

The Tektite Problem

Did these peculiar bits of glass originate on the earth or on the moon, in volcanic activity or in meteorite impact? The evidence is conflicting and the most reasonable answer is a surprising one

by John A. O'Keefe

In widely scattered locations around the world small glassy pebbles of curious surface configuration and distinctive composition are found, often in vast "strewn fields" that stretch across land masses and, on the evidence of cores drilled from the deep-sea floor, across intervening seas and oceans. These tektites, as they are called from the Greek word *tektos*, meaning molten, are much like the volcanic glass obsidian, but their chemical composition is different from that of any terrestrial lava and they contain far less water and none of obsidian's characteristic microcrystals. And, as the Austrian mineralogist Josef Mayer pointed out in 1787, no one has ever found the *Mutterstein*, or mother lode, of a field of tektites. They cannot, therefore, be the product of terrestrial volcanism.

Many of the most significant findings about tektites are negative findings, and the absence of a mother lode is one of them. Contrary to proposals advanced at one time or another, they are not man-made glass objects; neither are they the remains of some former planet or bits of antimatter or fulgurites fused by lightning from terrestrial sand. Recently acquired knowledge about the moon's surface confirms earlier indications that tektites cannot be bits of lunar soil propelled to the earth by the impact of meteorites on the moon. Painstaking evaluation of the evidence collected over the past century leaves two possibilities for the origin of tektites. One is that tektites are bits of terrestrial sedimentary rock excavated by meteorites striking the earth's surface, melted by the heat of impact and congealed into glass as they travel above the atmosphere to the scattered sites where they are found. The other possibility is that tektites are the remains of gobs of lava fired at the earth by volcanic activity on the moon.

If tektites are terrestrial, it means that some process exists by which soil or common rocks can be converted in an instant into homogeneous, water-free,

bubble-free glass and be propelled thousands of miles above the atmosphere. If tektites come from the moon, it seems to follow that there is at least one powerful volcano somewhere on the moon that has erupted at least as recently as 750,000 years ago. Neither possibility is easy to accept. Yet one of them must be accepted, and I believe it is feasible to pick the more reasonable one by rejecting the more unlikely.

In 1975 P. V. Florensky of the Institute of Geology in the U.S.S.R. Academy of Sciences announced the discovery of tektites at the site of the Zhamanshin structure, a shallow crater near the town of Irgiz in Kazakhstan. He called them irghizites, following the custom of naming groups of tektites for the place where they are found. This first major tektite discovery in about 25 years has already proved to be highly instructive. The crater where the irghizites were found is a shallow depression about five kilometers in diameter. It is filled, according to Florensky, with from 100 to 150 meters of lake sediments on top of broken rock. The crater shows strong evidence of impact by an object from space. Some of the local rocks have been shocked, according to Florensky's colleague Yu. P. Dikov, yielding the impact glasses coesite and stishovite: high-pressure forms of silica (silicon dioxide, SiO_2). Such a close association of tektites with an impact crater is not unique; other instances are the Auelloull tektites in Mauritania and perhaps the "Darwin glass" of Tasmania.

Either the tektites made the Zhamanshin crater or the crater made the tektites. A large block of tektite glass could have come out of space, dug the crater and disintegrated to form the irghizites; alternatively, a meteorite could have landed at the site, forming the crater and at the same time transforming some of the local rock into tektite glass, perhaps by boiling away some of its more volatile constituents. The two hypotheses are being tested by investiga-

tors in the U.S.S.R. and the U.S., who are cooperating to compare the tektites (samples of which have been lent by the Institute of Geology to laboratories in the U.S.) with the local rock and with tektites from other sites.

The irghizites are small black objects averaging about half a gram in weight. (Most tektites weigh a few grams.) They are warty, twisted objects that resemble the Auelloull and Darwin-glass tektites in shape. Their chemical composition, according to Kurt Fredriksson of the Smithsonian Institution, is remarkably uniform from specimen to specimen; it is unlike that of any local rocks and is very similar to that of the tektites found in Java. The resemblance to the javanites extends to the trace elements, it has been reported by Yu. F. Pogrebnnyak in the U.S.S.R. and by William D. Ehmann, John A. Philpotts, C. S. Annell, John W. Morgan and other investigators in the U.S. Like all other tektites, the irghizites are homogeneous glasses lacking even small crystals. On the face of it, the evidence is conflicting. The compositional studies seem to support the idea of an extraterrestrial origin, but after examining the samples, Florensky has accepted the hypothesis of meteorite impact.

The ultimate findings concerning this new discovery will have to be fitted into a matrix of facts and calculations accumulated over the years. The javanites are members of a huge family of tektites, perhaps 100 million tons of them, that fell about 750,000 years ago over the Indian Ocean, southern China, southeastern Asia, Indonesia, the Philippines and Australia. The extent of this Australasian strewn field has been defined by the discovery of tektites at one site after another ever since a specimen of one of its most distinctive forms was given to Charles Darwin during the voyage of the *Beagle*. The tektites have been dated to 750,000 years ago by isotope analysis (determining the proportions of potassium 40 and of argon 40, to which potassium 40 decays radioactive-

ly), by fission-track analysis (counting the tracks left by the natural fission of uranium) and by the presence of microtektites in sea-floor cores at the level associated with a particular reversal in the earth's magnetic field and in conjunction with particular marine microfossils. (Attempts to date dry-land specimens by stratigraphy have yielded inconsistent results even in the hands of very competent geologists; I think it is because of the inherent difficulty of applying stratigraphy to date fairly recent events.)

In contrast to the contorted tektites

found at impact craters, the Australasian tektites are roundish or chunky objects, often shaped like teardrops, dumbbells or disks, that show little evidence of internal strain. Most of them are very similar in composition, and there are subgroups of chemically identical specimens whose discovery sites form long streaks within the overall field. Everywhere the tektites are chemically distinct from the very diverse rocks on which they are found. All of this makes it clear that the Australasian strewn field's tektites originated at a single point, whether on the earth or in

space. Some launching mechanism must have fired them from that initial point to their scattered resting places on the earth. The search for the origin of tektites is therefore a search for a launching mechanism that could spread this gigantic array over an area whose longest dimension is some 11,000 kilometers and whose extent is perhaps a tenth of the earth's surface.

Similar considerations apply to two other vast fields of tektites, of which the larger is the North American strewn field. It is the oldest field known, dating from about 35 million years ago, and it



MOLDAVITE, a tektite from Czechoslovakia, glows in a photograph made by Joseph Walters of the Goddard Space Flight Center of the National Aeronautics and Space Administration. The moldavites are found in adjacent "strewn fields" in Bohemia and Moravia; they are

named for the Moldau River. This specimen from Koroseky in Bohemia, whose diameter is about 1.5 inches, has the characteristic green color of a Bohemian tektite. Moldavites were once thought to be bits of artificial glass because the region was an early glassmaking center.

must have had an aggregate mass of about a billion tons, much of which has long since been eroded away. When the field was formed, it extended at least from the southern coast of the U.S. across the Gulf of Mexico and the Caribbean Sea to a point near Caracas in Venezuela. The Ivory Coast strewn field, about a million years old, extends from the Ivory Coast into the South Atlantic and has a mass of perhaps 10 million tons. In each of these large fields the tektites are shaped not like the irghizites but like the Australasian tektites. There are a number of smaller fields and individual finds.

