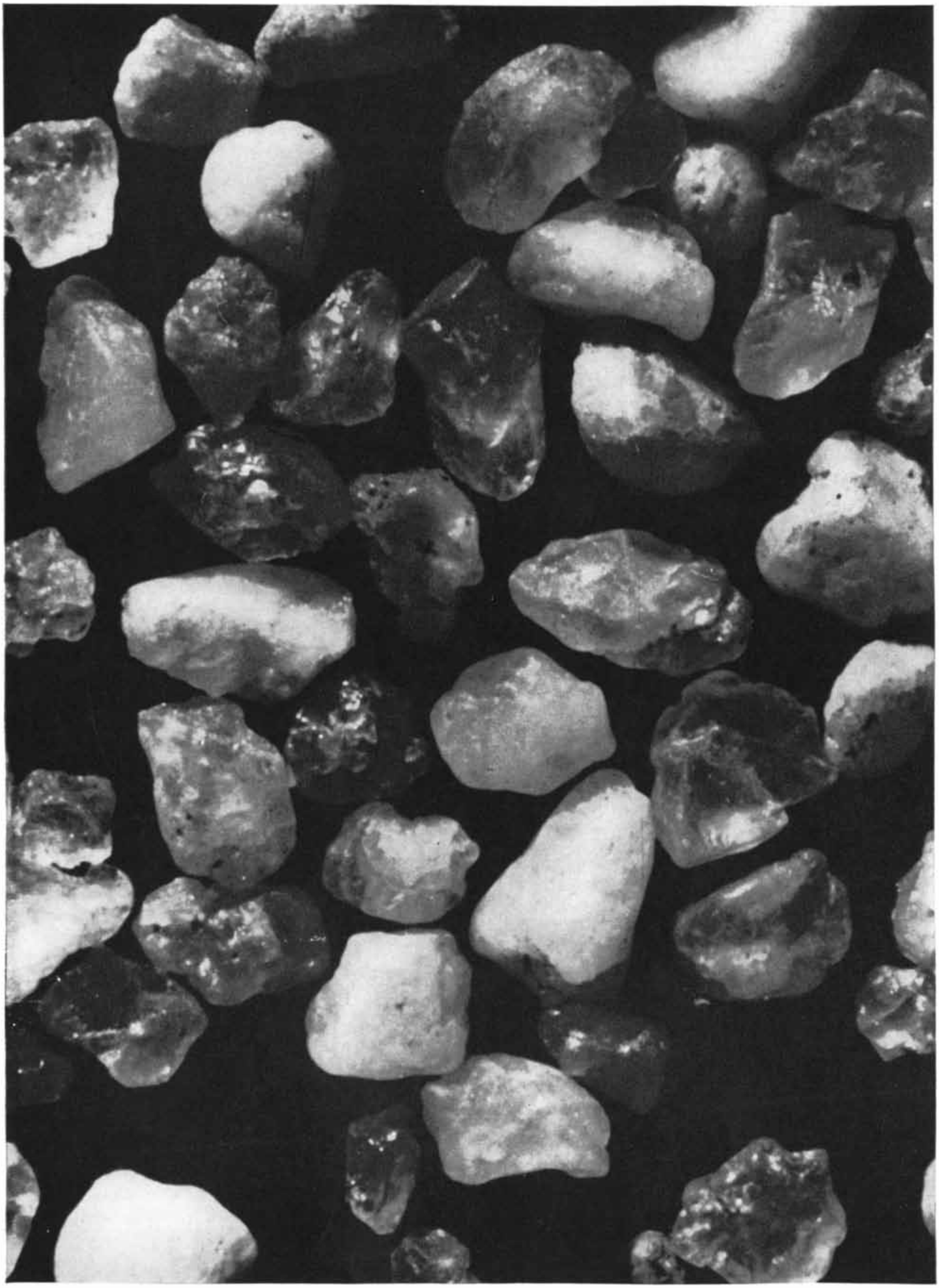


SAMPLE OF SAND from beach at Coney Island in New York City includes old grains that show typical rounding. This sand is principally quartz and originated in granite rock. To develop such a degree of rounding the grains may have been turned over in several cycles of erosion and consolidated more than once in sandstone over a period of some hundreds of millions of years.

SAND

The geologist defines it as particles of rock between .05 and two millimeters in diameter. The shape of sand grains, transported by water and wind, is a clue to their history

by Ph. H. Kuenen

Sand is one of the most common materials on the surface of the continents. Most apparent to the eye on dunes and beaches, it also makes up the bulk of river deposits, although it is often masked by clay or vegetation. Indeed, the prevalence of sand distinguishes the deposits accumulating on the continents from the materials on the ocean bottom. Beds of sand occur here and there on the deep-ocean floor, but clay is the dominant marine sediment. Both sand and clay are end products of the erosion of continental rock. The little grains of sand have been somewhat neglected by geology until recent years, although they have played a mighty role in the history of the continents.

The very abundance of sand has made it so familiar that even geologists did not stop to ask how it came to occupy its place in the landscape and why it tends to accumulate in masses of uniform grain size. Since the vast majority of the ancient sedimentary rocks exposed on the continents are of marine origin, most of them are shales (from clay) and limestones (chiefly from the skeletons of marine organisms); less than 25 per cent are sandstones (from sand). It also happens that sandstones contain fewer fossils than do shales and limestones. Shales and limestones therefore held greater interest in the days when geologists were concerned with general questions of the deformation of sedimentary rocks by mountain-building processes and sought to fix the age of the rocks by study of fossils enclosed in them. Now that the advance into the unknown has broadened, geologists are realizing that sandstones and sands hold the key to many questions still unanswered. The mineral composition of sands can reveal their source; the surface markings and lamination of sandstone beds show how the sediments were laid down and indicate the direction from which the sand came; sand-grain sizes and shapes tell whether the sandstone originated with sand in a river, on a beach or in a dune, and thus yield invaluable information about ancient geography.

Scientific interest in sands and sandstones has been encouraged by powerful economic motives. In glass, concrete, brick and building stone, these materials are the major commodities of the construction industry. Sands in the subsoil are the principal reservoirs of ground water, the supply of which is now so hard-pressed by the needs of urban civilization. Geological inquiry into sand derives its most compelling motivation, however, from the petroleum industry, which has been encountering increasing difficulty in prospecting for new sources of oil and gas.

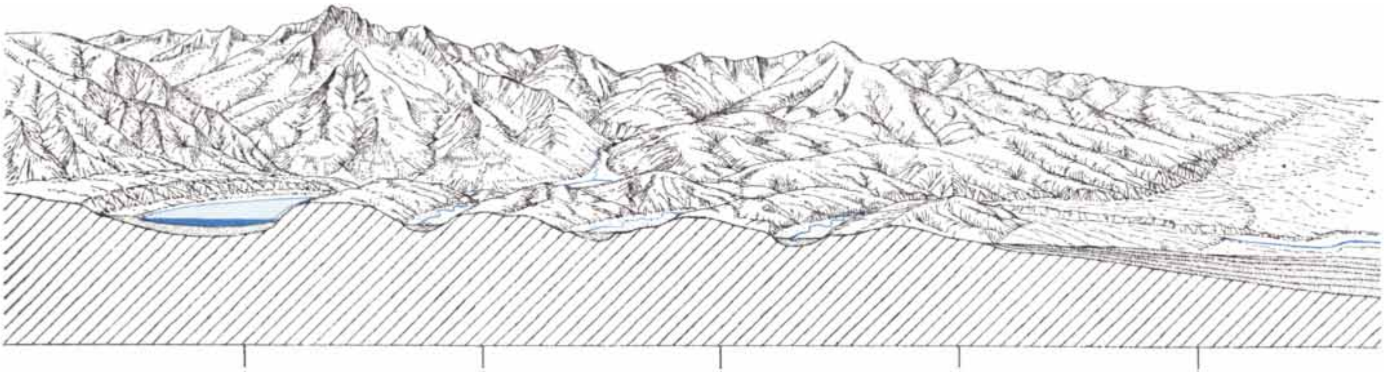
All the obvious places to drill for oil have long ago been drilled. They were indicated by the grander features of geologic structure: domes and major cracks and folds in stratified rock. Geologists are still discovering rich accumulations of oil, but in hoard chambers cunningly secreted by nature—in geologically little-disturbed areas where subterranean sand strata pass laterally into impervious clay-rich beds that keep the oil from escaping. Without the help of disturbed strata, the geologist must attempt to locate sandy channel-bottoms, beach ridges, reefs and similar formations deep underground. The more he can deduce from samples brought up by the first test well, the greater the chance of successfully reconstructing the ancient geographic situation and so of drilling the next well at a productive spot. It is like sitting on a roof with a long drinking straw tipped with a drilling bit and trying to find milk bottles in the building below. In effect the geologist must learn to interpret the various corings of wood, concrete, household utensils and so on in order to find the kitchen and then locate the refrigerator.

The term sand, as geologists use it, means an accumulation of sedimentary particles having a diameter between .05 and two millimeters. Larger grains are classified as gravel and finer ones as silt (.05 to .004 mm.) or as clay (less than .004 mm.). Sands may come from rocks composed of calcium carbonate (limestone), aluminum silicate (feldspar) or silicon dioxide (quartz). Quartz is so much the most abundant mineral occurring in sand grains that the term "sand" is usually taken to mean quartz sand.

The Origin of Sand

Ultimately all sedimentary materials stem from rocks that have formed from the cooling of hot molten matter: either lava or volcanic ash, or rocks such as gneiss and granite that have consolidated at great depths in the earth's crust. Mechanical breakdown produces boulders and pebbles. Chemical breakdown (mainly of feldspar) yields clay; chemical action also puts elements such as calcium and silicon into solution and so carries them over into the life cycles of plants and animals.

What then is the origin of sand? It is common knowledge that boulders and cobbles occur in mountainous areas, that gravels prevail downstream where the rivers descend from the mountains to broader valleys, and that sand and clay comprise the usual water-borne deposits in the lower reaches of the river. The first deduction from these observations is tempting: Mechanical wear during the long journey from source to mouth



SOURCE AND DISTRIBUTION OF SAND are shown in this imaginary landscape. The weathering of rock in the mountains and uplands (*left*) constantly renews the supply of angular grains. These are carried by mountain streams to a river in the lowlands (*center*). The river, in its meandering over the years, distributes the sand broadly over the floor of the valley, where it may be

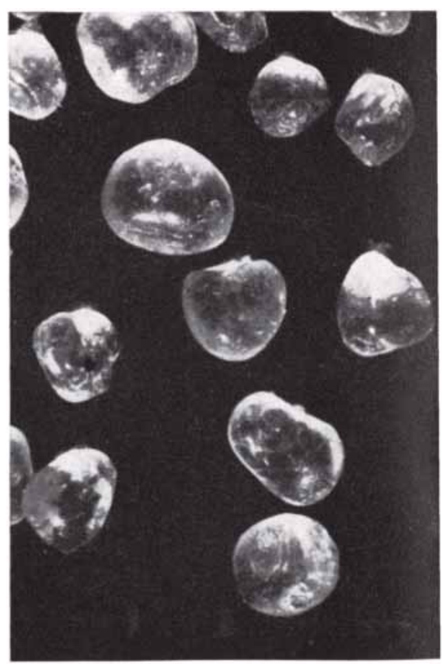
whittles down pebbles to sand sizes, the "chips" being silt and clay. But quantitative considerations quickly rule out this conclusion. The ratio between the volume of the pebble and that of the grain of sand which is supposed to be whittled out of it is such that to produce a drinking glass full of sand would require a shipload of gravel. The real reason for the downstream decrease in grain size is selective transport. As the river descends to gentler slopes and out onto the valley floor, the gradual slackening of current velocity allows progressively smaller particles to fall by the way, until at the mouth only the finest sand, silt and clay are carried into the sea.

