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Fossil Glasses Produced by Impact of Meteorites, Asteroids and Possibly Comets with the Planet Earth*

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Summary

(to be translated into French and German)

In recent times one of the most intriging mysteries of geology has been the occurrence of aerodynamically-shaped glasses on five continents of the earth. These glasses under discussion are obviously not of fulguritic origin. Recent research indicates that these glasses known as tektites are the result of meteorite, asteroid, or possibly comet impact. Impact glasses, in general, differ from volcanic glasses in that they are lower in water content, have lower gallium and germanium contents, and are not necessarily in magmatically unstable continental areas. These impactites may be divided as follows: (1) Glasses found in or near terrestrial meteorite craters. These glasses usually contain numerous spherules of nickel-iron, coesite, chunks of partially melted meteoritic matter and even stishovite. Shattered or fractured unmelted minerals such as quartz are commonly present. Aerodynamic-shaping may or may not be present in this type. Examples are Canyon Diablo and Wabar Crater glasses. (2) Impact-glasses associated with craters with no evidence of meteoritic material in the glass or surrounding the explosion site. The only known example is

*This work was supported by National Aeronautics and Space Administration Research Grant NsG-57-60 Supplement 1-62.

glass associated with Aouelloul Crater in the Western Sahara Desert. (3) Impact-glasses containing little or no aerodynamic-shaping and not associated with any known crater. These glasses usually contain some unmelted fractured quartz, coesite and high-melting detrital minerals. In one case crystobalite is present. The two known examples are Darwin glass from Tasmania and Libyan Desert glass. (4) Aerodynamically-shaped green to brown glasses containing only silica-glass and Ni-Fe spherules as inclusions. These glasses are not associated with nearby craters. They occur in strewn fields and are known as tektites. The author has associated two of these strewn fields with known asteroid or comet craters and from studies of the glass compositions in other strewn fields predicts the locations of two additional asteroid craters.

Introduction

Most pleistocene explosion craters produced by meteorite impact have glass occurring in the vicinity of the crater. Even the Ries Kessel, which is about fifteen million years old,[1] has abundant glass present.

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[1]W. Gentner, H. J. Lippolt and O. A. Schaeffer, Das Kalium-Argon-Alter einer Glasprobe vom Nördlinger Ries, A. Naturforschg. In Press (1962).

However, glass has not been found in fossil craters of great age even though the meteorite impacted in silicate material such as the Canadian Shield. Many fossil craters in the United States are in carbonate rock, so no relict glass could be expected.

It has been recently shown that glass can be produced by meteorite impact in soil.[2] One would expect the impact of meteorites in desert areas

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[2]H. P. Schwarcz, A Possible Origin of Tektites by Soil Fusion at Impact Sites, Nature, 194, 8 (1962).

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to produce abundant glass, as is the case. In one instance, at least, glass is present and the crater lost, probably buried under the desert sand.

Gold,[3] in considering lunar impact craters, suggests two mechanisms

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[3]T. Gold, The Lunar Surface, Monthly Notices, Roy. Astron. Soc., 115, 585 (1955).

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for production of glass. The first, conduction, would produce only a thin layer of melting below the vaporization surface in the short time during which heat is supplied at impact. This does not exceed a few centimeters for any material. The other mechanism Gold suggests is distribution of heat by shock wave through the material. The most favorable material suggested is sand, as its final density as fused silica at the end of the pressure cycle is much greater than before the pulse; namely, a large change in internal energy takes place. Most of the energy upon meteorite impact would go into vaporization of the meteorite and its surroundings; most of the remainder would go into shattering and pulverizing the surroundings and only a little into melting. The melting process requires a high degree of uniformity in the conditions and a small temperature range.

De Carli and Jamieson[4] have produced glass from quartz by shock pressure

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[4] P. S. De Carli and J. C. Jamieson, Formation of an Amorphous Form of Quartz under Shock Conditions, J. Chem. Phys. 31, 1675 (1959).

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of 600 kilobars at a temperature no greater than 1400° K during shock. Amorphous silica was also produced at 360 kilobars and at most 870° K. During transformation, silica becomes the denser phase. It is possible that the production of the high pressure silica paramorphs, coesite and stishovite, by meteorite impact involves a metastable glass phase.

In addition to glasses found in or around meteorite craters and glasses containing little aerodynamic shaping which may be near undiscovered meteorite craters, there are aerodynamically shaped glasses not found near meteorite craters; these glasses (tektites) will be discussed only briefly here because of the large literature involved. Much more research has been done on tektites than all other glasses discussed in this paper.