So much for the overall extent of the fields. Let me now summarize the reasoning that ultimately led to the two possibilities I outlined at the beginning of this article. Harold C. Urey of the University of California at San Diego has pointed out that the size of the strewn fields proves tektites do not come from space beyond the moon. A cloud of separate objects approaching the earth from space would (because of the differential effects of solar attraction) become so large and diffuse that it would of necessity cover an entire hemisphere of the earth, as a meteor shower does. On the other hand, the breakup within the earth's atmosphere of a single

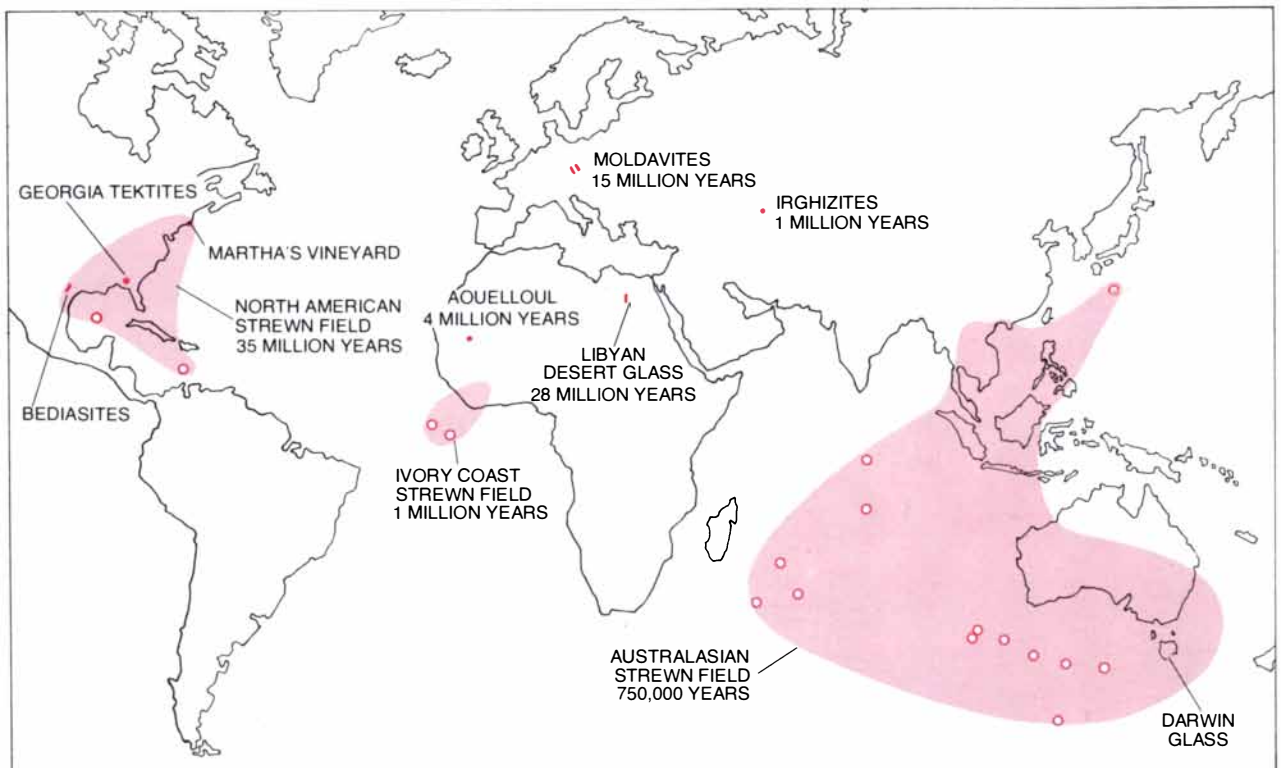
body would yield too small a distribution—a few tens of kilometers in the longest direction, as in the case of the fall of a meteorite. Further evidence against prolonged travel of a cloud of bodies in space comes from analysis of the tektites. They lack the usual signs of interaction with primary cosmic rays in space: the presence of neon 21, aluminum 26 or beryllium 10 or of the characteristic V-shaped cosmic-ray tracks made visible by etching with acid. The source, then, must be on the earth or on the moon.

The only mechanisms anyone considers capable of producing the necessary launching velocities are volcanism and meteorite impact. Winds cannot do it because even millimeter-size microtektites would fall out in a few minutes, which is too short a travel time to account for even a modest strewn field. People do move tektites around, but not hundreds of millions of tons of them, and not into the middle of the Indian Ocean 750,000 years ago. Given two conceivable launching mechanisms and two possible source locations, there are four origins to be considered: terrestrial volcanism, lunar volcanism, terrestrial meteorite impact and lunar meteorite impact.

One of the four origins has long been out of favor: terrestrial volcanism.

There are two arguments against it. The first, to which I alluded above, is that the chemical composition of terrestrial tektites is not the composition of terrestrial volcanic glasses. A typical tektite has a silica content of something over 68 percent; a volcanic glass with such a high silica content is defined as granitic. There are terrestrial granitic glasses, but they have a composition that can be represented as nearly equal amounts of three minerals: quartz (SiO_2 considered as a mineral), soda feldspar ($\text{NaAlSi}_3\text{O}_8$) and potash feldspar (KAlSi_3O_8). In addition no more than 20 percent consists of other minerals.

The reason is clear: for silicates this composition is the ternary (three-way) eutectic, the composition that crystallizes at the lowest temperature. As a somewhat basaltic magma cools, various minerals will crystallize out, each at the appropriate temperature and composition, until the melt reaches this eutectic composition. The liquid phase now has the composition of a granite. If the liquid is somehow separated from the crystals, it may be intruded and cool slowly to form a crystalline rock (granite), or it may erupt and be cooled instantaneously to form a granitic glass (such as obsidian). As an example, the "standard granite," designated G-1, has a mineral composition equivalent to 29



DISTRIBUTION OF TEKTES is not random. They are concentrated in a few large strewn fields (light color) and in smaller groups or as individual finds (colored streaks or dots). Microtektites have been

found in deep-sea cores (open circles), which help to establish the extent of the major fields. The ages of the tektites in each group, which have been established by various techniques, are shown on the map.

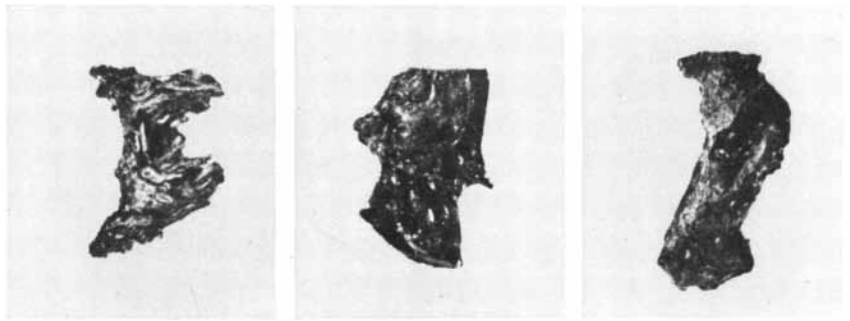
percent quartz, 32 percent soda feldspar and 28 percent potash feldspar, with the remaining 11 percent consisting of other minerals.

Not so the tektites. For them the equivalent mineral proportions are typically about 40 percent quartz, 13 percent soda feldspar and 15 percent potash feldspar, with 32 percent consisting of other minerals. Stating it another way, tektites contain more divalent oxides—lime (CaO), magnesia (MgO) and ferrous oxide (FeO)—than terrestrial rocks of similar silica content, and less monovalent oxides: soda (Na₂O) and potash (K₂O).