The angularity of most sand grains furnishes additional proof that they are not abraded pebbles. Sand must therefore have a different origin, and the true source is not far to seek. Chemical and mechanical disintegration constantly eat away at gneiss and granite rocks and at the boulders and pebbles of these rocks. In localities where there is strong chemical "weathering," promoted by vegetation and heavy rains, clay and quartz grains are the chief products. Where mechanical disintegration predominates, in deserts and alpine regions, feldspar and quartz grains come to life. Examination of the soil covering mountain uplands and of the screes—the rubble-littered zones—at the foot of steep peaks shows sand particles in abundance.

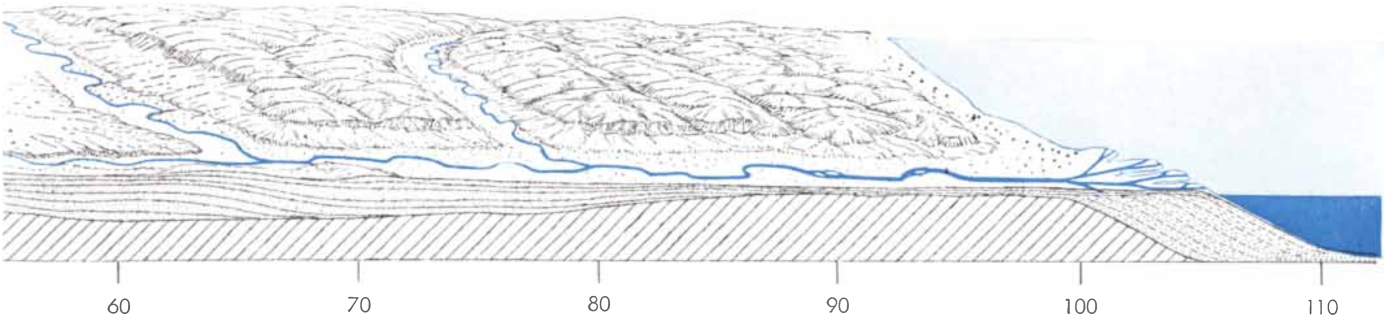
Transportation by Water

After birth the grains are washed downhill and eventually find their way onto the stream bed. The journey down a mountain stream can happen relatively quickly if the particle is taken into suspension. But this is unusual for a grain of sand. The sand grains tend to roll and bounce along the bottom for a short distance and then to accumulate in an eddying pool or in the lee of a boulder. Years may pass before the next lap in the seaward journey. At last the grain leaves

ANGULAR sand grains are relatively young. In this state the grain breaks free from the parent rock and starts out on its long journey by river, from the mountains to the continental lowlands.



POLISHED sand grains occur in river beds. Chemical action in water

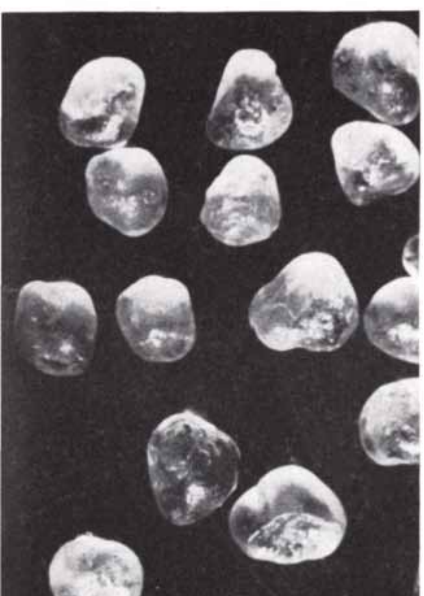


concealed by overlying deposits of silty clays and vegetation. In the process the angular grains begin to be slightly rounded. Where the sand is exposed on deserts, wind abrasion rounds the grains much more completely. Because sand grains are too heavy to be carried by the winds or transported by the rivers beyond tidal estuaries into the sea (*right*), sand accumulates on the continents.

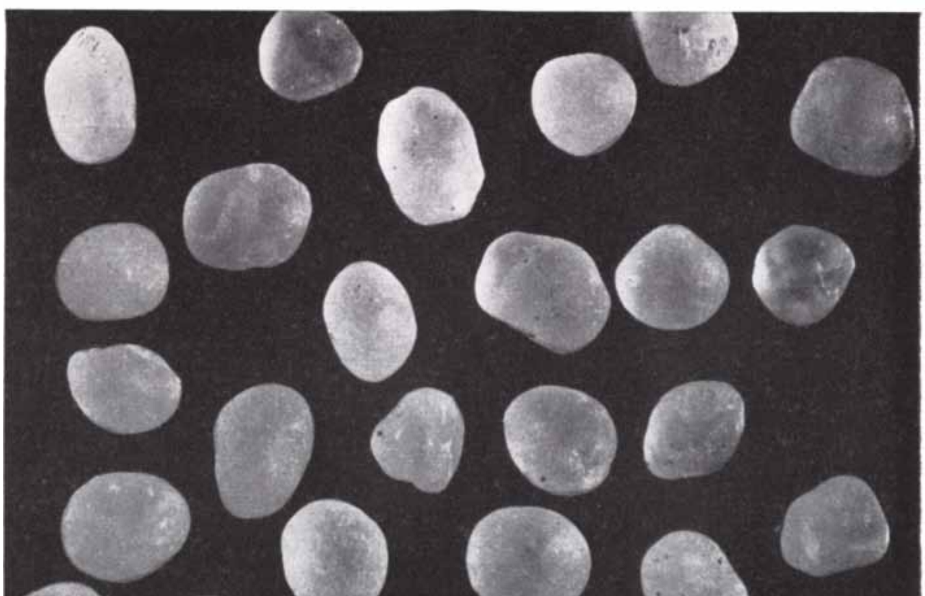
the mountains by way of a river. In the slower-moving water the same spasmodic kind of travel continues, but at a slacker pace. The grain may also be washed over the bank of the river and deposited on its flood plain; in that case a much longer period of rest may ensue. Not until the river alters its course, gradually reworking its own deposits, will it succeed in recapturing such a grain and set it going again on its downstream course. A medium-sized river will take something on the order of a million years to move its sandy deposits a distance of 100 miles downstream.

Few important rivers appear to be carrying sand out into the sea, and only silt and clay reach the oceans in large quantities. A short time ago, geologically speaking, when the glaciers covered the continents, and sea level was some 300 feet lower than it is now, the rivers ran more briskly into the sea. Then they carried some sand offshore. As the ice melted, however, and the sea returned to a more normal level, the slackening of current in the tidal estuaries of most of the world's great rivers caused sand to be deposited well inshore.

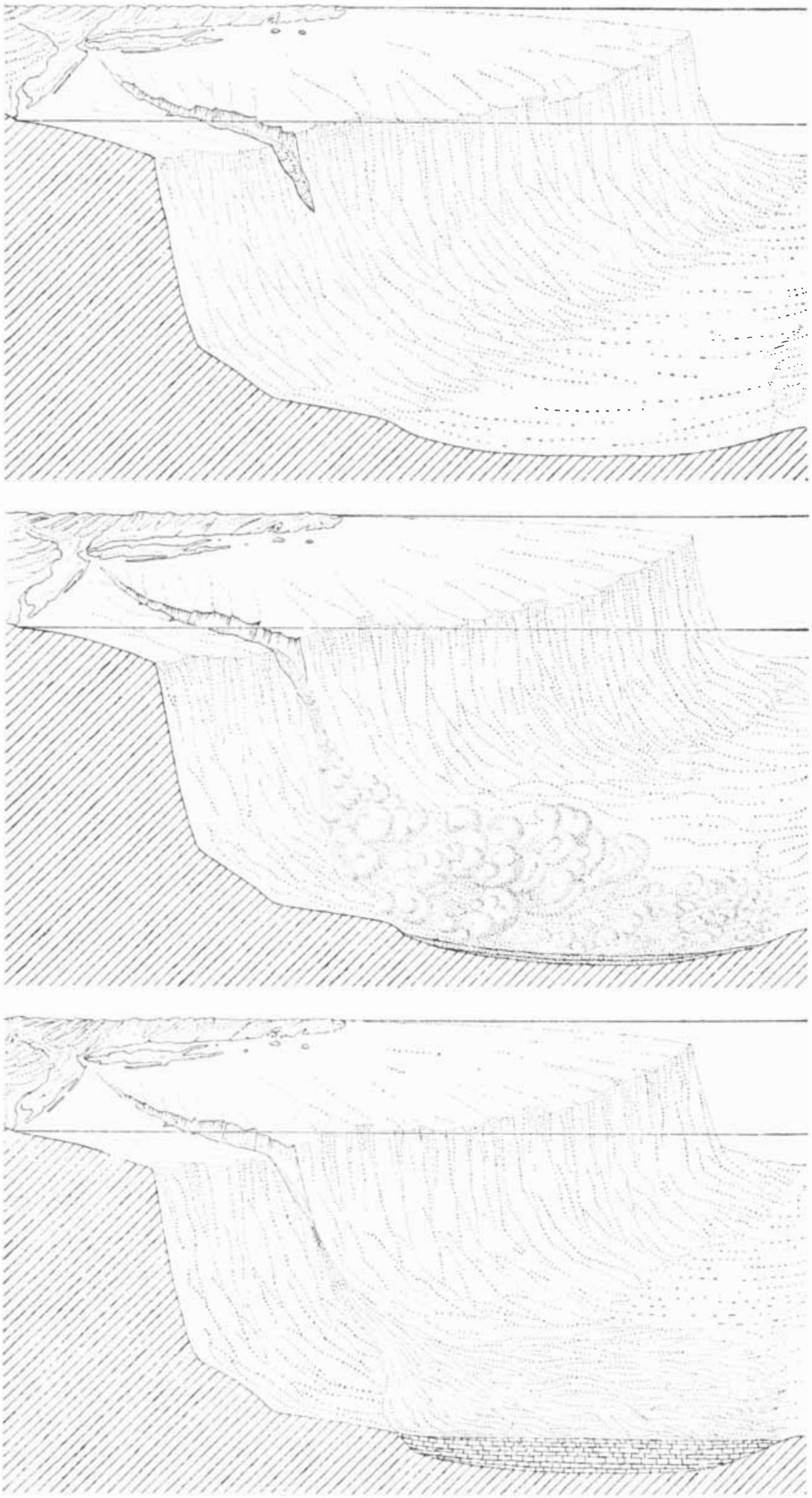
Along the coast and on the continental shelf several processes keep the sand in motion. The inflow and backwash of breakers sweep sand up and down the beach. Where the waves meet the beach at an angle, they carry the grains in a zigzag path downwind, as the water alternately rushes obliquely up the beach and runs back down the slope. Wave commotion dies out rapidly with depth, and even storm waves do not stir a sandy bottom at depths greater than 100 feet. Tidal currents shift the sand back and forth in a more leisurely rhythm. Ocean currents do not usually brush the bottom with sufficient force to carry sand. However, waves frequently join forces with currents, and their combined action may set the grains in motion at depths of 150 feet. There are some sandy areas on the sea floor at greater depths, but only because clay is being washed away from



imparts polish, but grains were probably rounded first by abrasion on land.



FROSTED sand grains are typical of deserts. Grains are rounded by abrasion in wind transport and subsequently frosted by the chemical action that attends wetting by dew and drying by sun.



TURBIDITY CURRENT explains the occurrence of sand deposits on the deep-sea bottom and the origin of sandstone beds in ancient marine basins now upraised on the surfaces of the continents. In these diagrams the vertical scale is exaggerated about 100 times. Sand and silt accumulating in submarine canyon at the edge of the continental shelf (*top drawing*) become unstable and start to slide. As the material slides, it churns up and creates a layer of water with a higher density than clear ocean water; the momentum of this turbid mass carries the sand long distances across the ocean floor (*middle drawing*). Successive deposits of sand, covered by layers of slowly accumulating silt, consolidate to form sandstone strata separated by layers of clay and shale consolidated from silt (*bottom drawing*).

these areas and not because new sand is being supplied to them. The sand on the deeper stretches of the continental shelf, at a depth of perhaps 300 feet, must have been laid down when the seas were shallower.

