Waste Isolation Pilot Plant

Compliance Certification Application

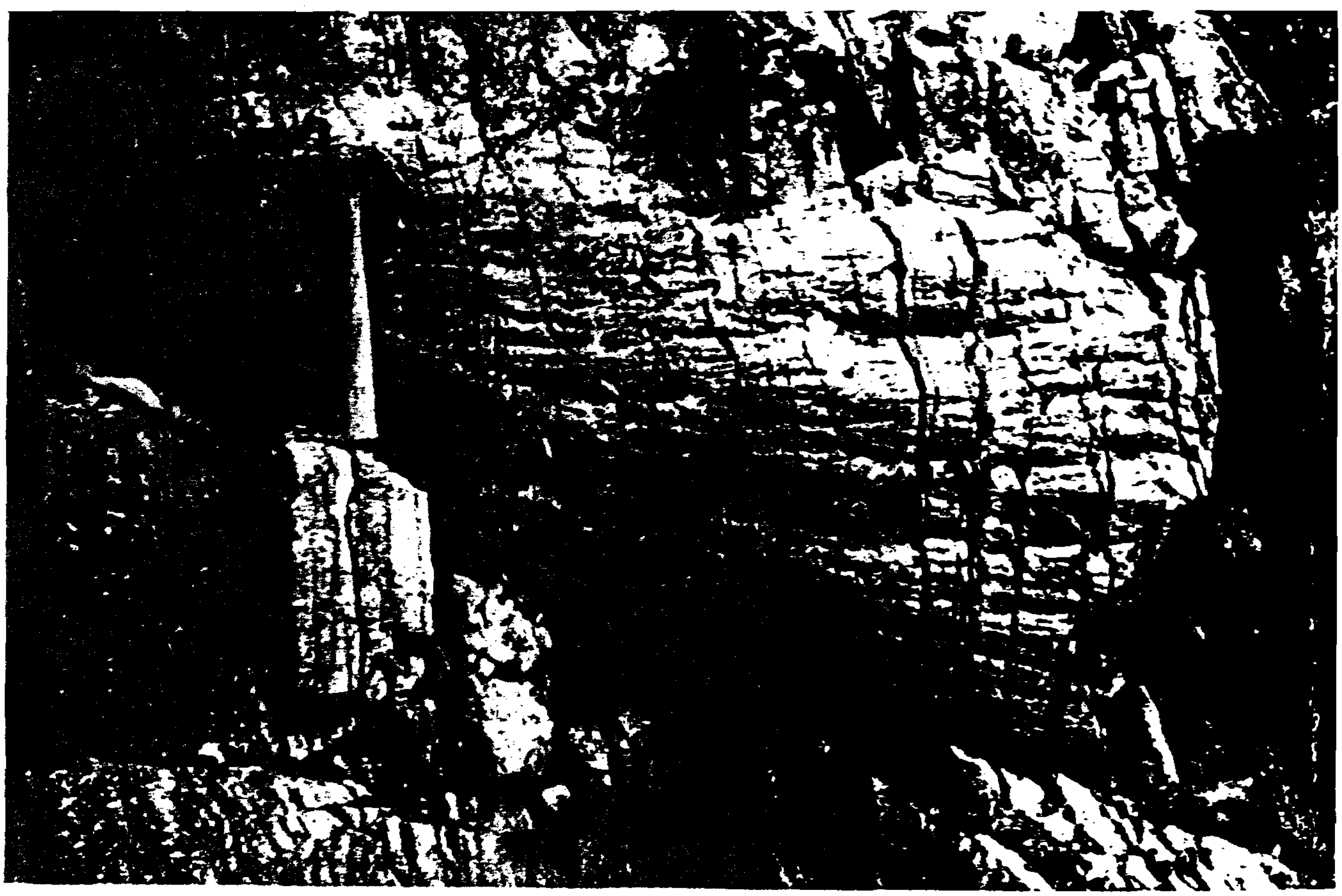
Reference 176

Dietz, R.S., August 1961.
Astroblemes, Scientific American, Vol. 205, #2, p 50-58.

Submitted in accordance with 40 CFR §194.13, Submission of Reference Materials.

SHATTER CONE four inches high is one of many in igneous rock of the Vredefort Ring in South Africa, a structure that is probably the remains of the largest meteorite crater known on earth.

NEST OF CONES in dolomite, a type of limestone, is from Wells Creek Basin structure in Tennessee. This group is 11 inches high. Shock pressures generated by meteorite impact create such cones.



GIANT SHATTER CONE, over four feet long, is shown in place at the Kentland limestone quarry in Indiana. These cones found among jumbled rocks in a flat, geologically undeformed terrain indicate that the quarry is an ancient meteorite-impact site.

ASTROBLEMES

This newly coined word refers to ancient scars left in the earth's crust by huge meteorites. The evidence for such impacts is largely the high-pressure mineral coesite and "shatter cones" in the rocks

by Robert S. Dietz

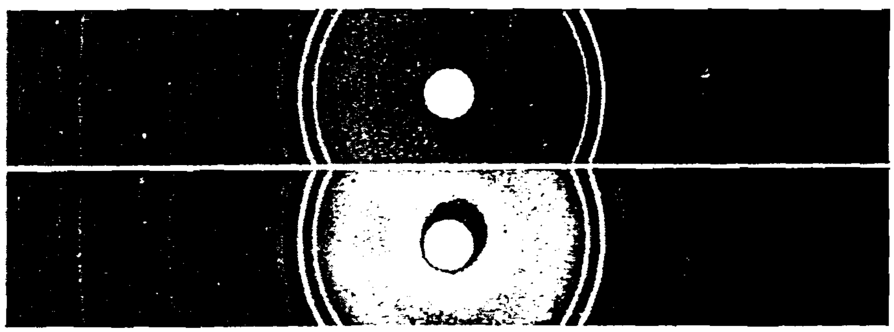
It is an awesome experience to stand on the rim of Barringer Crater in Arizona and reflect on the cosmic cataclysm that opened up this gaping hole, three-quarters of a mile across and 600 feet deep, in the crust of the earth. The Hopi Indians are said to retain the legend that one of their gods descended here from the sky in fiery grandeur. White sheepherders who came upon the crater a century ago found numerous lumps of metal lying about and intuitively concluded that a star had fallen at the site. Upon later analysis the lumps of metal proved indeed to be fragments of nickel-iron meteorite. Studies at the site have now established beyond doubt that the crater records the impact of a large meteorite that plunged to earth some 25,000 years ago. Barringer Crater is the first of an increasing number of geological structures to be recognized as the scars of an agelong and still continuing bombardment of the earth by rubble from elsewhere in the solar system.