The other argument against terrestrial volcanoes is that they cannot provide enough velocity. They are powered by steam, and at the temperature of a lava (no more than 1,200 degrees Celsius) the velocity of sound in steam is about one kilometer per second. Thermodynamic theory shows that for a gas escaping from an enclosure there is a limiting velocity of about twice the velocity of sound in the gas, or about two kilometers per second for steam. (Higher temperatures would allow higher velocities, but the temperature of a lava is limited by the fact that the lava must be contained in a crucible of rock; if the temperature rises much above the melting point of the rock, the walls will melt and cool the lava.) The maximum "muzzle velocity" that is actually observed for objects thrown from volcanoes is only about 700 meters per second. Yet the velocity required to reach the edges of the Australasian strewn field from a point at the center of the field would be a little more than six kilometers per second! The compositional argument and the deficiency in launching velocity certainly justify eliminating terrestrial volcanoes as a source of tektites.

Of the three remaining possibilities one, meteorite impact on the moon, seems to have been eliminated by the chemical data collected by the Surveyor, Apollo and Luna landings and by remote sensors that have surveyed much of the lunar surface. It seems clear that most of the surface consists of one or another kind of basaltic rock, or rock that is less than 55 percent silica. The lunar maria, or "seas," have iron-rich basalts and the lunar highlands have feldspar-rich basalts. Granitic rock is found only as fragments—including glassy ones—in the soils and in some breccias (rocks composed of fragments cemented together). From this it is deduced that granitic masses do exist, but they must either be small or be in limited areas that have not yet been observed. Almost all the lunar surface soil and rock is basaltic and cannot be the stuff of tektites.

That being the case, impact on the

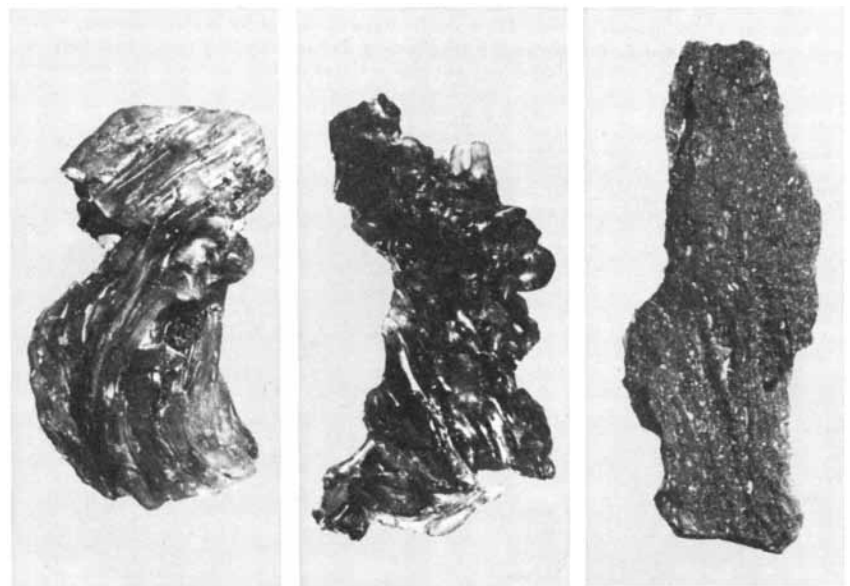


IRGHIZITES, from Kazakhstan in the U.S.S.R., are the most recently discovered tektites. These specimens, which range from about .8 inch to 1.1 inches long (portions were removed from two of them for analysis), were made available to U.S. investigators by Institute of Geology in U.S.S.R. Academy of Sciences through P. V. Florensky, who first reported on them.

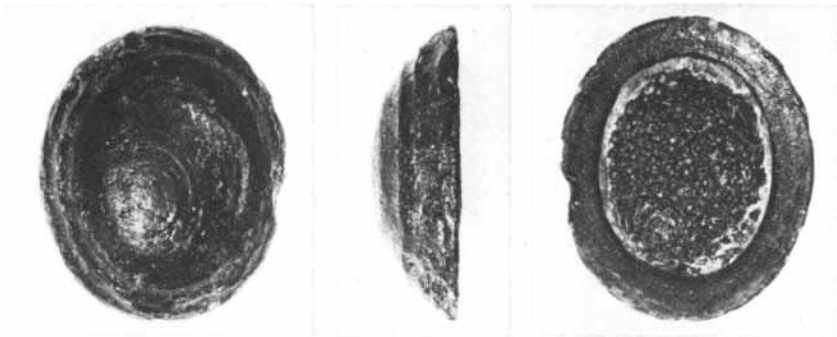
moon would seem to be eliminated as a source of tektites because impact is an indiscriminating process: an object from space is as likely to land in one place as in another. It is true that lunar rock fired at the earth by a meteorite impact would be subjected to some filtering action favoring granitic glasses, which would survive shock, entry into the earth's atmosphere and weathering better than basalts, but the differences do not seem large enough to account for the silicic nature of tektites; indeed, the finding of low-silica microtektites indicates that low-silica material can survive all these perils. (Even those microtektites, however, are not like the lunar basalts.)

It is not only tektites that fail to match the lunar basalts; there are no meteor-

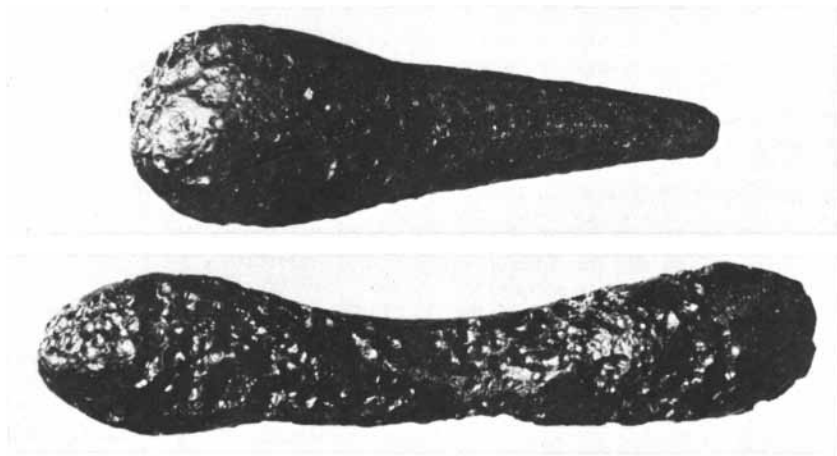
ites that match them either. It used to be assumed that some meteorites striking the earth had been splashed out of the lunar surface by an impact on the moon. Edward Anders of the University of Chicago and his co-workers noted, however, that the principal types of lunar rock that have been studied are unlike anything in the world's meteorite collections. It seems to follow, they pointed out, that a meteorite impact cannot eject matter from an object in the solar system (whether the moon, a planet or an asteroid) at a velocity as great as the lunar escape velocity, or 2.5 kilometers per second. This 2.5-kilometer limit, which I shall call Anders' limit, has become a cornerstone of post-Apollo meteorite theory. It means that meteorites cannot originate on Mars or Mercu-



CONTORTED STRUCTURE of many irghizites (such as those in the photograph at the top of the page) is similar to that of some "Darwin glass" tektites from Tasmania (two at left) and tektites from Auouelloul in Mauritania (right). Like the irghizites, the Auouelloul tektites are associated with a nearby impact crater; the Darwin glass also appears to be. These specimens, two to 2.4 inches long, were collected by Robert F. Fudali of the Smithsonian Institution.



AUSTRALITE, a tektite from Australia collected by Charles Darwin during the voyage of the *Beagle* and now at the Institute of Geological Sciences in London, is seen from the front (*left*), side (*middle*) and rear (*right*); the long dimension is just over an inch. The australites' curious flanged shape is the result of aerodynamic ablation on entry into the earth's atmosphere.



TEARDROP AND DUMBELL are typical "splash-form" tektites, suggestive of congealed drops of a viscous liquid. These tektites from Thailand are at the Smithsonian. The dumbbell is about 4.5 inches long. Such tektites are thought to have derived their shape from the breakup of a larger molten jet. Most tektites of this type are more massive than irghizites and other tektites associated with impact craters. Their shape suggests control by surface tension, which implies a rather stress-free environment during cooling. Presumably they tumbled as they entered the atmosphere, so that ablation was not concentrated on one face as in the australites.