Turbidity Currents

It is not surprising that geologists came to look upon sandstone beds anywhere among the rocks as indicative of quite shallow waters at the time when the beds were laid down. This axiom led to difficulties, because there are many thick sequences of sedimentary rock in which sand layers alternate with clay. In some cases these sediments contain fossils of animals that lived on the sea bottom in depths up to several thousand feet. This apparent contradiction has been resolved by the discovery of "turbidity currents." Where sand and clay accumulate on steep submarine slopes, the deposit tends to become unstable. It starts to slide and churns up to form a body of turbid water with a density higher than that of the clear ocean. This "heavy water" then accelerates down the submarine slope; with sufficient velocity to keep its load in suspension, it continues flowing out across the ocean floor. Such turbidity currents can carry along many tons of material and run for long distances over favorable stretches of submarine topography. R. A. Daly of Harvard University suggested 25 years ago that this mechanism might explain the excavation of great submarine valleys running down the continental slope. In our laboratory at the University of Groningen in Holland we have conducted experimental investigations that support Daly's hypothesis and show that turbidity currents have remarkable efficiency as agents of erosion. Our experiments have also indicated that the process will lay down sandy beds in which the size of the grains decreases gradually from the bottom of the layer upward, with clay at the top. Oceanographers have since found many sand beds far out in the deep ocean that show this "graded bedding." They have also deduced several contemporary instances of the flow of turbidity currents, recorded by the breaking of submarine telegraph cables [see "The Origin of Submarine Canyons," by Bruce C. Heezen; Scientific American, August, 1956].

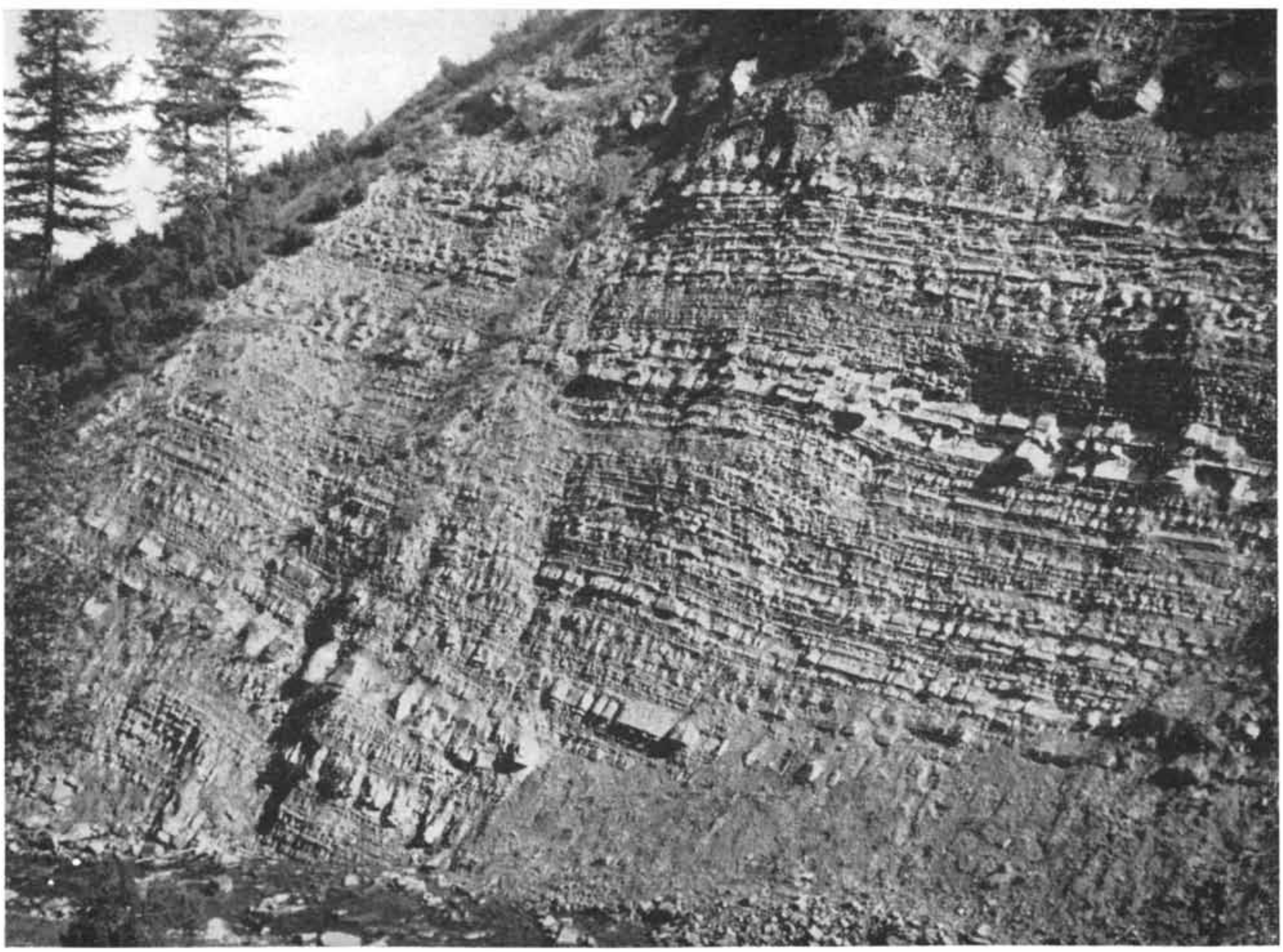
As a turbidity current spreads over the horizontal floor of the ocean, it must lose velocity and begin to deposit its burden. The driving force then disappears and the flow peters out. Examination of ancient rock-series has disclosed many formations built up by graded bedding. The graded sandstone beds alternate with beds of shale, showing that the ancient seas accumulated thick layers of clay and fine silt over the centuries and that once in perhaps 10,000 years a turbidity current came along, leaving a graded bed in its wake. The sandstones record much other evidence of the dynamics of turbidity currents. The churning flow of the current tended to dig out rounded trenches in the bottom mud; where it dragged along sticks and shells it drew grooves in the soft ocean floor. These markings were filled with sand dropping from the current. The resulting casts now stand forth on the lower surface of a sandstone bed from which the underlying shale has been removed. The laminations of the graded sand-grains within the sandstone show undulating patterns that preserve the ripples of the current; here and there the laminations are bent and twisted in a fantastic manner by pressure changes that attended the sudden deposition of the sand.

These and many other features bear testimony to the magnitude of the disturbance that accompanies a turbidity current in its invasion of the quiet ocean depths. Moreover, they record accurately the direction in which the current flowed and hence indicate the direction of the bottom slope. Such information makes it possible to reconstruct the topography of marine basins long since uplifted on the surfaces of the continents. In several cases ancient currents have wended their way for more than 100 miles down the long axis of former deep-sea troughs; recurrent flows have built up alternating sand and clay beds to depths as great as 6,000 feet. The study of such beds is barely 10 years old, but it has thrown interesting and unexpected light on the geography and history of ancient marine basins.

Transportation by Wind

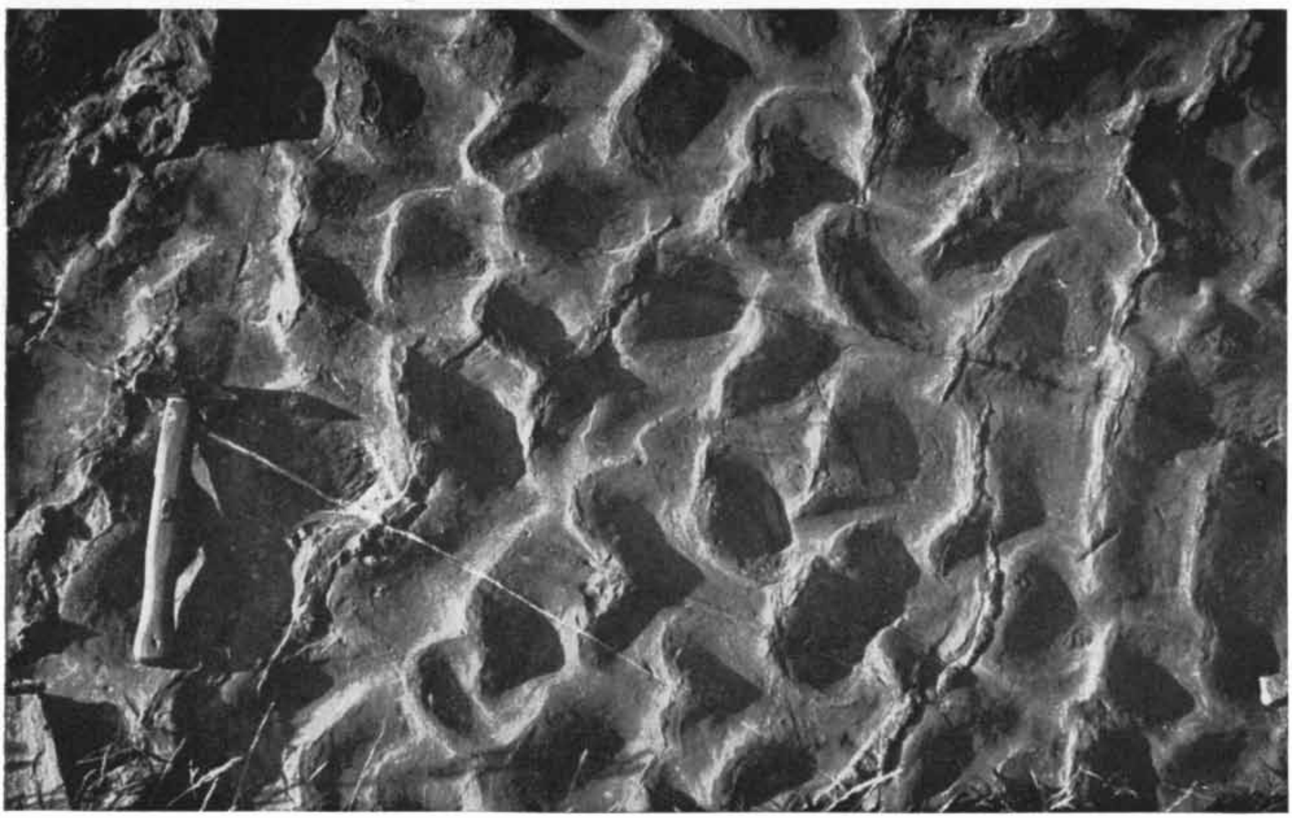
Wind as well as water plays a part in transporting and distributing sand, silt and clay over the earth. Wherever the cover of vegetation is meager or absent, the wind sets sand in motion. The grains bounce and wriggle along, the bulk of them not rising above knee height, but a few are high enough to sting the face if one stands in a strong wind. Silt and clay, on the other hand, will go into suspension in the wind and will travel for long distances above the ground. This explains the occurrence of the silty deposit called loess in the surroundings of certain deserts and formerly glaciated areas. The wind thus serves as an excellent sorting agent, separating silt, sand and pebbles from one another and leaving them at large distances apart. Desert sands, however, tend to have a wide assortment of grain sizes. Rivers sift their sediments more selectively, depositing grains of similar size close together.

The shapes of sand grains have much to tell about their individual biographies. A sand grain in the newborn state is irregular and angular in shape. When viewed with a pocket lens, however, many grains appear smoothly rounded. Roundness here does not mean spheric-



SANDSTONE STRATA alternating with shale reflect the action of turbidity currents (*see drawings on opposite page*) in ancient marine basin. In the centuries between the flow of such currents the silt and clay settling in the deep water laid down the shale.

DEEPLY CONTOURED SANDSTONE records the turbulence that attended the deposition of the sand from a turbidity current in the soft silt and clay on the floor of an ancient sea. Such natural casts are often found to occur on the underside of sandstone strata.