An extraterrestrial explanation of terrestrial events finds a readier acceptance today than it did in the past. One persuasive body of evidence supporting the meteoritic origin of Barringer Crater and craters like it is represented by the pockmarked face of the moon. As long ago as 1895 G. K. Gilbert, the most distinguished U.S. geologist of his time, advanced the hypothesis that the craters of the moon had been caused by the impact of meteorites. His explanation of these lunar features stands little changed even today. Yet after a visit to Barringer Crater, Gilbert read a philosophical paper entitled "The Origin of Hypotheses" to the Geological Society of America in Washington, in which he argued that the crater had a purely terrestrial origin—in a volcanic explosion—and dismissed the notion of a meteorite fall. Gilbert's authority was such that it took more than 30 years to reverse his judgment. But the sciences progress not so much by the discovery of new truth as they do by the correction of old error. Overwhelming evidence was forthcoming by 1928, and Barringer Crater was firmly identified as the site where a large meteorite had struck.

Acceptance of this prototype terrestrial meteorite crater opened the way for speedy recognition of others. In 1933 L. J. Spencer of the British Museum listed eight more, all of which have withstood closer inspection. Among them is the great Ashanti Crater (Lake Bosumtwi) in Ghana, which has a diameter of six miles. More recently discovered is the two-mile New Quebec Crater in subarctic Canada [see "The Canadian Meteor Crater," by V. B. Meen; SCIENTIFIC AMERICAN, May, 1951]. Four craters in Australia have also been identified as scars of meteorite falls.

The list of 14 well-certified terrestrial meteorite craters is impressive, but the record of bombardment preserved on the face of the moon plainly suggests that the list should be longer. At the conservatively estimated rate of one great fall every 10,000 years, some 50,000 giant meteorites must have struck the earth during the past 500 million years. Where are the craters they made? The answer is that on the earth's surface such craters are ephemeral features. Tectonic processes alter their round shapes, erosion wears away their rims and sedimentation fills them up; gradually they disappear as recognizable features in the terrain. On the airless, waterless and tectonically inactive surface of the moon, meteorite craters have remained unchanged from the most distant past except through the impact of later meteorites. The craters that remain clearly visible on earth today must all have been created by impacts during the last million years.

To lengthen the list of terrestrial meteorite craters one must now look for less obvious signs. A few "fossil" craters, scarcely discernible on the ground, have shown up in aerial photographs, appearing as faint circular features [see "Fossil Meteorite Craters," by C. S. Beals; SCIENTIFIC AMERICAN, July, 1958]. Geological maps of surface and subterranean rock formations have revealed still other



X-RAY-DIFFRACTION PATTERNS of synthetic coesite *(top)* and natural coesite found at Barringer Crater in Arizona are virtually identical. Coesite is a silica formed at high pressure. Diffraction patterns were made by E. C. T. Chao of the U.S. Geological Survey.

BARRINGER CRATER, also known as Meteor Crater, was made about 25,000 years ago by a meteorite impact. It is three-quarters of a mile across. Natural coesite was first found here.

BRENT CRATER in central Ontario is a shallow depression two miles across, first detected in an aerial photograph. It is a fossil crater approximately 500 million years old.

circular [illegible] structures, which [illegible] in the past have generally attributed to volcanic explosions. It now appears that many of these are the "root" structures of ancient meteorite craters. For those that prove to be obliterated craters made by a meteorite or the head of a comet I have proposed the term "astrobleme," from the Greek words for "star" and "wound."

Of course the discovery of the main body or of remnants of a meteorite embedded in the rocks would clearly identify an astrobleme. Gilbert looked for such evidence at Barringer Crater; because he could not detect the magnetic anomaly that would have indicated a buried mass of meteoritic iron, he was led to his negative conclusion. It is now known, however, that one can hardly expect to recover meteorite fragments from an astrobleme. The meteorite partly vaporizes on impact and the remaining fragments quickly weather away. Comet heads are largely composed of ices of water, methane and ammonia, and so they would leave little evidence.

But there is another kind of evidence that should persist. A meteorite large enough to cause an astrobleme enters the earth's atmosphere with the same high velocity as a small meteorite—at an average speed of some 10 miles per second. Because of its size, a big meteorite loses little of its enormous energy to deceleration by the atmosphere. The shock that it generates upon impact must therefore transcend that of any other earthly explosion, natural or man-made. It can be calculated that such impacts produce pressures of millions of atmospheres. (One atmosphere is about 15 pounds per square inch.) Volcanic explosions, in contrast, involve pressures of hundreds of atmospheres. Therefore at the site of a suspected astrobleme one should look for evidence of sudden, extremely intense shock waves.