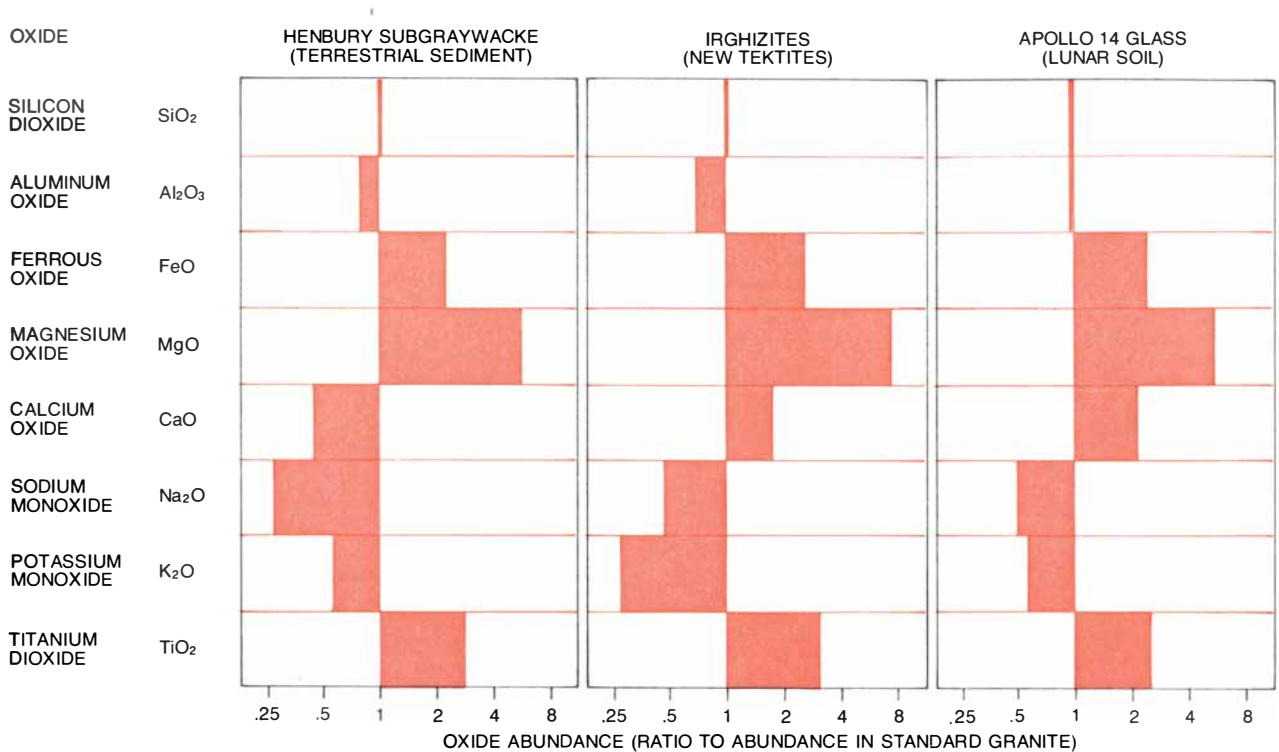
MICROTEKTITES in this photomicrograph were discovered by Billy P. Glass of the University of Delaware and his colleagues in a core from the floor of the Caribbean Sea near the island of Curaçao. Their composition is consistent with that of other tektites in the North American strewn field; stratigraphic and fission-track evidence dates them in the late Eocene epoch, some 35 million years ago. The actual size of the large dark microtektite (*center*) is .25 millimeter.

ry. It means that meteorites cannot be splashed directly from an asteroid in the asteroid belt to the earth: although the initial velocity needed for them to escape from a small asteroid would be insignificant, the velocity change required to put the asteroid material into an orbit intersecting the earth would be about five kilometers per second. And Anders' limit is certainly a further, and final, argument against meteorite impact on the moon as the source of tektites.

The logic does not stop there, however. We must face the fact that Anders' limit also excludes, even more strongly, the possibility that tektites originate from terrestrial meteorite impact! Velocities of from four to six kilometers per second are required by the geographic extent of the large strewn fields, even if one disregards atmospheric resistance.

The elimination of both impact hypotheses is surprising. In the 1960's almost all investigators were convinced—certainly I was—that tektites were generated by impact, whether on the earth or on the moon. What convinced us was the discovery by Edward C.-T. Chao of the U.S. Geological Survey of nickel-iron spherules in certain tektites. Nickel-iron is the characteristic component of meteorites, and such spherules are found in nontektite glasses formed by meteorite impact. The spherules do testify against terrestrial volcanism, since unoxidized iron is rare in lavas. Given the relative frequency of nickel-iron spherules in the Apollo lunar samples, it is now hard to see why, if the spherules are associated with lunar impact, they are so rare. And with the advantage of hindsight it seems strange that they tend to be associated with a particular kind of tektite glass and that their nickel content is low—much lower than that of meteorites. The low nickel content is hard to reconcile with a terrestrial origin for a particular reason. Robin Brett of the Geological Survey has pointed out that the partial loss of iron from a spherule in terrestrial impact glass by oxidation usually results in a spherule with a very high nickel content (and with an iron-rich halo around it, which is not seen in tektites). There is evidence from the Apollo samples that some low-nickel spherules are generated internally by the moon; perhaps the spherules in tektites really point to lunar volcanism.

There are several attractive aspects to the hypothesis that tektites have been fired at the earth by a volcano on the moon. In the first place the inadequate-velocity argument, which knocks out terrestrial volcanism as well as lunar and (I believe) terrestrial meteorite impact, is answered. Lunar rock is so avid for oxygen—so "reducing"—that a lunar volcano seems likely to be powered by



TEKTITES, LUNAR GLASS AND SANDSTONE are remarkably similar in their major-element composition. The bars show how each of the three materials differs from standard granite (G-1) in its con-

tent of major oxides. Tektite composition is somewhat closer to that of the lunar glass represented here, certain glassy *Apollo 14* particles, than to that of the Henbury subgraywacke, a terrestrial sandstone.

hydrogen rather than by steam. More specifically, the equilibrium ratio of hydrogen to steam in contact with lunar basalt (or tektite glass) at 1,200 degrees C. should be four to one. The acoustic velocity in that mixture of gases is three kilometers per second. Particle velocities of up to six kilometers per second are therefore possible in principle. The lunar escape velocity is only 2.5 kilometers per second. A hydrogen-powered volcano should be able to attain that velocity, particularly in the absence of an atmosphere.

The lunar-volcano hypothesis also survives the discovery that the moon's surface is chiefly basaltic, the finding that eliminates lunar impact as an origin because tektites are typically silicic in composition. The kind of explosive volcanism required to launch the tektites is associated (on the earth at least) with silicic volcanoes. If tektites are propelled by lunar volcanism, it is reasonable that tektites should be predominantly silicic: they originated not on the lunar surface but in a granitic magma somewhere below the lunar surface, and there is evidence for such magmas even though the moon's surface is almost entirely basaltic.

The hypothesis of tektite origin by meteorite impact on the earth continues to be widely supported in spite of the implications of Anders' limit. Let us suppose my application of the limit

to the terrestrial-impact hypothesis is faulty and thus allow that there are two serious possibilities for the origin of tektites: lunar volcanism and terrestrial impact. The next step is to evaluate both possibilities in the light of more detailed data concerning the composition of tektites.