RIPPLE MARKS on the top of a sandstone stratum show that the turbidity current which laid down the sand on an ancient sea floor was flowing from right to left. Overlying mud, which consolidated into clay or shale, has weathered away, exposing sandstone.

ity, but the opposite of angularity; for example, a cylinder with hemispherical ends is said to be rounded. The difference between the young grain and the apparently old one warrants the conclusion that abrasion has taken place in the course of transportation. Here is a clue to whether sand has been carried by wind or by water, an indicator of the age of sand and perhaps a record of the geological revolutions in which it has participated.

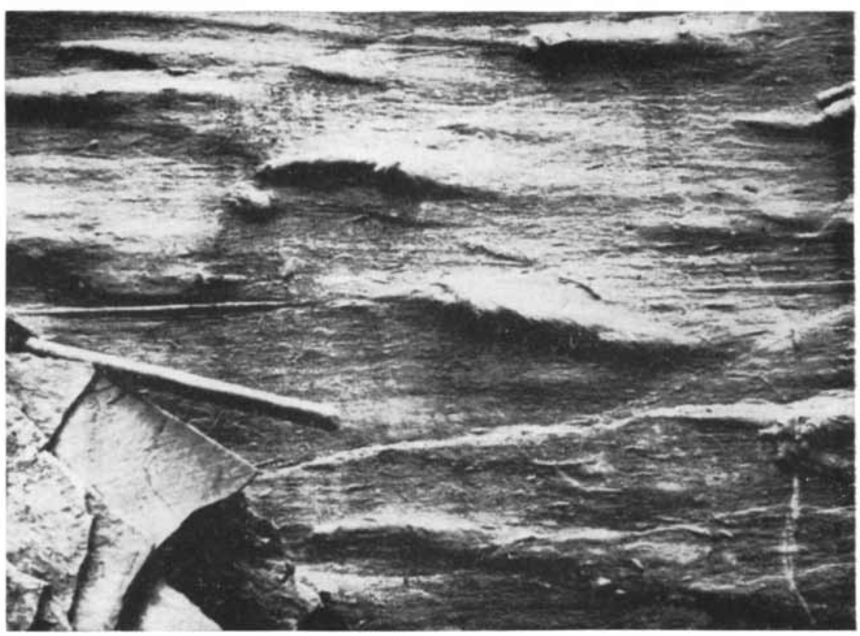
The Rounding of Sand Grains

Since the gravel in a stream bed shows progressive rounding downstream from the source, it has been thought that sand grains also are rounded by transport in running water. Surveys along river courses that showed the roundness of sand grains increasing slightly downstream seemed to support this deduction. Curiously enough, however, a decrease in roundness downstream was detected in some rivers. This could be explained by assuming that the angular grains are picked up more easily and so are carried more swiftly by the water. But it could just as well be argued that the more rounded grains roll more easily and so outstrip their angular competitors in the migration downstream. In either case the influence of selective transport seemed to overshadow any action by abrasion.

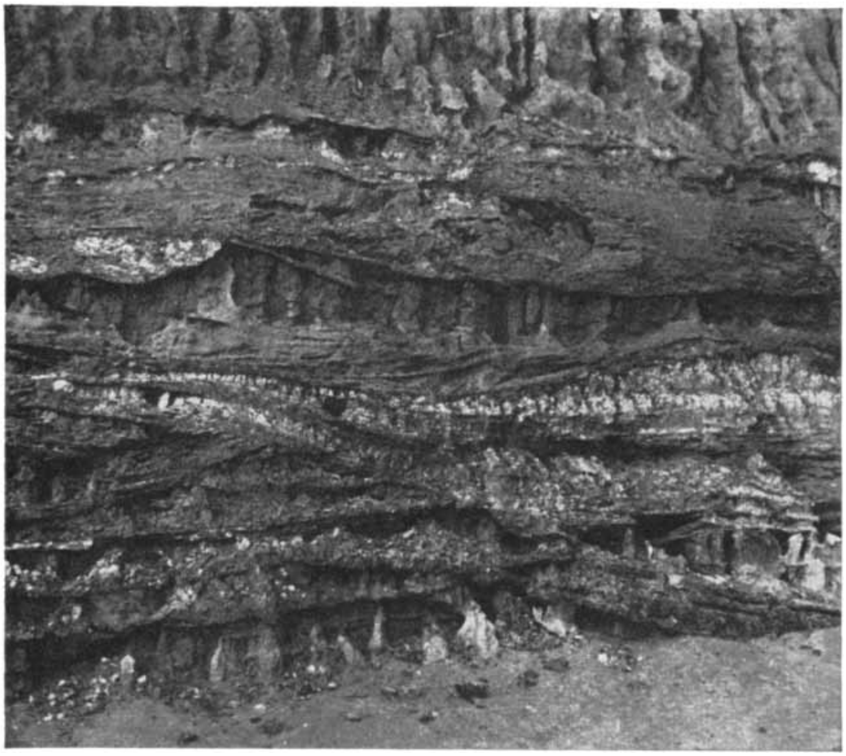
Investigators accordingly turned to experiment. Almost a century ago the French geologist Gabriel Auguste Daubrée put sand and water in a revolving horizontal cylinder and found that the sand lost about .01 per cent of its weight per mile of travel. The grinding motion of a heap of sand churned through and through in this manner poorly imitates the bouncing and rolling movement of the separate grains in a running stream. Nevertheless several authors have repeated Daubrée's experiment with minor variations and have obtained roughly the same measurement.

Recently I have attempted to approximate the natural situation more closely by rolling test grains around a circular moat of concrete in a current propelled by a sort of churn. The concrete, as compared to a loose bed of sand, does increase the rate of abrasion, but only slightly. In order to eliminate the influence of variable shapes I employed specially prepared cubical grains. An extensive series of runs showed that larger grains in a fast current lose about .2 per cent of their mass per 100 miles of travel, and that medium-sized grains lose only

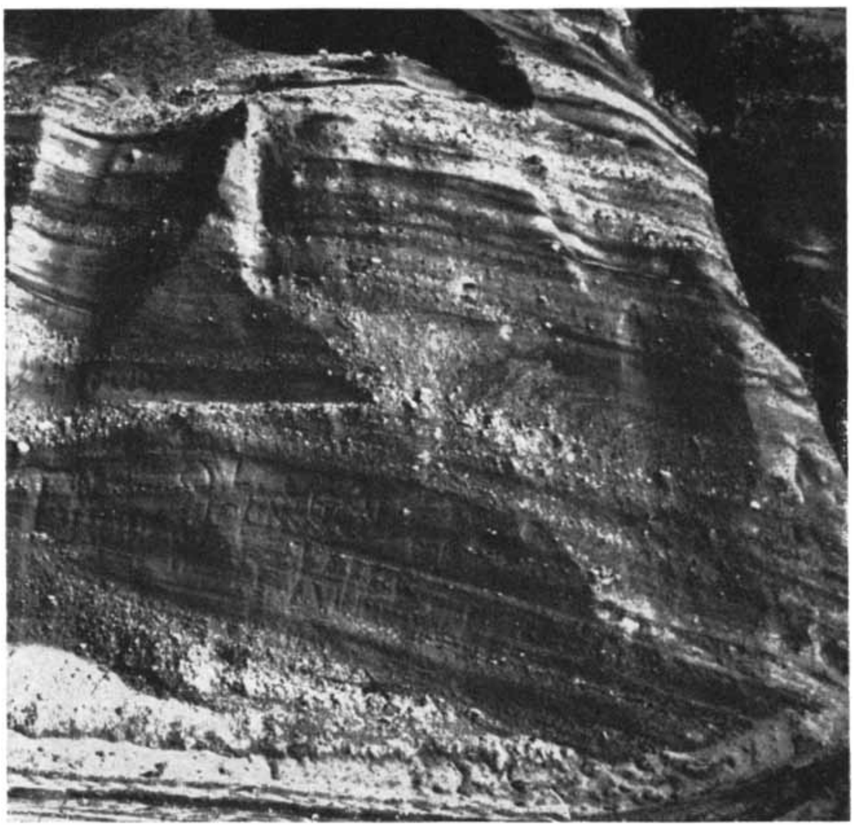
GRADED SANDSTONE-BED reflects the sorting action of the turbidity current as it settled out its burden of sand on the bottom of an ancient sea. The largest and heaviest grains are at the bottom of the bed; the lightest and finest, at the top. Above sandstone is a layer of clay that accumulated over many years following sudden deposition of sand.



GROOVES CUT IN SILT by the flow of a turbidity current across the bottom of an ancient marine basin are preserved in the undersurface of a sandstone stratum. Fine details in the pattern of the grooves show that the current flowed from left to right in this photograph.



SANDY RIVER-DEPOSITS created these sandstone strata. The succession of strata shows that the river departed from and returned many times to the channel in which it laid down the sand. A wandering river thus reworks its deposits, spreading sand over the valley floor.

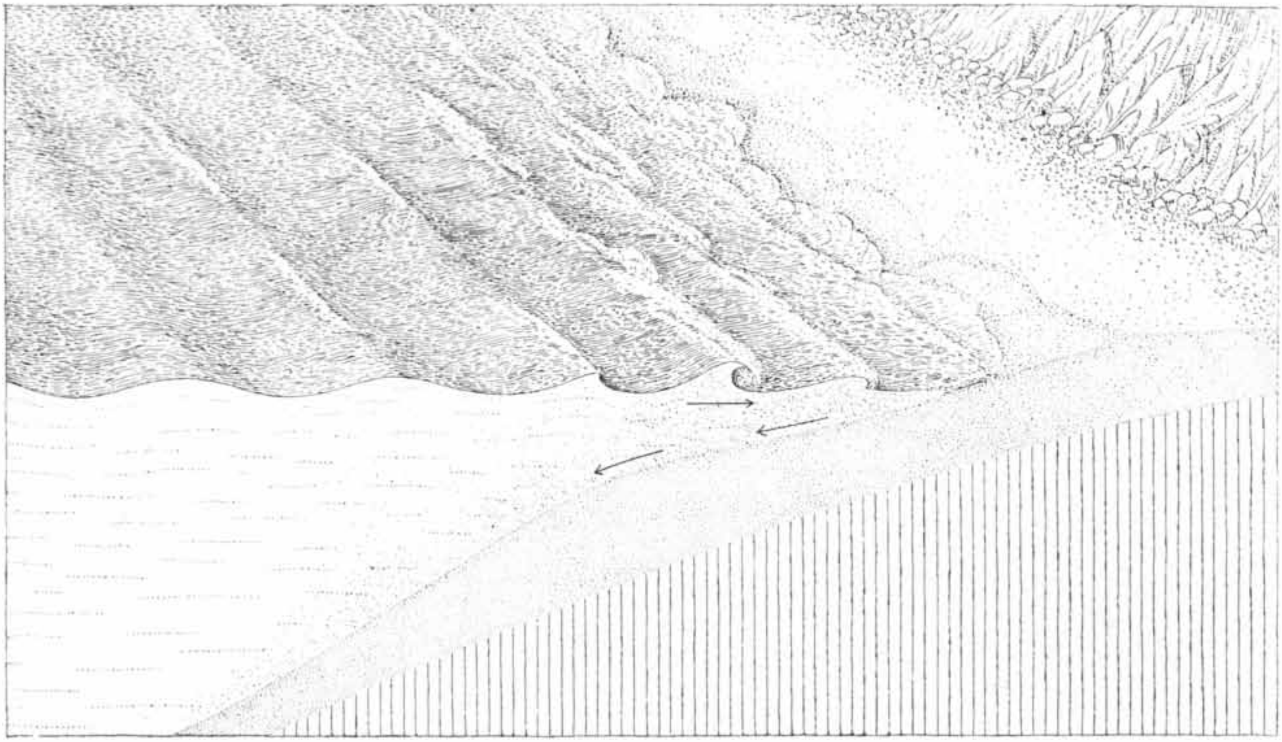


GRAVELLY RIVER-DEPOSIT is preserved in sandstone. The intersection of strata and the varying angles at which they lie show that the river at times scoured away earlier deposits. Differences in texture of the successive strata indicate changes in the rate at which the river flowed and in the character of the material it carried from one period to the next.