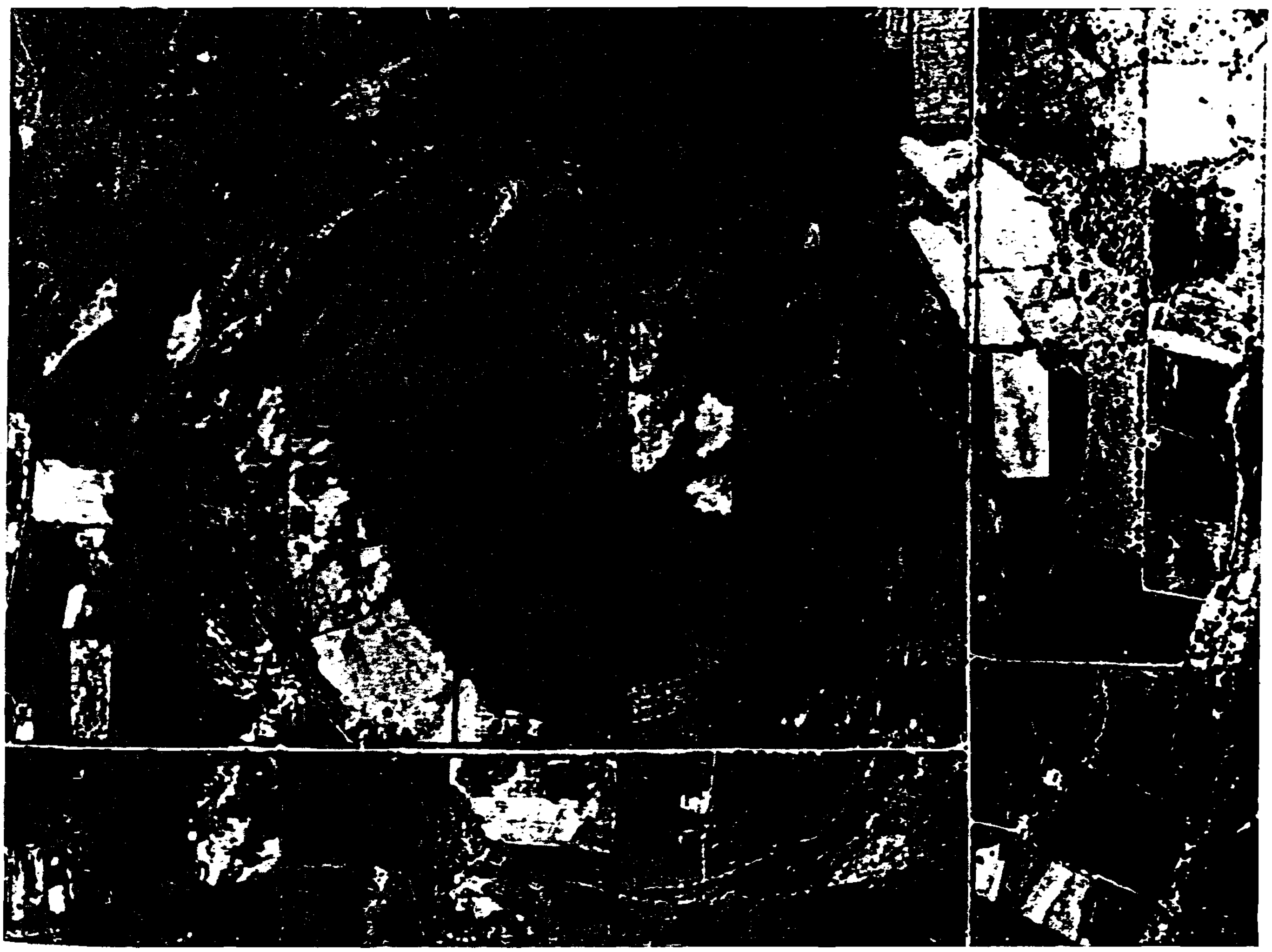
In recent years two conclusive pieces of evidence for shock waves of this kind have been recognized: (1) curious conical fracture patterns in rocks known as shatter cones, and (2) a form of silica, called coesite, created under extremely high pressure. One or both of these products of the action of intense shock waves on rock have now been discovered at a dozen sites previously attributed to volcanic events. The map of the world will never be marked with as many identified meteorite craters and astroblemes as the moon, but it is beginning to show enough of them to support Gilbert's contention that most of the 30,000 craters on the visible side of the moon were made by meteorites.

Shatter cones are conical fragments of rock characterized by striations that radiate from the apex. Such cones vary in size from a fraction of an inch up to many feet, depending largely on the thickness of the stratum deformed as a unit. Their conformation suggests that the parent rock was subjected to a sudden shearing stress so intense that the splintering of the rock ignored the natural lines of fracture weakness. Moreover, a shatter cone breaks up into smaller shatter cones when struck with a hammer, showing that the pattern of striations forms interlacing cones within the rock. Fine-grained, homogeneous rocks such as limestone or sandstone appear to favor their development, but they form in any type of rock. Shatter cones were first discovered at the beginning of this century in the Steinheim Basin in southern Germany, the site of an immense natural explosion. The Germans called them *Strahlenkalk* (*Strahlen*, rays; *kalk*, lime) and regarded them as being products of the same volcanic explosion to which they attributed the formation of the basin.

I first became interested in shatter cones nearly two decades ago when I was at the University of Illinois. The operators of a big limestone quarry at nearby Kentland, Ind., had uncovered the aftermath of some ancient cataclysm. Splintered, crushed and jumbled rock strata about 400 million years old lay in the midst of a flat terrain that showed no signs of folding or other tectonic processes. Geologists invoked a deep-seated volcanic steam explosion to explain the condition of the rocks, but the minerals and clays one would expect to find associated with such an event did not appear in the quarry. Shatter cones, however, abounded; they ranged from an inch to six feet in length. The cones were nearly all oriented at right angles to the sedimentary strata and pointed upward. If the blast had not jumbled the strata, all the apexes of the shatter cones would have been pointing to the zenith. Thus it appeared that the impulse that had shattered them came not from below, as in a volcanic explosion, but from above, as in the shock of a giant meteorite impact. It seemed to me also that in nature only the impact of a meteorite could supply the *brisance*, or shattering effect, necessary to form shatter cones.

My supposition that shatter cones must be the product of such intense shock rested largely on intuition and faith. To some observers the cones appeared to be merely "slickensides"—striated fragments produced when rock shears along faults. But the striations in slickensides are always parallel, whereas in shatter cones they flare out in radiating bundles from the apex of the cone. Others supposed that these shatter cones were a variety of cone-in-cone, a structure commonly found in limestone. But at Kentland shatter cones are present in sandstone and shale.