Adherents of terrestrial impact assume that the impact was on sedimentary rock (perhaps metamorphosed) because the chemical objections cited against volcanic glasses apply also to igneous rocks in general. By unfortunate coincidence terrestrial sedimentary rock and a lunar volcanic source are about equally capable of yielding the major-element composition observed in tektites. Among terrestrial sediments the sandstones, and in particular the rocks called subgraywackes, yield the best match because some kind of sorting process has enhanced their quartz content. Quartz is pure silicon dioxide, and because it has no natural cleavage planes it is tougher than other common minerals and tends to form larger grains; any sorting process that respects particle size will tend to separate quartz from the other minerals. The high content of lime, magnesia and ferrous oxide compared with soda and potash, which is observed in tektites and distinguishes them from granitic glasses, is remarkable only in rocks of high silica content; in intermediate or basic (basaltic) rocks

it is quite usual. Hence all that is needed to achieve the major-element composition of tektites in a terrestrial rock is to raise the rock's silica content, leaving everything else as it is in more basic rocks. Sedimentary processes can do just that.

It was this point more than anything else that led geochemists to support a terrestrial origin for tektites during the 1960's. They believed that the moon probably would not make granite (and in fact it apparently does not make much). They assumed that if granite were made on the moon, it would be much like terrestrial granite because the laws of magma evolution should be the same on the moon as they are on the earth. And on the moon, of course, there would be no sedimentation to sort the granite into a material having the typical tektite composition.

A number of different granitic compositions have now been found on the moon, and none of them is of the classic terrestrial type. At the *Apollo 14* site about 1 percent of the very fine soil is silica-rich glass. Most of it is also rich in potash and thus quite unlike known tektites; the reason may be that potash-rich tektites do not survive because they are rapidly destroyed by weathering. A significant fraction (some 10 to 20 percent) of the lunar granitic glass has only moderate amounts of potash, however. Billy

P. Glass of the University of Delaware identified some glassy *Apollo 14* soil particles that are much like known tektites in their major elements. In particular they show the characteristic excess of the divalent oxides lime, magnesia and ferrous oxide and deficiency of the monovalent oxides soda and potash. Similar particles have been noted in the material from *Apollo 12* and *Apollo 15*.

The process by which lunar granites come to be different from terrestrial granites is being studied by Paul C. Hess and Malcolm J. Rutherford of Brown University. They have found in laboratory experiments that the reducing character of a simulated lunar magma makes it tend to become rich in iron as various crystals settle out; the ferrous iron tends to remain in solution, whereas more oxidized ferric iron would be trapped in magnetite (Fe_3O_4) and would settle out. The iron-rich magma then divides into two liquids that, like oil and water, do not mix. One of them is a granitic liquid with the peculiar composition of tektites or lunar granites. (The other is a very iron-rich liquid, evidence for which seems recently to have been found in lunar rocks.)

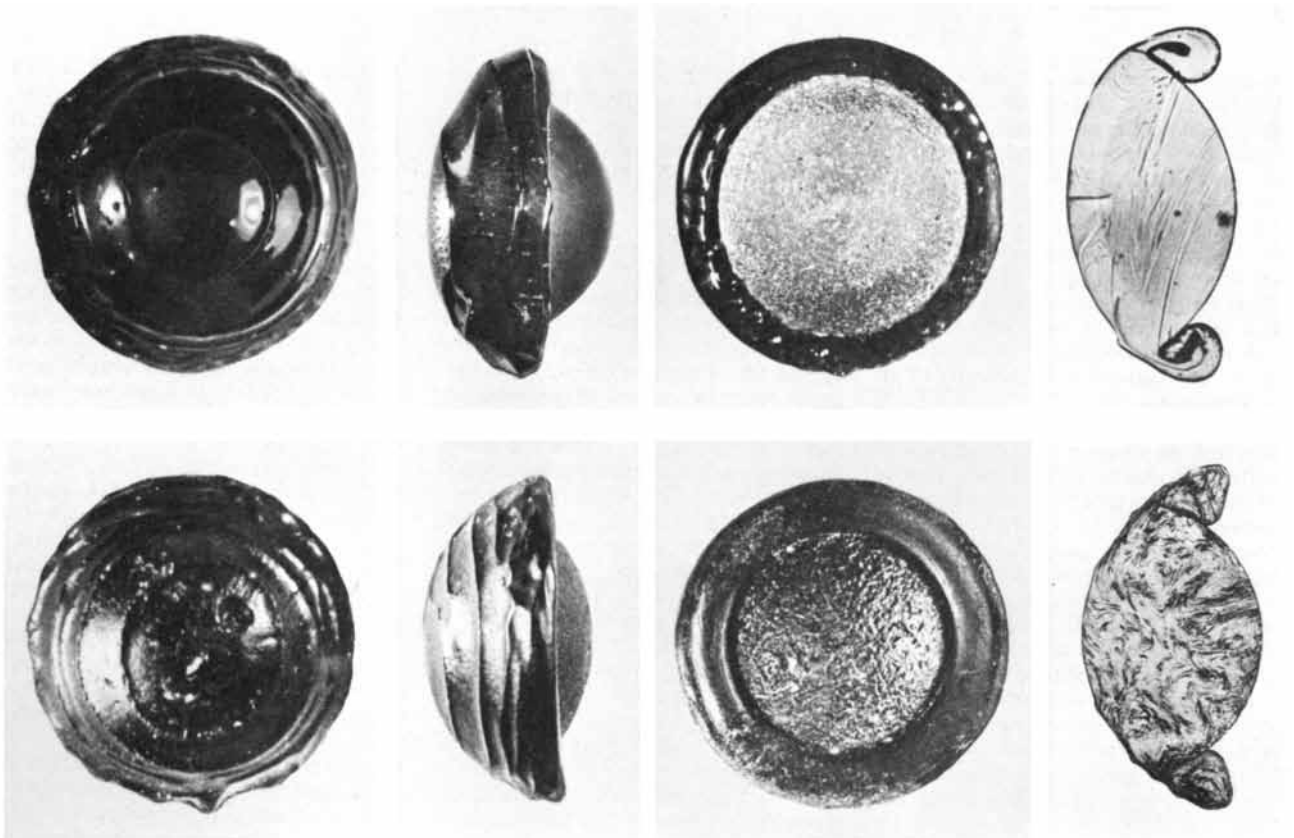
Going beyond the major-element

composition, one can compare the water content, the minor and trace elements and the "oxygen fugacity," or the state of oxidation, of tektites and their possible source materials. Tektites are much drier than terrestrial sediments: they contain about a fiftieth as much water. Compared with terrestrial sediments tektites are deficient in the elements whose compounds are still volatile at 1,000 degrees C., such as lead, thallium, copper and zinc. Finally, there is the strong reducing character of tektites. At about 1,200 degrees C. the oxygen fugacity (or equilibrium oxygen partial pressure) is only about 10^{-14} atmospheres in tektites as against about 10^{-8} in terrestrial basalts.

For a lunar-volcanism origin, on the other hand, those three characteristics present no difficulty. Dryness, low content of volatile elements and low oxygen fugacity are the three hallmarks of lunar-rock composition, as was noted in the first reports on the *Apollo 11* specimens. Brett has recently shown that at magma temperatures the oxygen fugacity of tektites is quite close to the lunar value. (Just before the first lunar landings, incidentally, some of us who had

been studying tektites predicted that lunar rock would have a low water content and be deficient in volatile elements.)