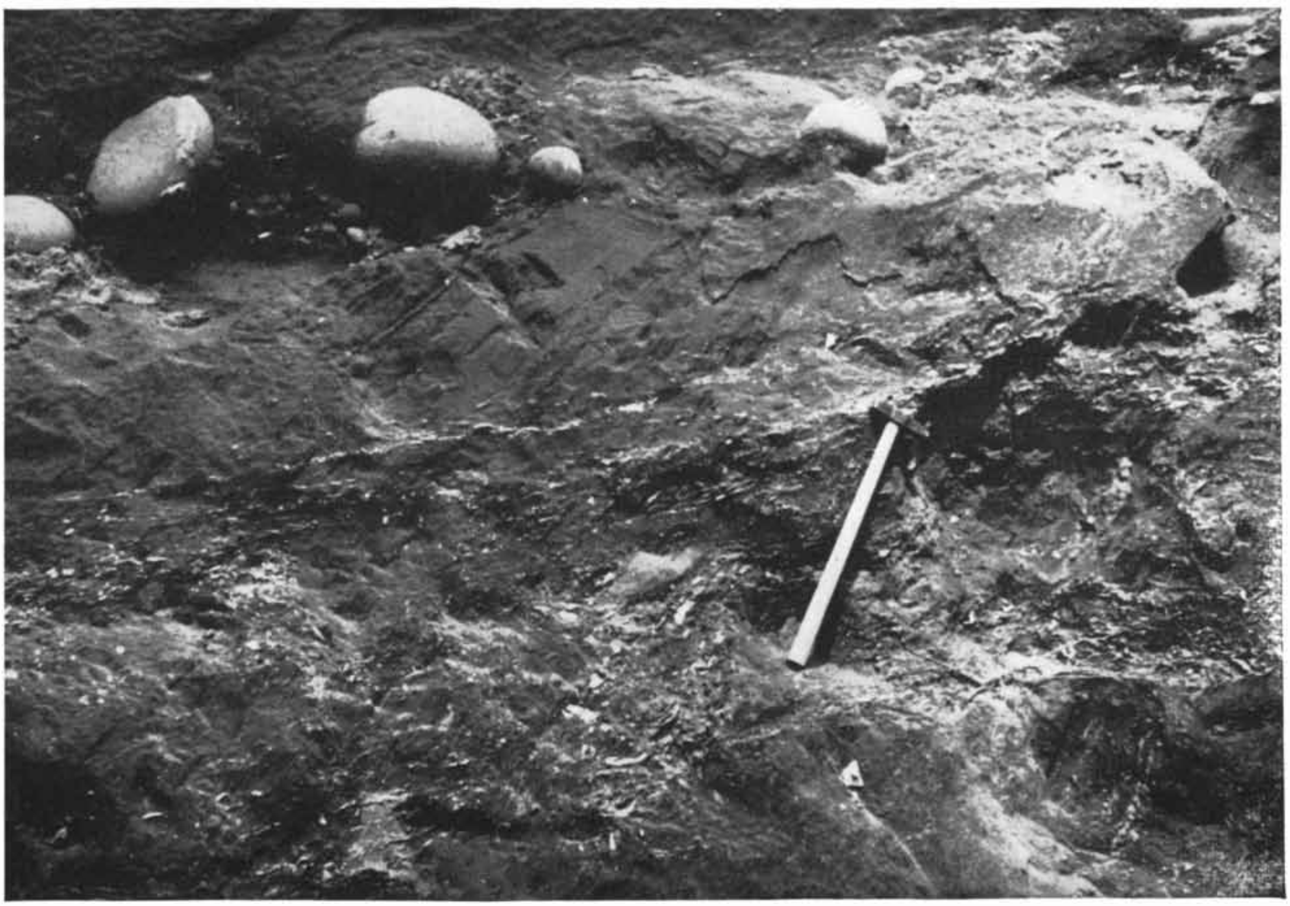
.01 per cent. This means that to round a .5-millimeter cube to a sphere, the particle would have to be rolled 50 times around the Equator. The first dulling of sharp angularity requires a 1- or 2-percent loss and can happen in the first few hundred miles. But thereafter mechanical abrasion of this kind has little effect on quartz sand with medium-sized grains. Experiments with feldspar showed that this mineral also possesses strong resistance to abrasion in water. Even though feldspar is softer than quartz and cleaves more easily, it showed only twice as much loss.

In the past it has often been claimed that the angularity of sand grains in an ancient rock is proof that the sand originated nearby. This contention is not upheld by the results of our experiment. Conversely it has been argued that a well-rounded grain must have had a long history. Abrasion in running water, however, could not in itself account for the roundness of even the most ancient grain of sand.

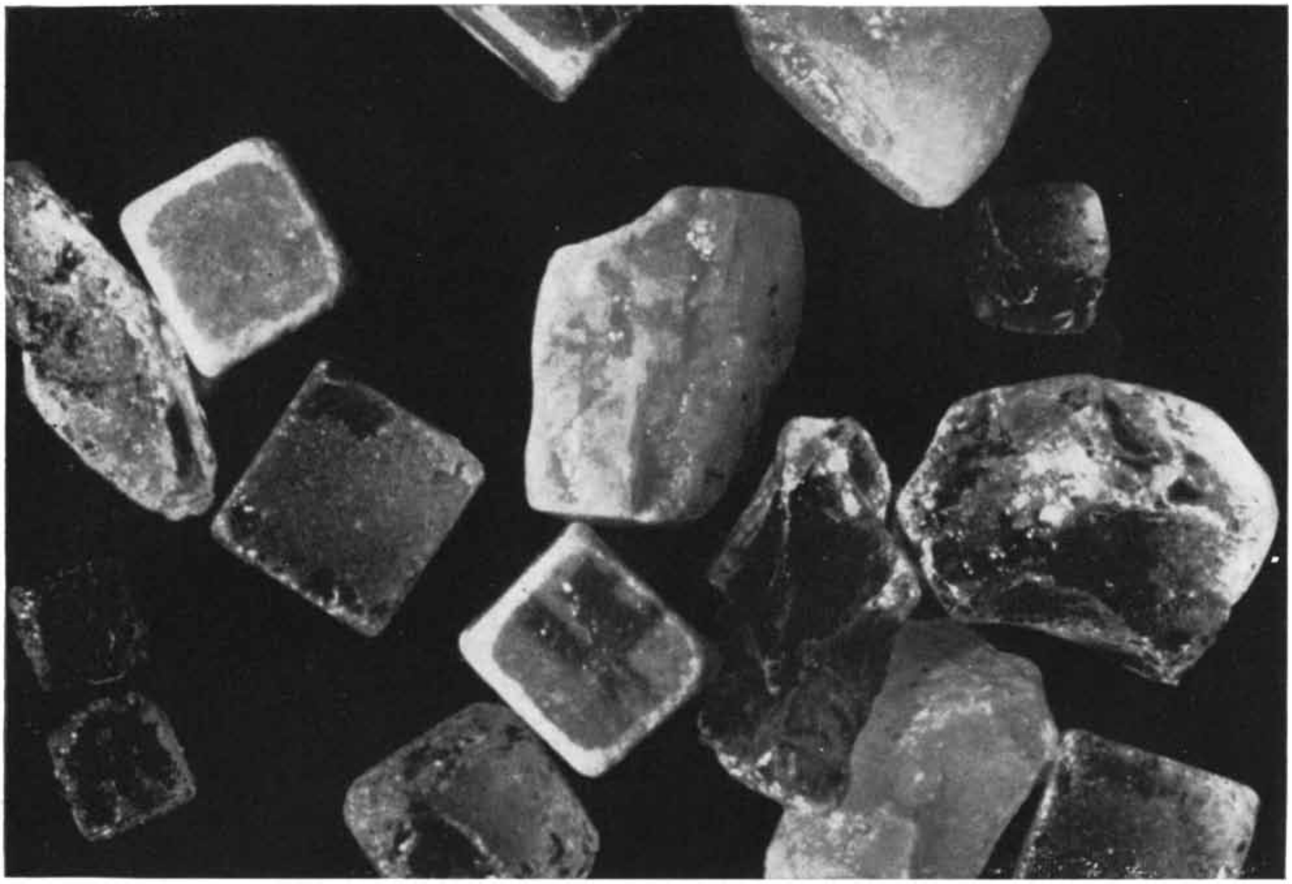
Water has another effect upon the sand grain which must be considered in connection with rounding. While the grains of sand in deserts have opaque, heavily frosted surfaces, many river sands contain grains with glossy, highly polished surfaces. The polishing could not have been accomplished by abrasive action, for the indentations and crevices in a polished grain that are out of reach of abrasion show the same perfect surface. It is possible to impart a polish of sorts to frosted grains by rolling them dry in a bottle, but the indentations in these grains remain opaque. It must therefore be concluded that river sands get their polish by chemical action. A crystal of alum that has been sandpapered can be "polished" by immersion in a saturated solution; precipitation from the solution smooths out the roughened surface. If river waters are sufficiently saturated with silicon dioxide, it will precipitate in the same way on quartz; hence this mechanism can be postulated for the defrosting of sand grains. The opposite action—the dissolution of silicon dioxide from the roughened surface of sand grains in waters that are undersaturated with the oxide—has been suggested as the mechanism for the rounding of sand grains. If such chemical action were significant in rounding, then one would expect to find that the effect is most pronounced on the smallest grains because the surface of such a grain is largest in comparison to its volume. Inspection shows that, on the contrary, in nearly all sands the smaller the grains,



ACTION OF WAVES ON BEACH causes some rounding of sand. Most of the abrasion occurs in the shallower reaches of the waves, where they carry sand up on the beach and wash it back again. At a depth of 50 feet the wave action scarcely disturbs the sand.



BEACH-SAND DEPOSIT contains boulders and also some fragments of shells. Compared to shales and clays, however, sandstones are usually barren of fossils. This deposit formed on the shores of a Pleistocene marine basin, afterward raised above sea level.



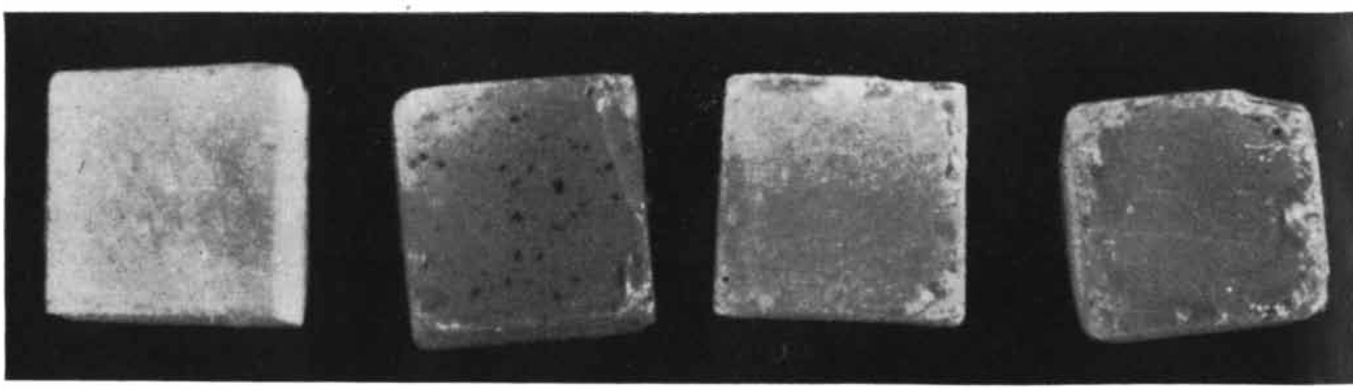
ABRASION OF SAND by wind transport was studied by author in experiments employing cubes of quartz and limestone cut to various dimensions; the cubes are shown here together with natural irregular sand grains. The photographs indicate the abrasion

the sharper their corners. It appears highly improbable that chemical action is the cause of more than a slight dulling of the sharpest angularity of quartz grains.