Proof of the shock origin of shatter cones came first from experiments with shaped charges. This technique for focusing the energy liberated by a given weight of explosive produces intense shock waves when used with ex-



HOLLEFORD CRATER, a slight depression a mile and a half in diameter in Ontario farmland, is a fossil crater, eroded and filled with sediments. A meteorite impact created it some 500 million years ago. It was also discovered in an aerial photograph.

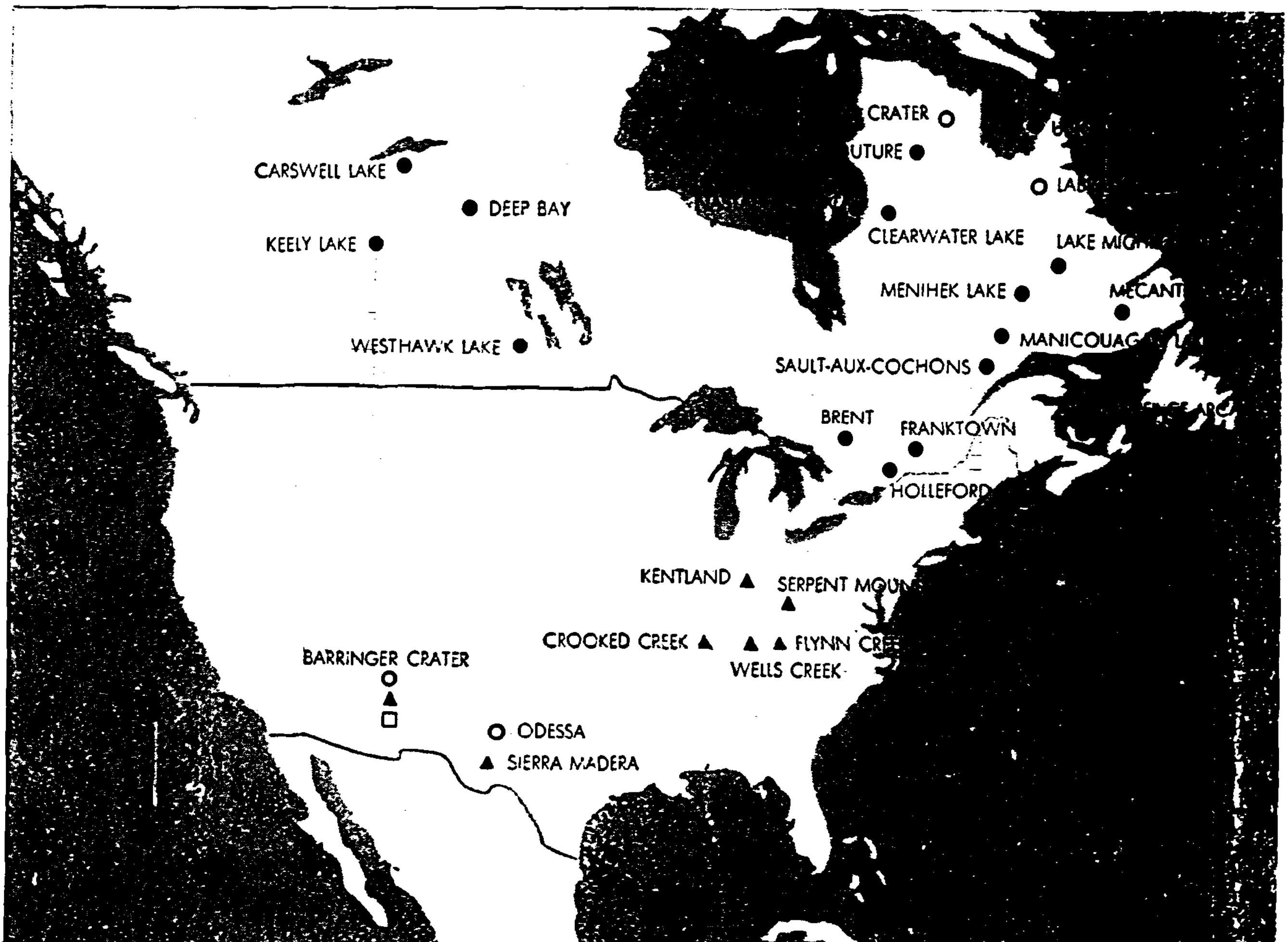
plosives that have great shattering power. In limestone shaped charges produced shatter cones closely similar to those found in nature. A heaving explosive, such as TNT, sometimes produces a rude sort of cone but one without striations. In 1960 Donald Gault and Eugene Shoemaker of the U.S. Geological Survey achieved an even closer simulation of a meteorite collision with the earth. They fired small pellets from a gas gun at the ultrahigh speed of 18,000 feet per second into limestone and produced minute but perfect shatter cones.

A search of the literature showed that shatter cones had been discovered in several other interesting structures. In 1933 Walter Bucher of Columbia University had reported finding them in the center of the Wells Creek Basin in Tennessee, a site similar to the Steinheim Basin. Herbert E. Hendriks of Cornell College in Iowa had described shatter cones from the middle of the Crooked Creek structure in Missouri; in dissent from the standard volcanic explanation for this site, he put it among those caused by meteorite impacts. Particularly interesting was the report of shatter cones from the great Ashanti Crater, a structure young enough to have been identified on other grounds as a true meteorite crater.

In Texas, not far from the MacDonald Observatory of the University of Texas, there is a chaotic circular structure known as the Sierra Madera that has attracted the interest of geologists for many years. On the strength of its resemblance to oil-bearing domed structures, prospectors have drilled two deep test wells there. In 1936 J. D. Boon and Claude C. Albritton of Southern Methodist University listed the Sierra Madera as a possible impact structure, involving rocks about 250 million years old. Two years ago, on a visit to the MacDonald Observatory, I seized the opportunity to visit the site and was rewarded with the discovery of shatter cones in the dolomite and limestone near the bull's-eye of the structure. The cones had previously gone unnoticed in spite of the active interest in the site; it seems that even exposed shatter cones are not observed unless one is searching for them.