It is true that the loss of volatiles, water and oxygen might also be explained by the process of meteorite impact on the earth, at least qualitatively and in principle. If a rock is heated to a sufficiently high temperature and for a sufficiently long time, water, volatile elements and oxygen will escape from it. Serious difficulties arise, however, if one attempts to account for these losses quantitatively. Volatiles can escape at a reasonable rate only by forming bubbles that rise to the surface of a liquid. Within a tektite propelled by a meteorite into a ballistic trajectory the gravitational acceleration is zero; the bubble cannot rise because there is no "up." Even under normal terrestrial gravitational conditions the process of eliminating bubbles from glass, which glassmakers call fining, takes hours or days; it is a major factor in the cost of commercial glass and has been given much attention. Fining is difficult enough with dry, clean glass components and with a glass of low viscosity; in the case of wet, dirty components and a very viscous glass it would be surprising if fining could be



ABLATION OF AUSTRALITES was mimicked in the laboratory by Dean R. Chapman of the Ames Research Center of NASA. He subjected artificial tektite glass to a heated airstream in an arc jet, producing the models shown at the top in (left to right) front, side and

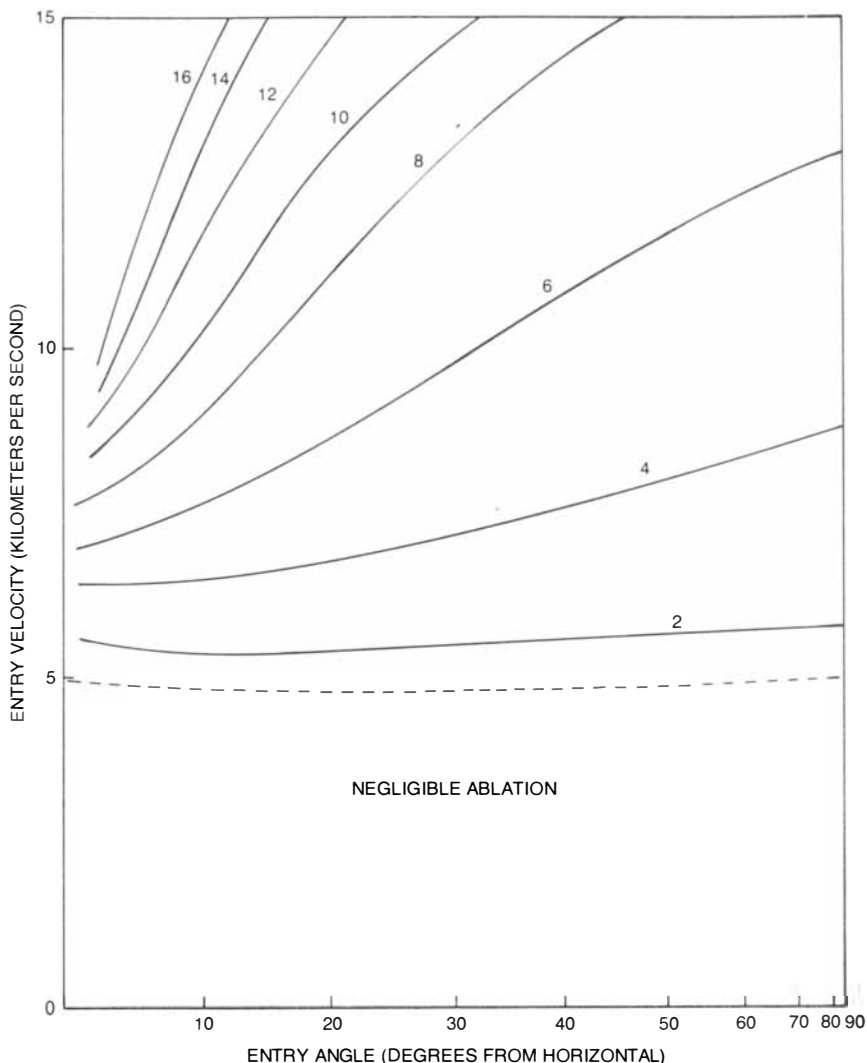
back views and as a thin section seen from the side. The same views of natural australites are seen at the bottom. The striae in the thin sections meet the back surface at a sharp angle; at the front surface, however, they turn and follow the surface as a result of liquid flow.

accomplished within the few minutes before the tektite material congeals and in the absence of an effective value of gravity.

The large reduction in oxygen fugacity required to transform a terrestrial glass into tektite material leads to a similar difficulty. It means that ferric oxide (Fe_2O_3) must be changed into ferrous oxide (FeO) by the liberation of a volume of oxygen substantially larger (at atmospheric pressure) than the volume of the tektite. Experiments show that at atmospheric pressure the reduction stops at a ratio of ferric to ferrous oxide that is about eight times higher than the ratio in tektites, even at very high temperatures.

There are minor discrepancies between tektite trace elements and the only lunar granite that has been thoroughly analyzed, sample 12013 from *Apollo 12*. The lunar sample is richer in chromium and has a lower potassium-to-uranium ratio, a higher ratio of lead 206 to lead 204, a different set of rare-earth abundances and a lower ratio of oxygen 18 to oxygen 16. On the other hand, some of the more recent analyses have turned up tektites with chromium in the lunar range and lunar material having a potassium-to-uranium ratio in the tektite range, a lead-isotope ratio basically similar to the ratio in tektites and rare-earth distributions much like those in tektites. As for the oxygen-isotope discrepancy, since somewhat similar relations are found on the surface of lunar dust grains it may simply reflect the fact that tektite material has spent some time in the form of very fine particles, a possibility that is supported by some aspects of tektite morphology. On balance, then, the chemical data support a lunar origin rather more strongly than they support a terrestrial one.

The most telling arguments in favor of the lunar hypothesis, however, are based on striking aerodynamic evidence produced by Dean R. Chapman and his colleagues at the Ames Research Center of the National Aeronautics and Space Administration. Chapman and others had calculated that tektites launched from the ground could travel only a few hundred meters through the undisturbed atmosphere. Shao-Chi Lin of the University of California at San Diego suggested that the atmosphere might not have remained undisturbed: that the air might have been set in motion by a gigantic meteorite impact and so might have conveyed the tektites at ballistic velocity to the top of the atmosphere. Lin calculated that the energy required to launch tektites in this way would have produced a crater some 300 kilometers in diameter and 40 kilometers deep. Chapman and Donald E. Gault confirmed Lin's calculation and



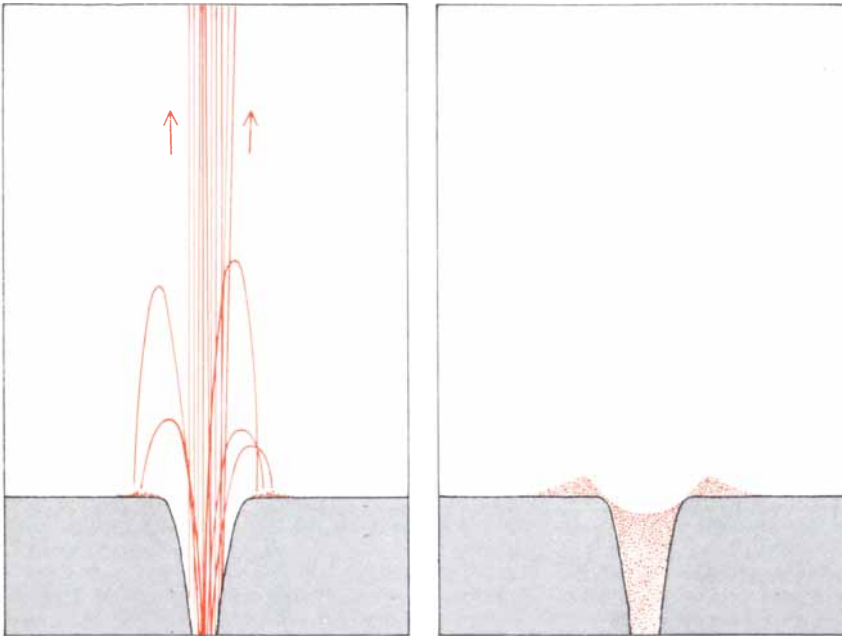
DEPTH OF ABLATION was calculated by Chapman and Howard K. Larson, for various velocities of entry into the atmosphere and for various angles of entry, according to the generally accepted ablation theory. The numbers on the curves give the amount of ablation in millimeters. Since the australites appear to have lost about 10 millimeters to ablation, the calculations indicate an entry velocity of at least 11 kilometers per second at likely angles of entry.

suggested that it would be rather difficult to conceal such a crater. Indeed, the existence of three such craters, undiscovered and in the correct positions to account for the Australasian, North American and Ivory Coast strewn fields, is very doubtful indeed.