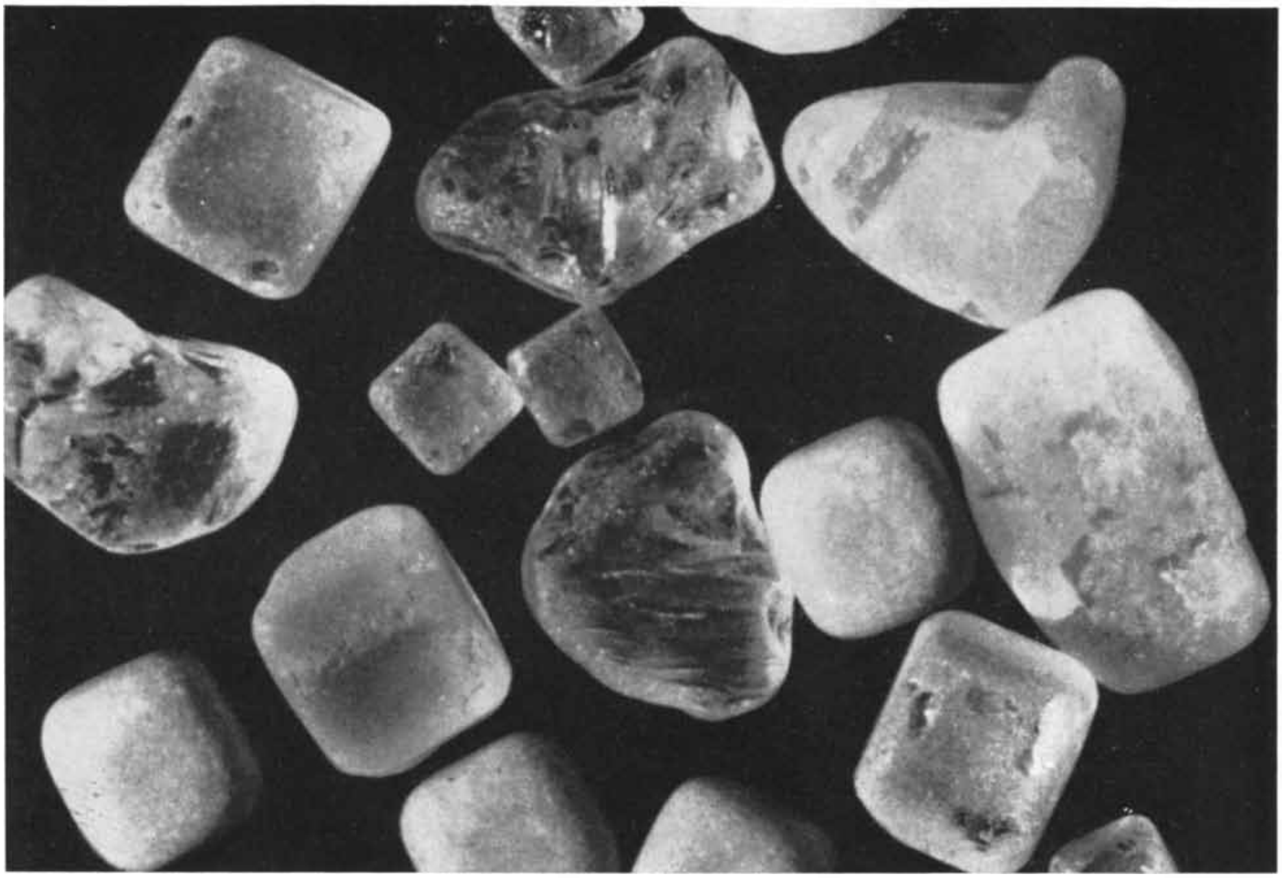
Wind Abrasion

The cause of roundness in sand grains must therefore be sought in some other mechanism. Perhaps the wind is the agent. Well-rounded grains are abundant in deserts and dunes, and geologists have long suspected that transport by wind powerfully abrades the grains. This deduction is open to doubt, however, because it is also observed that the wind selectively sorts the better-rounded grains from beach sands and carries them inland to coastal dunes.

In a wind tunnel in our laboratory we have just completed an investigation that seems to offer a reliable answer. The wind picks up the sand grains from a moving belt, redepositing them downwind on the belt for another ride upwind. The movement of the grains as they bounce and roll over the deposit that is traveling up the belt closely approaches their natural behavior, and the distance they travel can be accurately measured. By this means we have made the unexpected finding that transport by wind causes quartz grains to lose 100 to 1,000 times more mass than water transport causes them to lose over



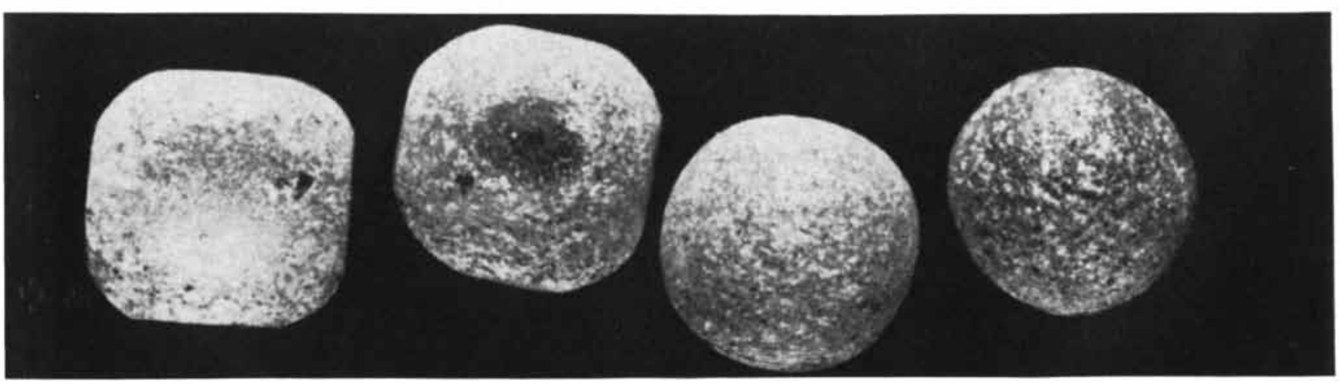
ROUNDING OF A SAND GRAIN is demonstrated by the rounding of an experimental quartz cube to a sphere. The rounding was accomplished in a wind tunnel. In the earlier stages of the process the sharp edges and corners of the cube are roughly chipped. As



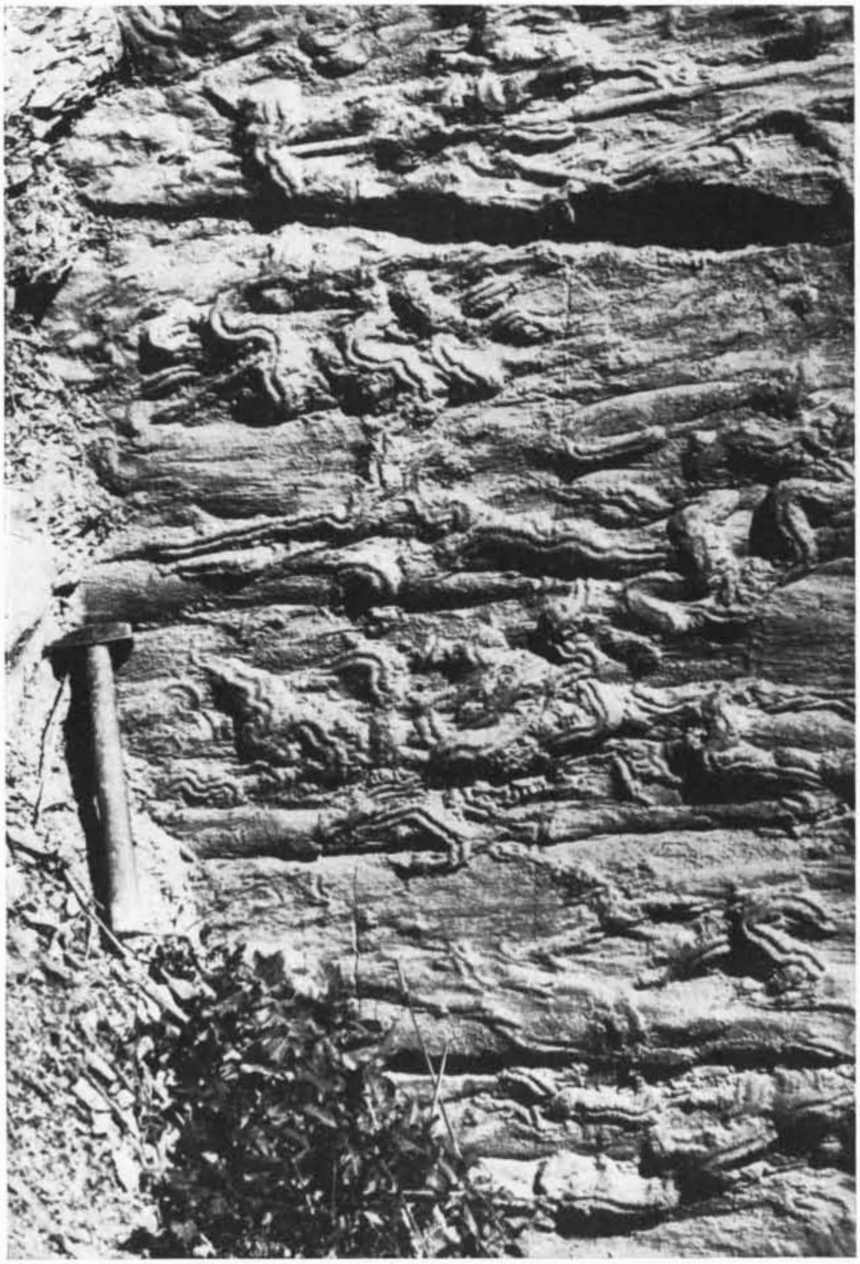
and hence the rounding sustained after 20 miles of experimental transport in a wind tunnel (*left*) and after 40 miles (*right*). Comparison of cubes with natural grains of equivalent roundness at each stage yields estimate of volume lost by the latter to abrasion.

the same distance. Moreover, wind abrasion reduces quartz almost as rapidly as it does feldspar or limestone. Apparently the brittleness of quartz causes it to flake off in the impact of a bouncing grain against a stationary one. On the other hand, we found that well-rounded and polished quartz-grains remain perfectly intact even after prolonged, violent wind action. It must be that they rebound elastically, as billiard balls do. Cubes of quartz change gradually to perfect spheres. This demonstrates that abrasion takes equal effect in all planes of the crystal. The oblong shape of most rounded natural grains may therefore be attributed to the original irregular shape of the particle.

In tests of samples containing a wide assortment of grain sizes we found that the smaller the particle the less abrasion it suffers. Particles with a diameter of .1 mm. or less show no abrasion at all. Apparently these smaller particles cannot hit one another with sufficient momentum to cause a crack in a grain. In mixed samples the minimum size of a grain showing loss goes down to .05 mm.; a larger grain landing on a smaller one can apparently chip a piece from it. But .05 mm. appears to be the bottom limit of the size of particles that show abrasion. The fragments chipped from the grains form an impalpable dust. In nature the wind carries this finer material outside the unvegetated desert and



the cube becomes rounded, however, the rate of abrasion slows down. In its final spherical form (*right*) the cube has lost more than half its mass. Rounding of a cube to a sphere indicates that rounded oblong natural grains started as angular oblong grains.