With this new stimulus I began to seek shatter cones at other places in the U.S. thought to be the sites of natural explosions. I soon found them at the Serpent Mound structure in southern Ohio and also at the Flynn Creek structure in eastern Tennessee, which C. W. Wilson, Jr., of Vanderbilt University had long believed to be an impact site. Apparently these two structures may now be regarded as astroblemes along with the Sierra Madera.

The most obvious place to look for the cones, of course, is Barringer Crater. Attempts to find them there were at first unsuccessful. This negative finding was discouraging but not conclusive. A shock wave attenuates with the sixth power of the distance from the impact point. Except in the most gigantic meteorite craters one must expect that most of the cones will be concentrated at the center and may be buried deep under the floor where only careful drilling can expose them. Nonetheless, E. C. T. Chao of the



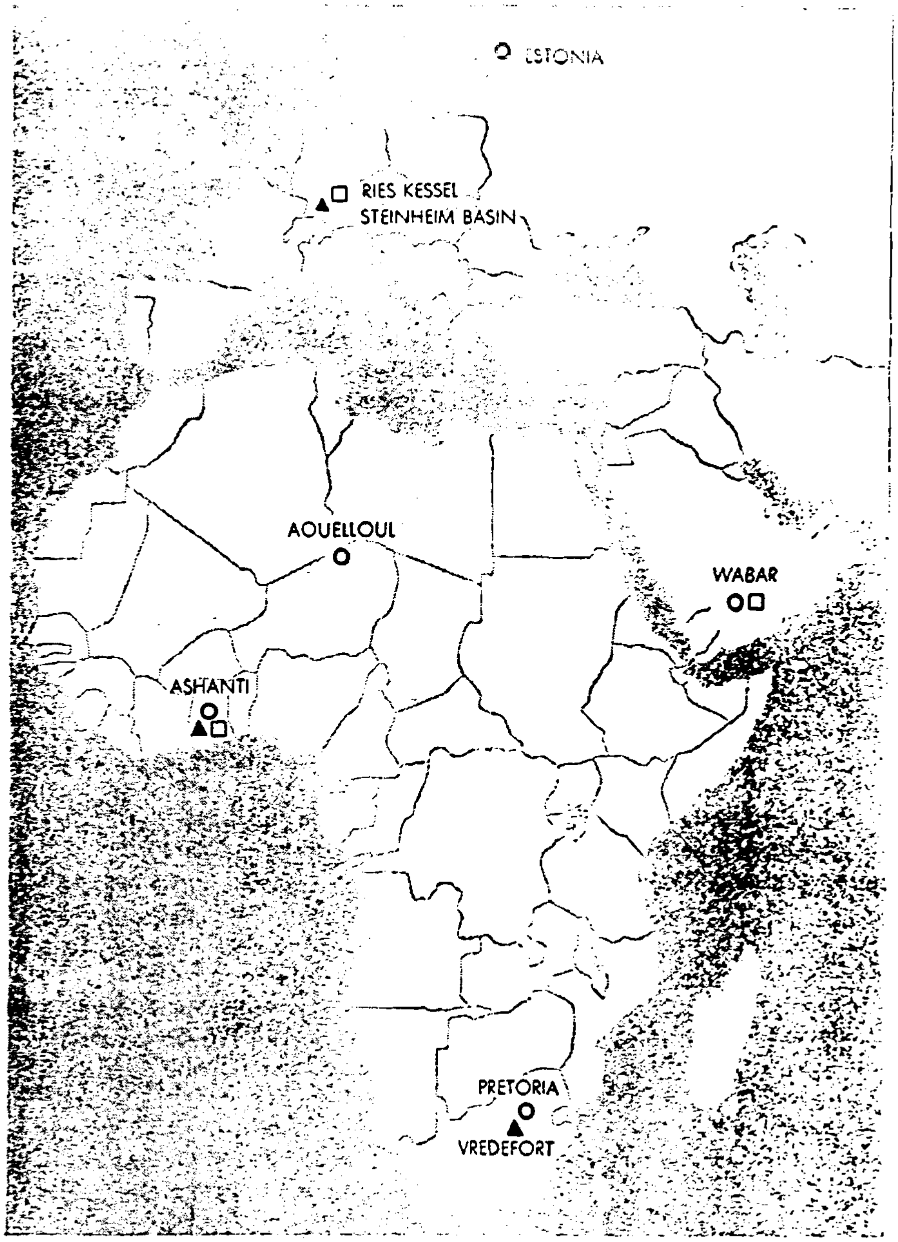
METEORITE IMPACT SITES in North America, including craters, fossil craters and probable astroblemes, are widely scattered. The Quaternary craters were made during the past million years. The other sites are much older and the craters have disappeared

U.S. Geological Survey recently discovered a small shatter-coned fragment of sandstone in the fallout debris on the south slope of Barringer Crater.