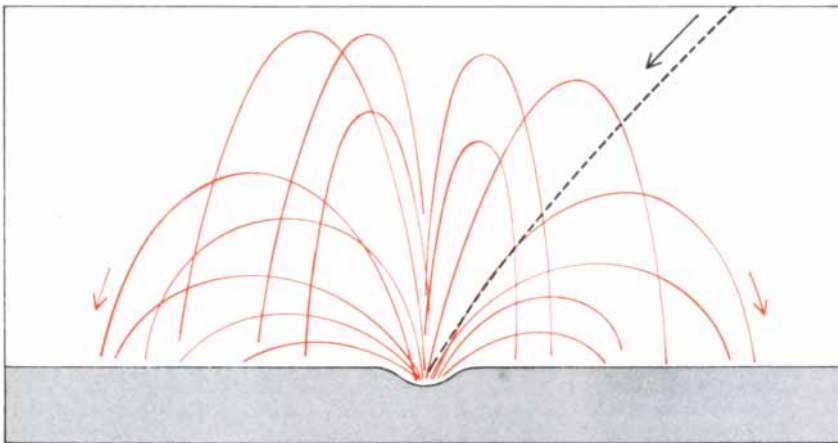
In a brilliant series of experiments and calculations Chapman demonstrated just how the curious flanged shape of the tektites from Australia called australites, such as the one brought back by Darwin, is generated by aerodynamic ablation. As early as 1893 the German geologist A. W. Stelzner had suggested that the australites had begun as spheres and had been partially melted, with the melt flowing back from the front face of the tektite under air drag. Chapman had glass made up to mimic the chemical composition of the australites and sub-

jected samples to a heated airstream in an arc jet. The glass flowed back from the front surface and coiled into the characteristic flange, identical even to the circular or spiral "ring waves" of the natural tektites.

Chapman showed that the flange, the amount of ablation and the pattern of the ring waves are inconsistent with origin on the earth. The australites could develop a flange only in stable flight. (Most tektites presumably do not begin as smooth spheres; they tumble in flight and are shaped by ablation into irregular forms.) The australites would be stable only during passage through an increasingly dense medium; the amount of ablation indicates a velocity of from 10 to 12 kilometers per second. That is consistent with descent through the atmosphere at the entry velocity (11.2 kil-



LUNAR VOLCANIC ERUPTION, which the author favors as the most likely source of tektites, could eject material at the lunar escape velocity, about 2.5 kilometers per second. The material would be tightly "clustered" in speed and direction (*left*). Not much of it would fall back to the lunar surface and what fell back would not be spread very far (*right*); that would explain why the moon has not been found to be littered with material of tektite composition.



METEORITE IMPACT ON THE MOON, on the other hand, would presumably eject material in many directions and at many different speeds, thus spreading material over lunar surface.

ometers per second) expected for an object coming from the moon. Chapman's calculations, which were confirmed by my colleagues and me, depend on the well-tested theory of ablation that underlies the design of heat shields for NASA spacecraft and military missiles.

In choosing between terrestrial impact and lunar volcanism we are in the position the pioneer French meteoritist Antoine François de Fourcroy described in 1804: "compelled to choose between ideas that are just as unprecedented the one as the other." Fourcroy wrote that in such a case "it is only by eliminating the absurd or the impossible that one is forced to accept what would at first have seemed almost unbelievable" (that meteorites fall from the sky).

It is absurd to suppose the earth has a number of undiscovered Cenozoic craters larger than Ireland or that the standard heat-shield calculations contain gross undetected errors leading to underestimation of ablation by a factor of five. It is impossible to make substantial chunks of glass of good quality and devoid of water instantly from common rock and soil, or to launch large particles from the earth at six kilometers per second by shock, or to penetrate the atmosphere with gram-size bits of glass at hypersonic velocities. And so one is forced to accept the conclusion that tektites, in spite of their remarkable resemblance to terrestrial rocks, have been fired at the earth by a volcano or volcanoes on the moon.

If tektites come from the moon, they are a selected group of volcanic glasses. Volcanism yields nearly vertical launch directions (at least on the earth), which means that material can be propelled to the earth only from a limited set of locations on the moon. That being the case, tektites constitute a limited subsample of lunar granitic materials. It is not reasonable, then, to expect that the average properties of lunar granites would match those of tektites. One can only expect that those properties would not be inconsistent with tektite compositions, and that requirement appears to be satisfied by the lunar granites that have been studied. The compositional argument against a lunar origin for tektites can therefore be met.

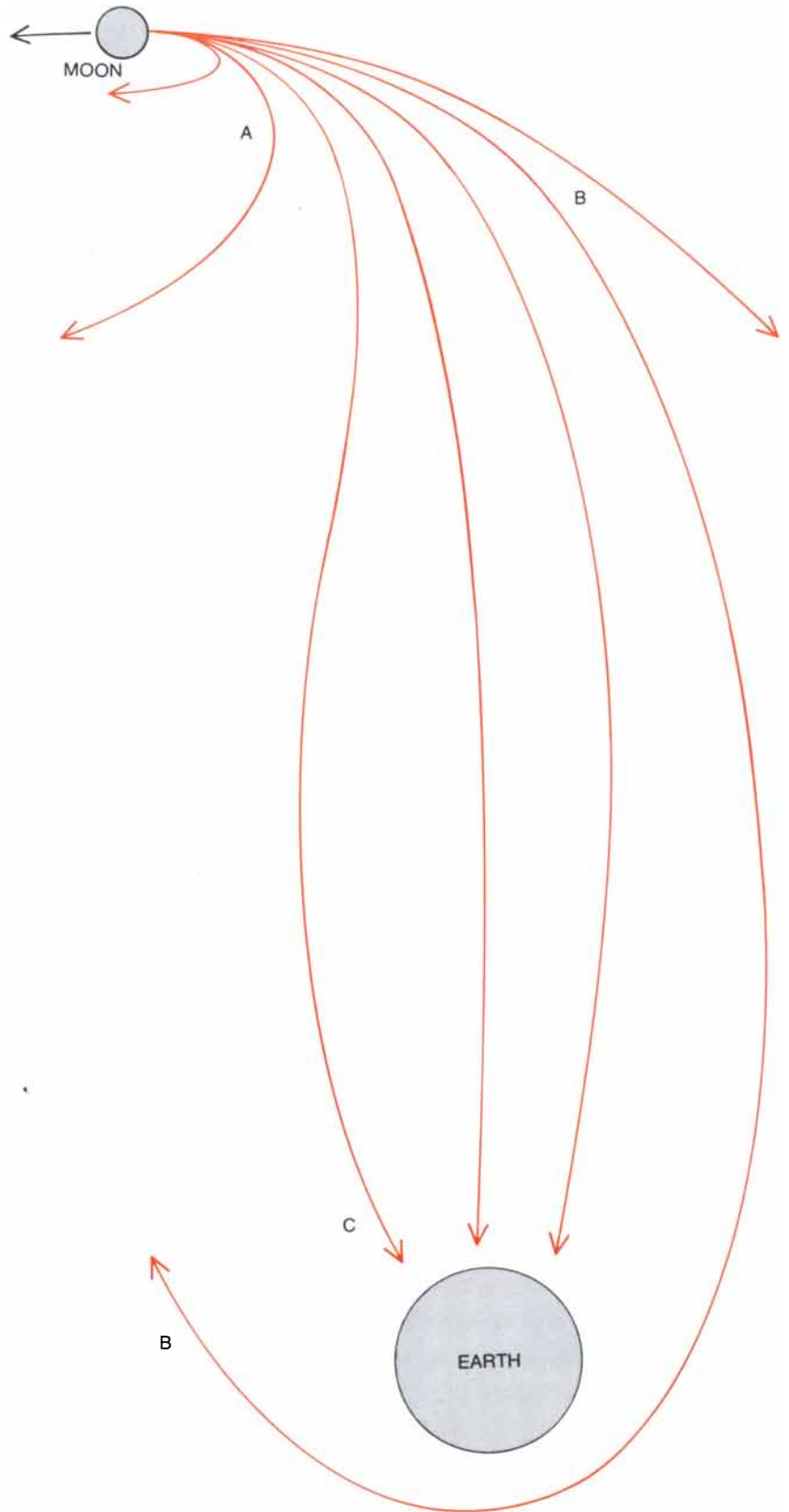
Another argument against lunar origin derives from the localized distribution of tektites on the earth. It is held that tektites that miss the earth on a first pass would go into orbit around the sun, would eventually be captured by the earth and would fall out in a uniform distribution over the earth's surface—unless there is some mechanism that destroys them before they are recaptured. Such a mechanism does exist, however. If the albedo, or reflectivity, of a small body moving through the solar system is so distributed that on the average the