MARINE-WORM BURROWS are preserved in the undersurface of this sandstone bed. The sandstone also records grooves cut in the soft ocean-bottom by flow of the turbidity current.

dune areas, leaving sand-sized grains behind.

Curiously one does not find the tiny sand chips in the loess laid down by ancient dust storms. The bulk of loess is quartz, but its particles fall outside the size range produced by wind action on sand. This shows that loess must have been formed in some other way, perhaps by the crumbling of cracked grains and the weathering of fine-grained rock.

In the absence of evidence to the contrary it appears that wind is the principal agent in the rounding of sand grains. One way to check this conclusion is to make some round-number estimates involving, first, the average abrasion loss that all sand grains have suffered; second, the current rate of loss occurring in all deserts and sand dunes; and third, the yearly production of new angular grains. Such estimates would incidentally yield a rough measure of the age and hence the durability of sand grains. This in turn relates to the role that sand has played in maintaining the continents against the forces of erosion.

Age and Durability

In a preliminary approach to these estimates we made a chart of 16 shapes observed in cubes of different sizes that had sustained known percentages of

ELECTRONICS CONSTANTLY AVAILABLE —ANYWHERE

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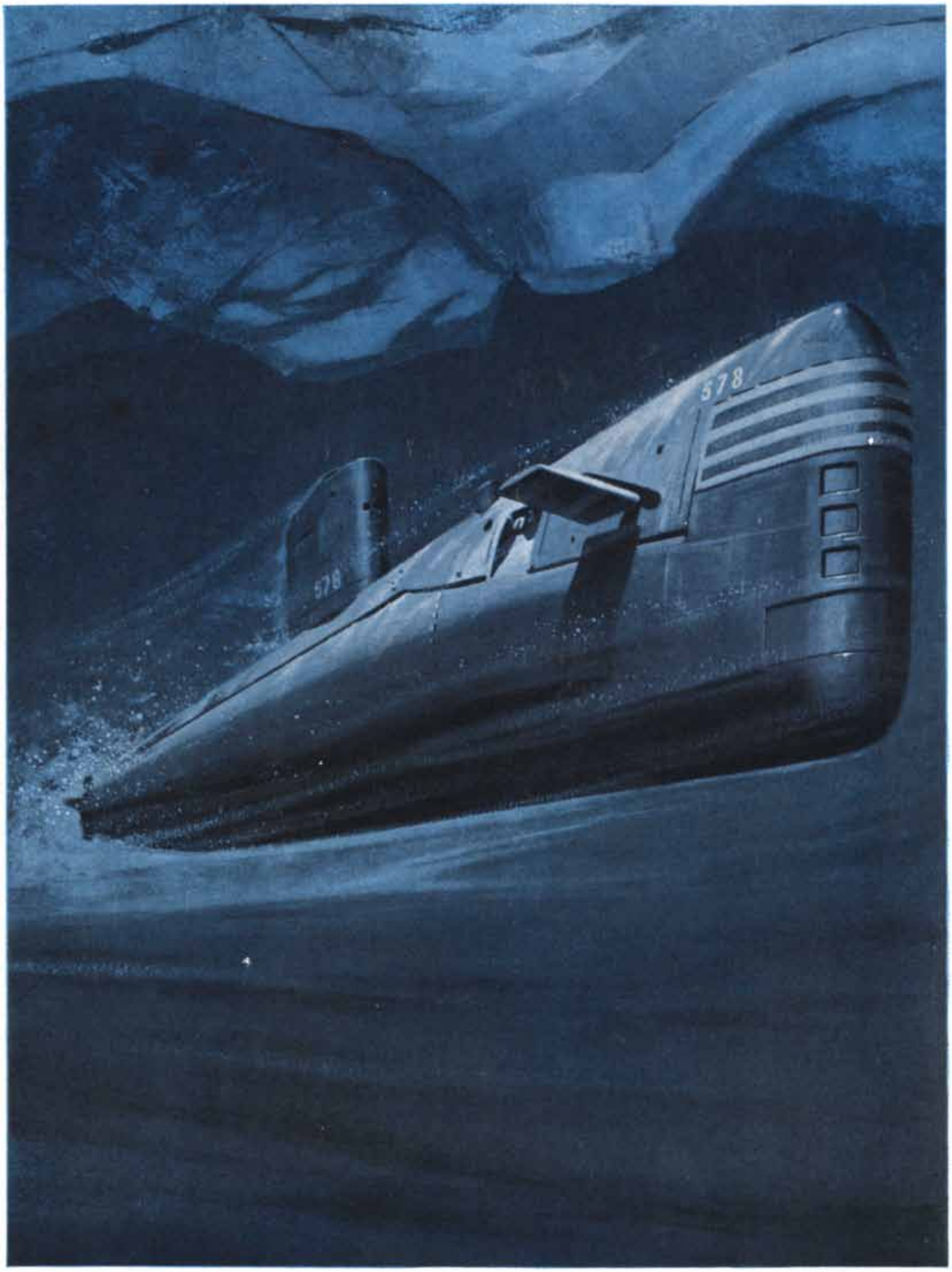

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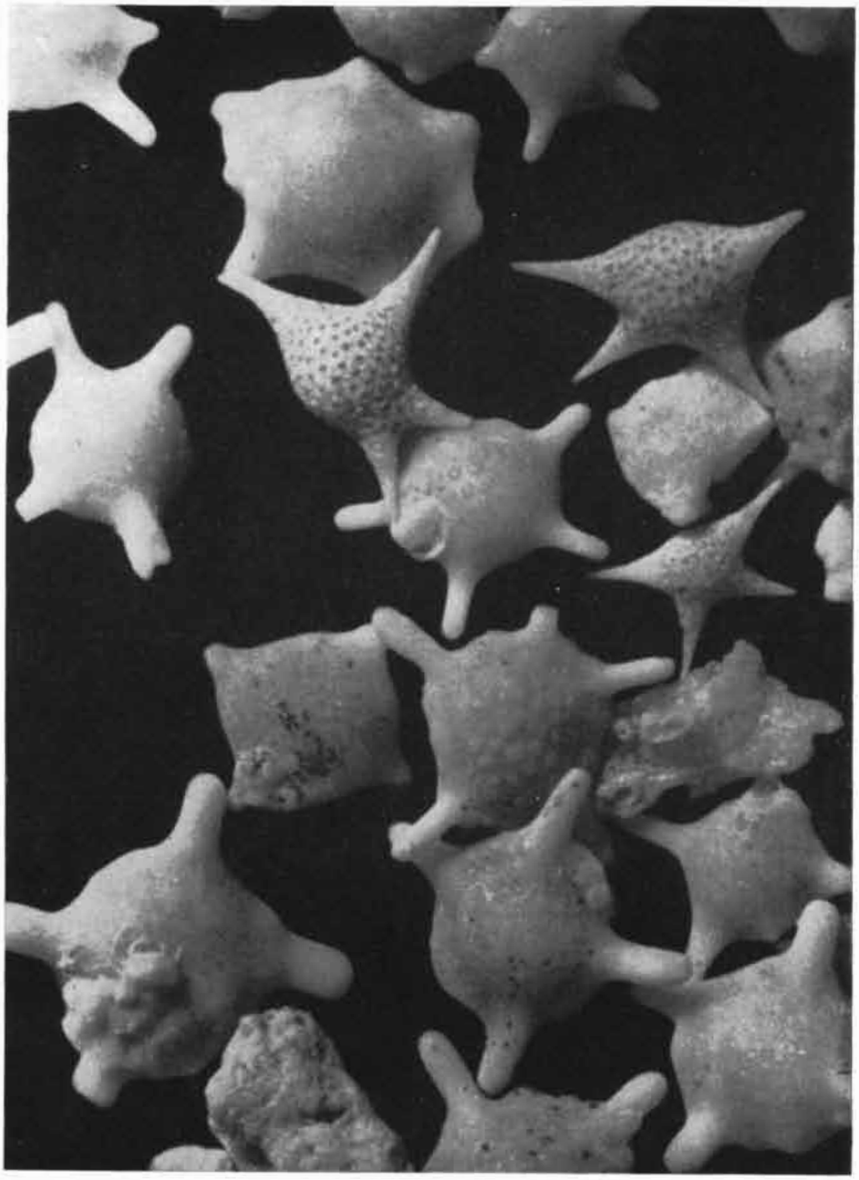


CORAL-REEF SAND is composed of the limy skeletons of minute marine creatures and the debris of coral itself. In comparison to quartz grains these particles are highly fragile.

abrasion loss. By comparing the cubes with natural sand-grains we made a rough appraisal of the losses the natural grains must have sustained. With due allowance for the diminution of roundness with grain size, we found an average loss of about 10 per cent. This serves as the estimate of the average abrasion sustained by all sands. To determine the average current rate of abrasion in desert sands we drew upon our wind-tunnel experiments, plus some values for the average wind-force in deserts, and found that the figure is equivalent to 10 per cent of the weight of 300 cubic yards of sand per square mile per year. The most uncertain estimate is the third: the yearly production of sand grains by weathering of hard rock and the crushing of old grains. The addition of new angular particles to the existing stock of sand would decrease the percentage of rounded grains in the total. To maintain the average abrasion-loss constant at 10 per cent, in accord with our first estimate, the annual loss of all sand must equal 10 per cent of the volume of new grains produced each year. Only a tentative estimate can be made. It would appear that some 200 million cubic yards of sand would have to be undergoing a current abrasion loss of 10 per cent. By combining these results one finds that about 750,000 square miles of desert will do the trick. The present area of sandy deserts is three times as large. This suggests that the average roundness of sand on earth should be increasing. But since the desert area has been much smaller in the past, there is no contradiction in the result. Plainly wind abrasion can more than account for the roundness of the world's sand grains.

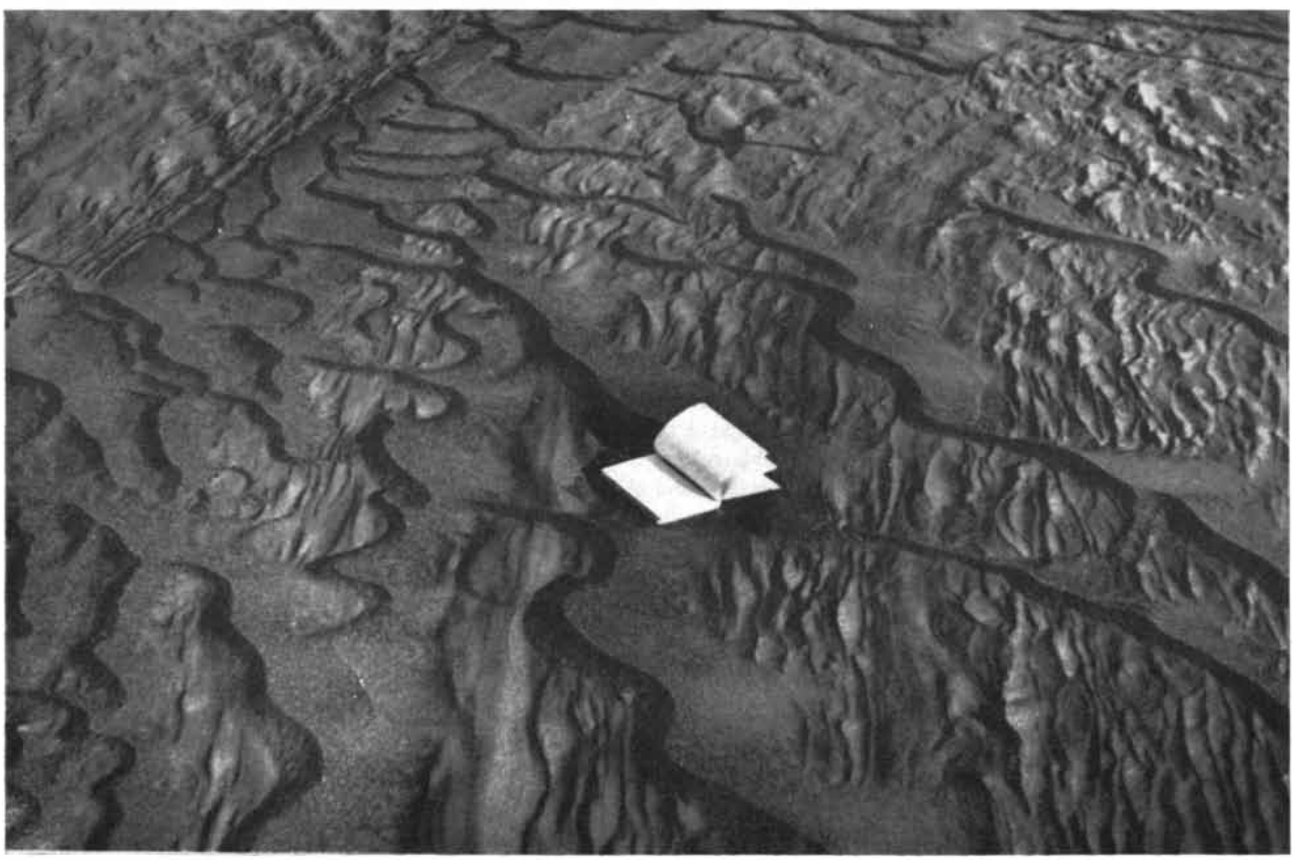
The same calculations confirm the laboratory finding that a sand grain is a durable object. After having been born from some parent rock, it begins the travels that are to wear it down. Its movement is intermittent, and the periods of stagnation vary from a few minutes in a river bed to eons on a flood plain or beach ridge. But ultimately it finds a final resting place where the sand is covered by younger deposits and is no longer disturbed.