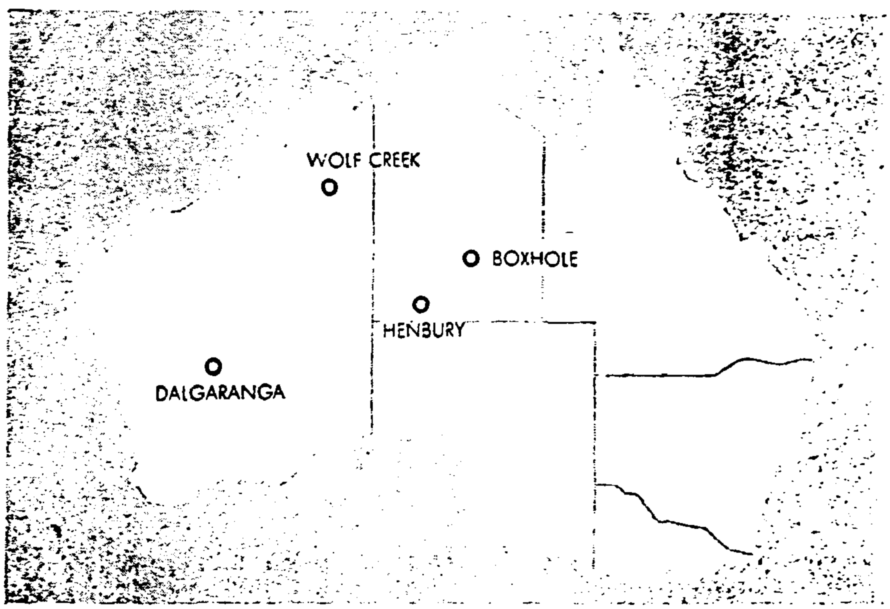
Shatter cones provide the conclusive evidence for the identification of the most spectacular of all astroblemes, the peerless Vredefort Ring in the Transvaal of South Africa. Practically nothing of the original crater remains, but geological study has revealed a worn-down "dome" of granite 26 miles in diameter surrounded by an upturned and even partially overturned collar of Pre-Cambrian rock (the Pre-Cambrian era ended some 600 million years ago). A great ring syncline (the trough of a fold in the rocks) surrounds the collar, making the entire deformation 130 miles in diameter. Geologists have traditionally attributed this huge structure to a long sequence of tectonic events. A few months ago I asked Robert Hargraves of the University of the Witwatersrand to search for shatter cones. He found them in abundance and showed also that if the rocks were returned to their original positions, the cones would all point inward toward the center of the ring.

Upon reconstruction, the event that produced this structure emerges beyond doubt as the greatest terrestrial explosion of which there is any clear geological record. Apparently an asteroid a mile or so in diameter plunged into the earth from the southwest, for the structure is overturned somewhat to the northeast. The huge object drilled into the earth and released enormous shock forces, causing a gigantic upheaval. Strata nine miles thick peeled back like a flower spreading its petals to the sun, opening a crater 30 miles in diameter and 10 miles deep. The shock must have reached with shattering force down through the entire 30-mile thickness of the earth's crust. Shock pressures of many millions of atmospheres spread through the collar, forming scattered pockets of pseudotachylite (fused rock) like raisins in raisin bread. Rock that had lined the cavity was melted and injected into the rock walls as great dikes of fused rock (of a type called enstatitic granophyre) 100 feet across and several miles long. Except for these rocks, which remained molten until the shock had passed, the collar rocks are intensely and wonderfully shattered, and it is in these that the shatter cones abound.

This grand-scale event took place at least 250 million years ago, because sediments laid down since then cover part of the astrobleme. Its energy must have been comparable to that of the im-



EUROPEAN AND AFRICAN SITES include Steinheim Basin, where shatter cones were first found; the Ries Kessel, where coesite has been found; and the Ashanti Crater in Ghana.



AUSTRALIAN SITES are all craters less than a million years old. They are located in the arid regions of the continent, where the processes of erosion and sedimentation are very slow.

pacts that produced the magnificent rayed craters Tycho and Copernicus on the moon. The Vredefort blast was a million times larger than the 1883 Krakatoa volcanic explosion in the East Indies and probably several thousand times larger than the greatest possible earthquake. In the terminology of nuclear explosions it was at least a 1.5-million-megaton event (one megaton is equivalent to the force exerted by the explosion of a million tons of TNT). By comparison the meteorite impact that produced Barringer Crater was a mere five-megaton explosion.

Although the Vredefort impact would seem to have been large enough to have generated secondary volcanic phenomena, the rocks hold no record of such a reaction. The disturbance did, however, bring into play the longer-term forces of isostasy, which make for equilibrium in the crust of the earth. Isostatic processes pushed the bottom of the crater up into its maw so that the collar now surrounds a thrust-up plug of early Pre-Cambrian granite. The eroded structure of today is neither a crater nor a fossil crater. The term "astrobleme" best describes it. The Vredefort Ring shows that tectonics, isostasy, erosion and sedimentation all conspire to give meteorite impact sites on the earth an appearance quite different from those on the moon.

Coesite, the second shock-wave product that may serve to identify an astrobleme, has been sought and found so far at only five sites. Unlike the shatter cone, which was known in nature for decades before it was duplicated in the laboratory, the first known coesite came out of the laboratory in 1953. The mineral is named for Loring Coes, Jr., of the Norton Company in Worcester, Mass., who made it in an apparatus that produces pressures exceeding 20,000 atmospheres. Such pressures occur within the earth only at depths greater than 40 miles. Just as diamond and graphite are forms of pure carbon, so coesite and quartz are different forms of silica. There are many other silicas such as opal, chalcedony, geyserite, tridymite, cristobalite, lechatelierite and diatomaceous earth. Coesite is the superdense and high-pressure form of silica and may be defined as the "diamond" of the family.

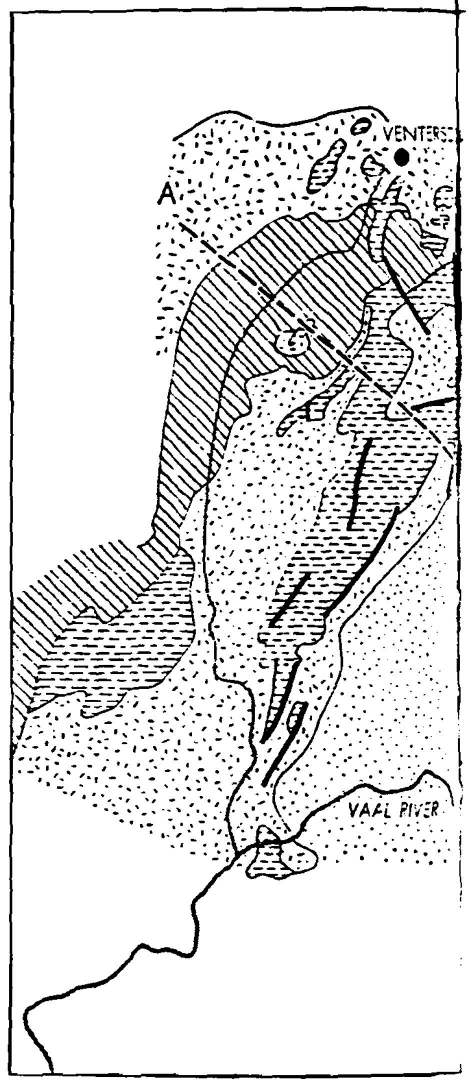
Soon after its creation in the laboratory, coesite was sought in nature. Because diamonds are created by pressures deep within the earth and carried to the surface in "explosion pipes," investigators reasoned that the diamond pipes might also carry coesite. The South African diamond pipes, however, yielded none. Some condition for its formation may not have been fulfilled. Perhaps silica was absent; at best the diamond fields are quite poor in the mineral.