albedo of the right side is even slightly different from the albedo of the left side, the object will be caused to spin by the differential radiation pressure of sunlight. The spinning will increase to bursting speed in a few tens of thousands of years, thus destroying an orbiting tektite.

Finally, how is one to account for the few craters that do appear to be associated with certain tektite assemblages: the irghizites, the Aouelloul tektites and perhaps the Darwin-glass tektites? Not all tektites need to have come from the moon as small objects. Large blocks are sometimes ejected from terrestrial volcanoes. It is at least conceivable that a block of tektite material weighing some millions of tons could have been propelled toward the earth by a violent eruption on the moon, by a violent eruption on the moon, could have excavated the Zhamanshin crater and in the process disintegrated, after which its material would have recongealed to form the irghizites.

The key to solving the tektite problem is an insistence on a physically reasonable hypothesis and a resolute refusal to be impressed by mere numerical coincidences such as the similarity of terrestrial sediments to tektite material. I believe that the lunar-volcanism hypothesis is the only one physically possible, and that we have to accept it. If it leads to unexpected but not impossible conclusions, that is precisely its utility.

To cite just one example of the utility, the lunar origin of tektites strongly supports the idea that the moon was formed by fission of the earth. Tektites are indeed much more like terrestrial rocks than one would expect of a chance assemblage. If tektites come from a lunar magma, then deep inside the moon there must be material that is very much like the mantle of the earth—more like the mantle than it is like the shallower parts of the moon from which the lunar surface basalts have originated. If the moon was formed by fission of the earth, the object that became the moon would have been heated intensely, and from the outside, and would have lost most of its original mass, and in particular the more volatile elements. The lavas constituting most of the moon's present surface were erupted early in the moon's history, when its heat was concentrated in the shallow depleted zone quite near the surface. During the recent periods represented by tektite falls the sources of lunar volcanism have necessarily been much deeper, so that any volcanoes responsible for tektites have drawn on the lunar material that suffered least during the period of ablation and is therefore most like unaltered terrestrial mantle material. Ironically, that would explain why tektites are in some ways more like terrestrial rocks than they are like the rocks of the lunar surface.

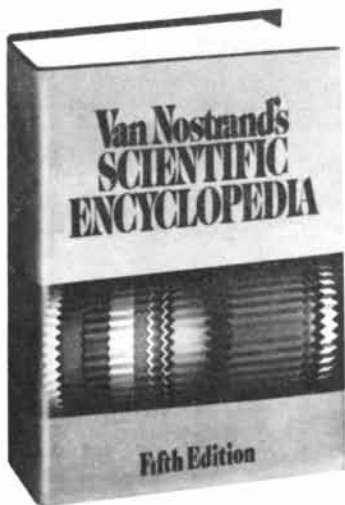


PATHS FROM MOON TO EARTH of tektite material ejected by lunar volcanism are shown. Material ejected at just a little more than escape velocity would (given the velocity of the moon around the earth) go into an orbit like that of the moon (A). Material ejected at very high velocity would go into a retrograde orbit (B), missing the earth and eventually orbiting the sun. Only material ejected within a narrow velocity range (C) would enter an orbit that would intersect, or that could be skewed by the earth's gravitational attraction to intersect, the earth.

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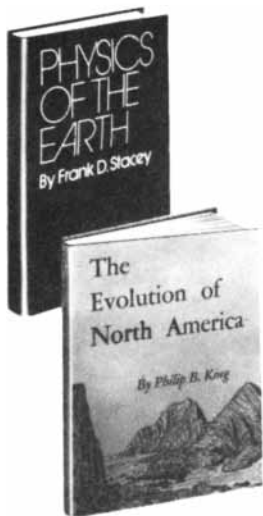
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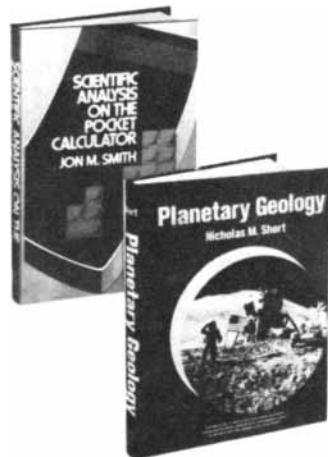
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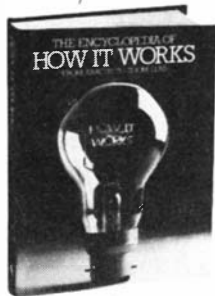


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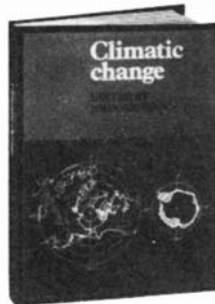
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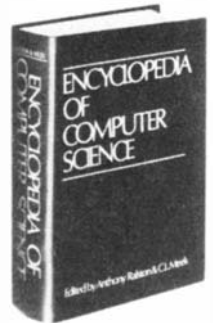
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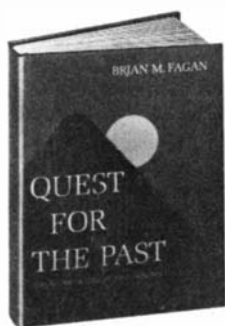
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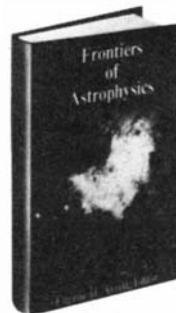
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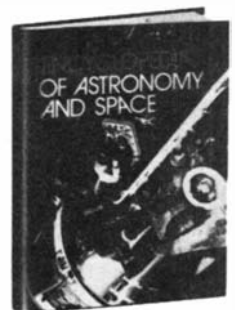
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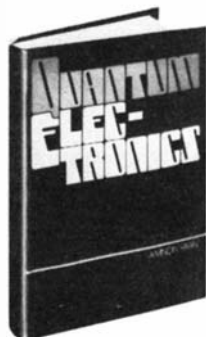
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