No sharp distinction can be made, however, between a temporary halt and the final goal. There is always the possibility that a sleeping grain will be reawakened or that a buried one will become the victim of body-snatching. Deposits on land tend to be disturbed sooner or later by erosion, and not even a cemetery on the floor of a sinking marine basin remains secure for all time. Pressure, temperature and chemical reaction may combine to bond the grains in sandstone. The cement is usually lime, silica or an iron oxide. Yet even when it is sealed in this coffin, a sand grain is no more inviolate than a Pharaoh's mummy is secure from plunderers or archaeologists. It is true that when the grain is part of rock that has been submerged to great depth and subjected to intense heat and pressure, it "returns to dust"; its crystal is disassembled and its molecules recrystallize to form a gneiss or a schist. More likely, however, the sedimentary strata are raised to produce a mountain range. As a result erosion starts to disinter and break down the sandstones and other rocks. In some cases the cement is so strong that pebbles are formed. But usually the breakdown sets the grains free again, with their shape at burial still intact. When this happens, the particles enter a new erosion cycle with the inheritance of the rounding acquired before.

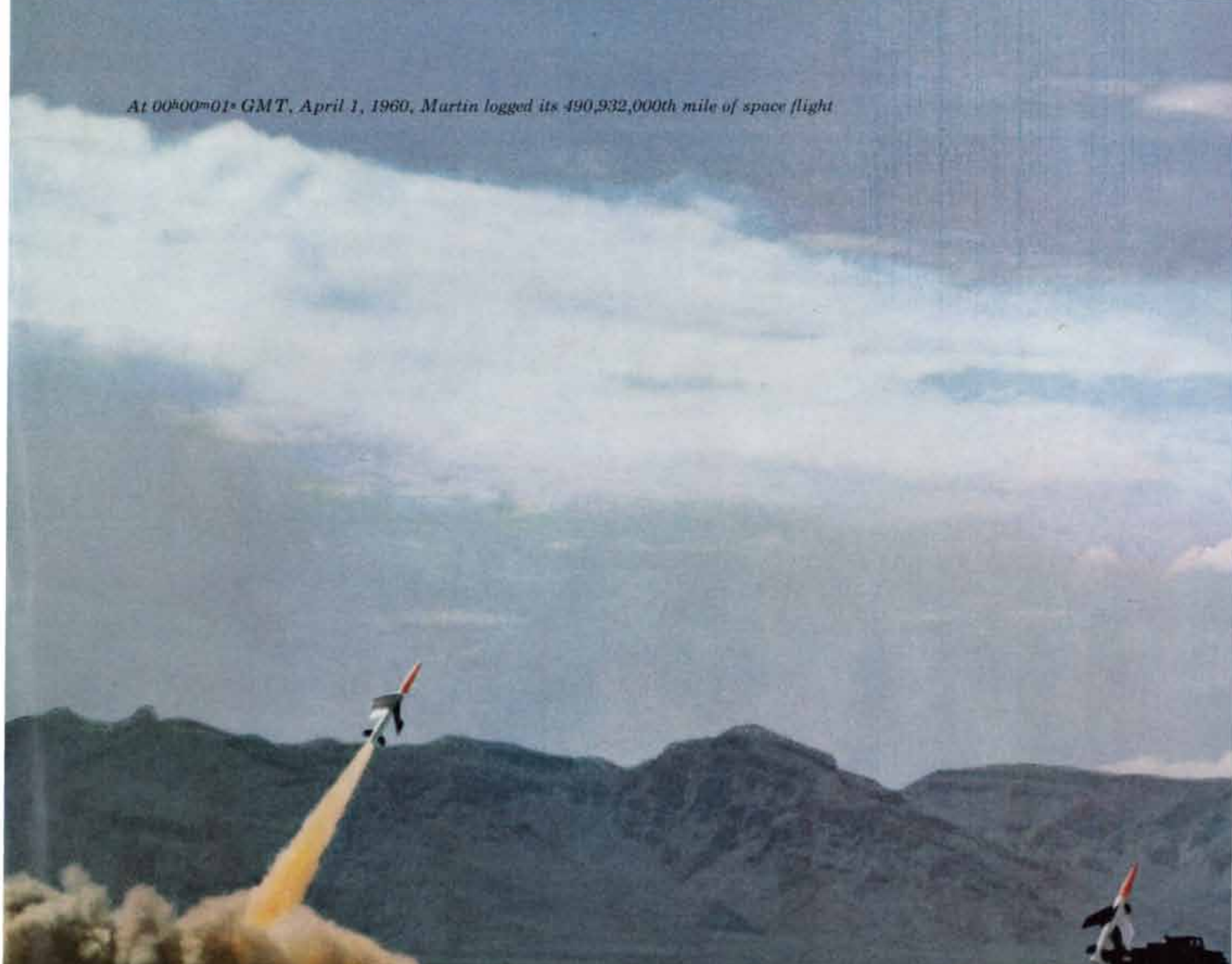
Sand on the Continents

Some investigators hold that more than half the grains partaking in transport and deposition are newly formed, or at least much altered from their former shape. Others maintain that the great majority are held over from former cycles. If the results of our investigations can be relied upon, however, a large proportion of the world's stock of sand grains must have undergone many cycles.

There is another reason for holding that the average age of quartz grains is very high. This is the huge volume of sand now lodged on the continents. Some of it has been lost to the deep-ocean bottom by turbidity currents, but this loss cannot be significant. Abrasion losses amount to only 10 per cent; a certain volume of the fine material thus produced must have been carried from the continents in dust storms and dropped into the deep ocean. Finally, some of the sediment deposited in ancient sea basins now uplifted on the continents has been changed to crystalline schist and gneiss at great depths. The significance of all these losses cannot be assessed, but it is certain that in spite of them quartz has been concentrated in the sandy sediments of the continents to about twice its abundance in the source rocks. This is due to the chemical stability, hardness and comparatively large size of the quartz particles as they are borne from the parent rocks. These properties protect the grains from wear and tear and save them from being wafted into the deep-ocean basins. During geologic time the continents were thus covered with a layer of quartz sand that partly shelters them, in their turn, from the agencies of erosion.



DESERT SAND-DUNE has been eroded by the wind so that its irregular internal structure stands out in ridges. Across these ridges the wind has blown winding ripples of coarser sand. The book in center of photograph shows the scale of distance between ridges.



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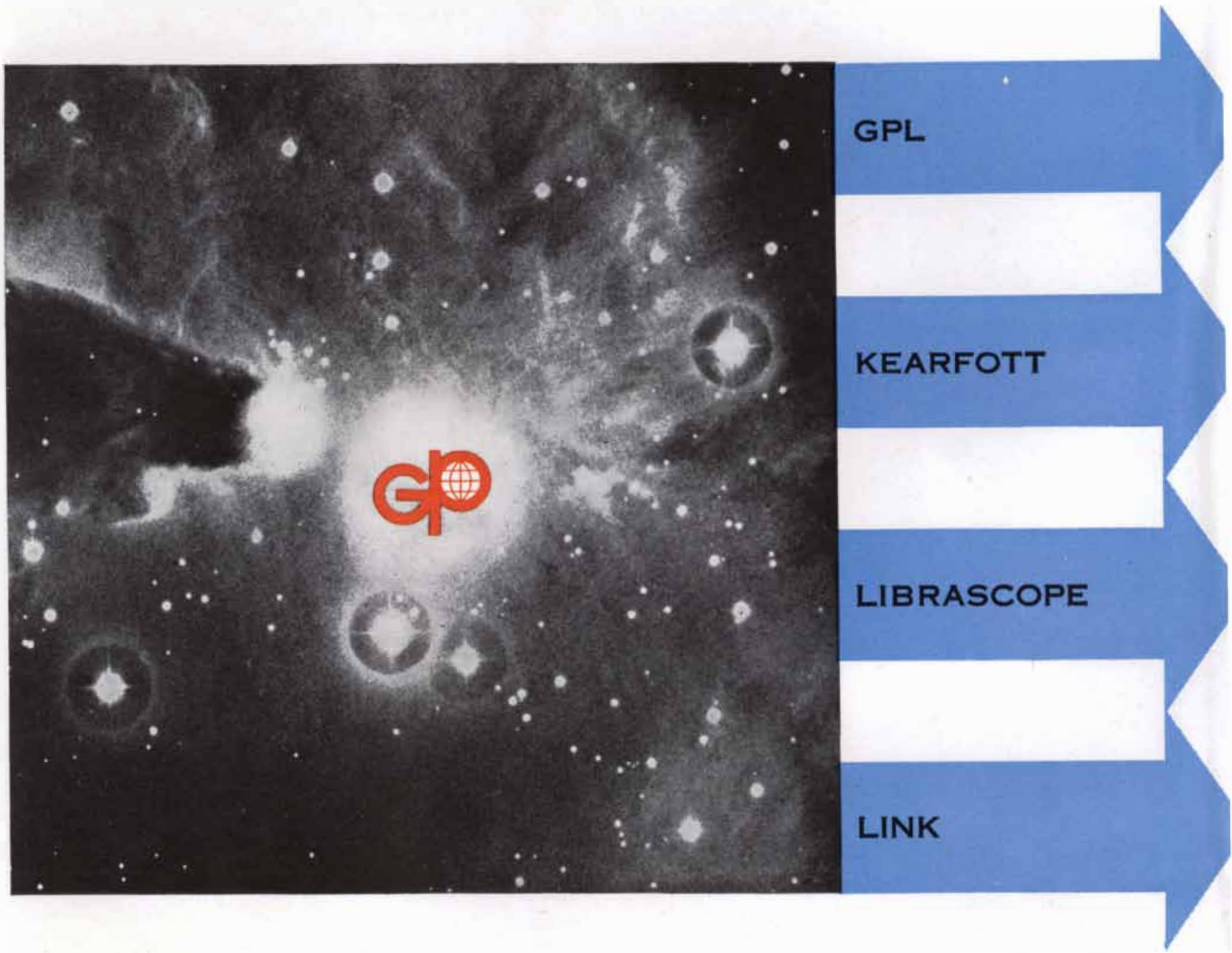

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