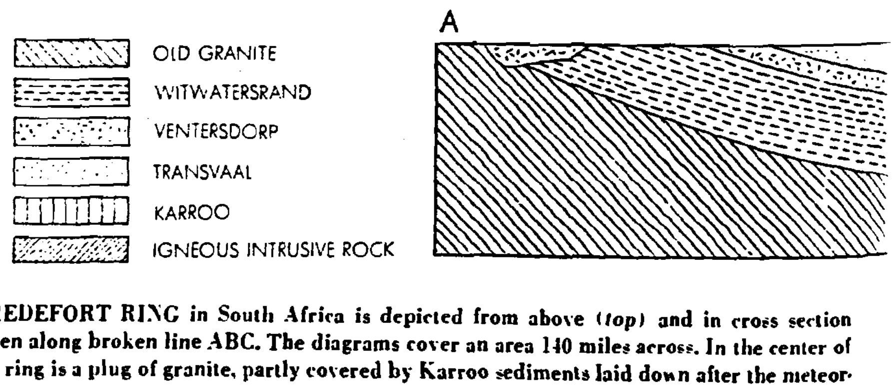
It happens that minute diamonds of the carbonado type have long been known to be present in the highly shocked meteoritic fragments from Barringer Crater. This circumstance prompted Shoemaker, Chao and B. M. Madsen of the U.S. Geological Survey to search the highly sheared and fused sandstone at Barringer Crater for coesite. Last year they found minute crystals of it in intimate association with lechatelierite, or silica glass.

Shoemaker and Chao next looked for coesite in the "cryptovolcanic" Ries Kessel (Giant Kettle), an ancient basin formation 17 miles across located 26 miles from the Steinheim Basin in southern Germany. The supposed evidence for volcanism there is suevite, a rock that resembles the pumiceous tuff that comes from volcanoes. In the Ries Kessel suevite Shoemaker and Chao found coesite, once again associated with a high-temperature silica glass. Suevite therefore appears to be an "impactite" rather than a volcanic product, and the Ries Kessel is apparently an astrobleme. Shatter cones have not been found at the Ries Kessel, perhaps because they are buried in the central region, now covered by sediments deposited by the ancient lakes that once filled the basin. The Ries Kessel coesite is nevertheless indirectly associated with shatter cones, because geologists agree that the nearby Steinheim Basin is a twin structure formed at the same time and by the same process.

This year coesite was found with unusually large amounts of silica glass around the Wabar craters in the Empty Quarter of Arabia. These craters are undoubtedly "recent" impact sites; three decades ago an explorer collected fragments of the meteorites that struck there and they now rest in the British Museum of Natural History. As I was preparing this article, coesite was found in suevite-like rock at the Ashanti Crater. Still another coesite locality is the Teapot Ess Crater at the Nevada Proving Grounds of the Atomic Energy Commission, where the mineral was created by an atomic blast. The quick discovery of this mineral at these five sites is encouraging, particularly because the suspected sample must be transported from the field to the laboratory for examination by X-ray diffraction.

The search for coesite and shatter cones is now to be extended to other





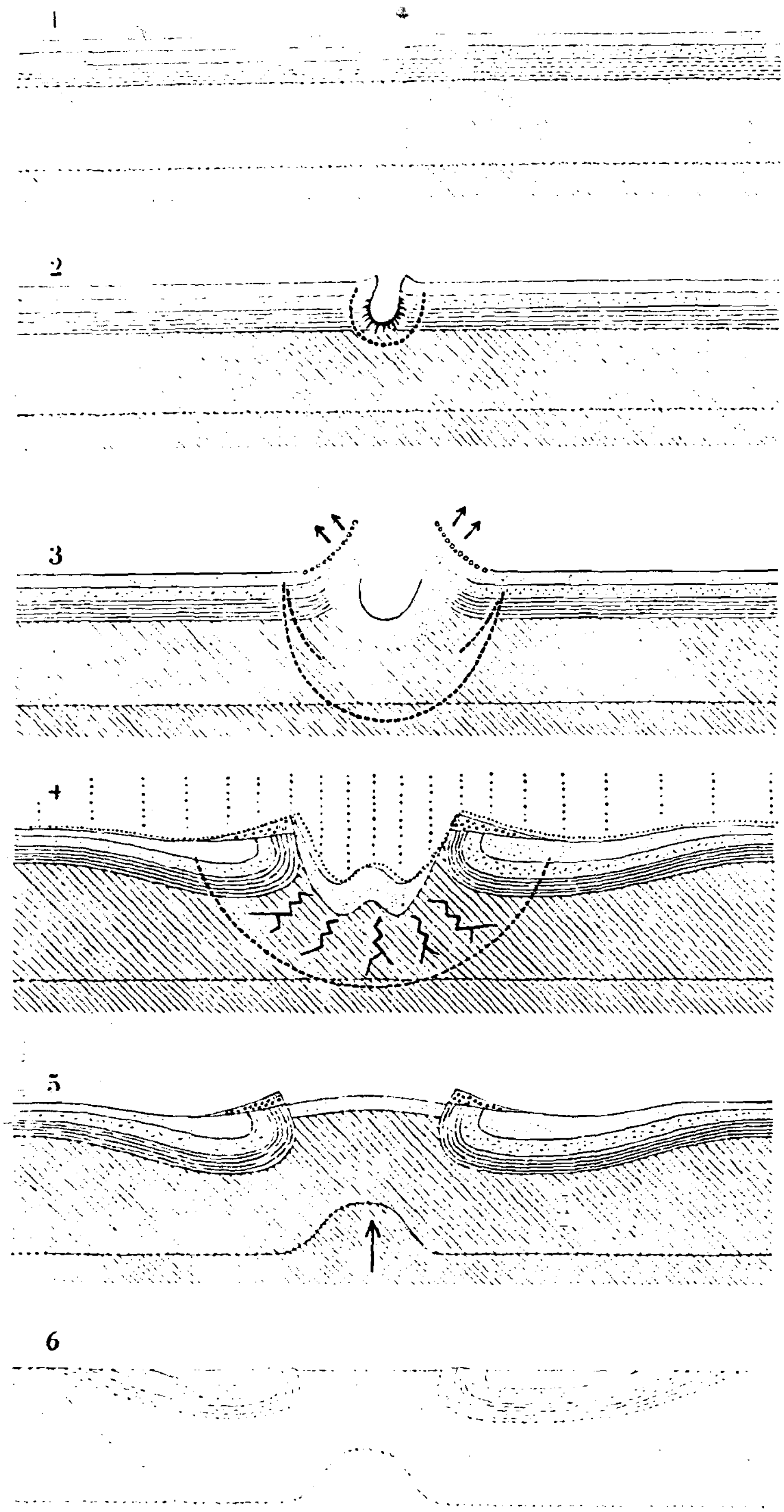
VREDEFORT RING in South Africa is depicted from above (*top*) and in cross section taken along broken line ABC. The diagrams cover an area 140 miles across. In the center of the ring is a plug of granite, partly covered by Karroo sediments laid down after the meteor-

putative astroblemes, including the fossil craters of Canada. Meanwhile, as geologists become familiar with the shatter cones, they will be able to recognize astroblemes even in sites deformed by later tectonic upheavals. If the location of the center of the impact is obscured at these sites, it may be difficult to find the shatter cones. But where the bull's-eye can be identified the shatter cones can be brought up in drill cores, as they have been at the Kentland and Wells Creek sites.

The creation of coesite and of minute [illegible] opens up the new field of "impact metamorphism." Meteorite impacts are natural "experiments" in ultrahigh pressures on a scale that can never be equaled in the laboratory. Doubtless geologists will soon unearth other pressure minerals through the study of astroblemes.

One puzzling mineral that is evidently the product of impact metamorphism is the tektite. Small masses of silica glass containing metallic oxides, tektites are strewed widely over several regions of the world and are known from rock strata as [illegible] as 40 million years. [illegible]hao has recently found minute nickel-iron meteorite spherules embedded in some tektites, proving that tektites are not the result of lightning, volcanism or other purely terrestrial events. Some investigators argue that they may have been splashed upward from meteorite impacts on the earth and are scattered at long distances from ground zero. I am among those who find evidence, in the molding and shaping of their surfaces, for the idea that tektites were ejected earthward from the moon's surface by meteorite

ite impact. It is surrounded by a collar of upturned and overturned rock strata. Around them lies a great ring syncline, much of it under the Transvaal stratum. At its outer edges, strata of the collar appear again. Heavy black lines are faults. Blank areas are regions for which data were not available. Tectonic processes, sedimentation and erosion have destroyed the original gigantic crater.



FORMATION OF VREDEFORT RING is shown in this sequence. An asteroid a mile in diameter *(1)* strikes the earth *(2)*, liquefies and turns partly to gas. Shock wave *(broken lines)* spreads out. At maximum crater development *(3)* the meteorite is a thin lining of the crater; debris flies off, rock strata peel back and shock wave spreads further, to be reflected back. Soon rocks recoil *(4)* to form a dome in the crater. Fallout settles slowly. Later viscous rock of earth's mantle pushes solid granite up into maw to form a plug *(5)*. The ring structure today *(6)* has been badly eroded but roots of ring remain as hills.

falls and that they were shaped into the droplike form in their fiery passage through the earth's atmosphere.

During the 20th century two great impact events have occurred, both in Siberia. One, at Tunguska, was probably the fall of a comet head. The other, at Sikhote-Alin in 1947, was the fall of a very large meteorite that disintegrated in mid-air, leaving more than 100 craters on the ground. The two events show that bombardment from space continues even today.

Like the Siberian events, all known meteorite impacts have occurred on land. But with the largest part of the earth's surface covered by water, it is inevitable that the majority of meteorites must have fallen into the sea. Delving into historical records, N. H. Heck of the U.S. Coast and Geodetic Survey has compiled a list of 270 tsunamis (so-called tidal waves) since 479 B.C. Earthquakes doubtlessly generated most of them, but a few could certainly have resulted from meteorites. The effects of a really large impact, like those that leave astroblemes, are terrifying to contemplate. A giant meteorite falling into the middle of the Atlantic Ocean could generate a wave 20,000 feet high that would overwhelm vast areas of the continents surrounding the ocean, sweeping over the entire eastern seaboard of the U.S. and across the Appalachians.

From modern theory on the origin of the solar system and study of the lunar craters, it seems that the major meteorite bombardment of the moon—and so of the earth—must have taken place three billion years or more ago, during the first half of the life span of the earth-moon system. Radioactive dating gives the oldest rocks of the continents an age of about three billion years. The tectonic and meteorological processes that molded the present surfaces of the earth must therefore have obliterated the scars of the early period, still so much in evidence on the moon. But the earth should retain a geological record of cosmic damage comparable to that indicated by the youngest of the lunar craters. These craters have associated ray systems—lanes of debris radiating from the center of impact. (The ray systems of older craters were presumably erased by "weathering" due to radiation and by later meteorite falls.) The near side of the moon displays about 130 of these in an area roughly equivalent to that of North America. So it seems reasonable to expect geologists someday to find something like that many astroblemes dotted across the continent.