Glasses Found in or Near Terrestrial Meteorite Craters.

Probably large amounts of the glass produced on impact are thrown out of the crater and will be found on the rim or beyond. In ancient eroded craters, this glass would be largely or completely lost. Perhaps in very old craters, such as the Precambrian Holleford Crater in Ontario, the glass has devitrified. For these reasons, all of the craters discussed here, with one exception, are pleistocene and most likely relatively recent.

The smallest explosion crater where glass has been reported is Campo del Cielo in Argentina. The largest crater in this group is 78 meters by 65 meters. One, 56 meters in diameter and 5 meters in depth, has been excavated and transparent glass found. No scientist competent in the glass field has studied or even examined glass from this crater. Spencer[5] suggests

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[5]L. J. Spencer, the Campo del Cielo Craters, Geogr. Journ., London, 81, 237 (1933).

That "This transparent glass, if examined, would most probably prove to be silica glass."

Canyon Diablo Crater (Meteor Crater) in Arizona is the best known crater in the world and is one of the tourist attractions of Arizona. This crater is 1,265 meters in diameter and is of comparatively recent age. About 30 tons of meteorite fragments have been recovered around the crater. Core drilling has shown that the crater is underlain with fused and partially fused rock and meteoritic material dispersed in glass. It was in pumice glass from this crater that both natural coesite and stishovite were found by Chao and co-workers at the U. S. Geological Survey indicating that the shock wave pressure at impact of the coarse octahedrite meteorite was in excess of 100 kilobars. The presence of pumice glass produced from the local sandstone may indicate that the glass was formed below the water table at the time of impact, the resulting steam producing the frothy glass. There are some aerodynamically-shaped pieces of glass found, in many cases enveloping a piece of shocked sandstone.

At Odessa, Texas, are three small craters, the largest, 162 meters in diameter, which were probably produced by portions of the same meteorite as that causing Canyon Diablo Crater. This supposition is based on the fact that the meteorite fragments found at Odessa are identical to those found at

Meteor Crater, Arizona, both being coarse octahedrites. There is no definite record of any glass having been found at the Odessa Craters.

Near Henbury Cattle Station in the McDonnell Ranges, Central Australia, a group of thirteen craters were discovered in 1931. The largest crater was produced by at least two impacting bodies as it is not circular but 200 by 110 meters. In crater 13, 9 meters in diameter, 441 lbs. of iron meteorite were found buried. This was the first time that a considerable mass of iron was found in a crater. The iron is a medium octahedrite. Impact glass was found north of the main crater which is in sandstone and slaty rock. The glass consists of dark brown to black cellular masses containing magnetic spherules. According to Spencer,[6] some pieces are sintered fragments of

[6]L. J. Spencer, Meteoric Iron and Silica-Glass from the Meteorite Craters of Henbury (Central Australia) and Wabar (Arabia), Minerol. Mag. 23, 387 (1933).

sandstone with the bedding planes curved and crumpled. The largest piece of Henbury glass mentioned by Spencer is a piece 10 X 10 cm. His paper reports 7.26 per cent as the nickel content of the meteorite and 0.28 per cent as the NiO content of the glass.

Scoriaceous rock collected by H. H. Nininger 1/4 to 3/4 mile east of the main crater was examined by the writer. It consisted of brown earth and blackened material. After dissolving 0.9 gm. in 1:1 hydrochloric acid containing 5 per cent hydrofluoric for 24 hours, a residue of 0.3 gm. was obtained. This consisted of colorless lechatelierite of the elongated, twisted shapes, as seen in tektites (See Fig. 7) and angular quartz. Many crystal grains are present which appear optically to be coesite; however, X-ray identification was negative.

Arch M. Reid of this laboratory has also studied Henbury glass and found quartz, limonite, zircon and a few grains optically similar to coesite after all glass had been dissolved away by treatment with an HF-HNO_3-HCl mixture for 50 hours. An X-ray powder diffraction study showed quartz and zircon to be present. Coesite was absent. The coesite-like mineral is probably a mica or clay according to Reid. Further search of shocked material from Henbury Craters needs to be made before concluding coesite was not formed by the impact.

Table One gives analyses of Henbury black glass, sandstone and an analysis of the medium octahedrite (iron) meteorite producing the craters. It is difficult to understand the high titania content of the glass reported in the analysis. Ehmann[7] reports 520 p.p.m. nickel and 44,200 p.p.m. iron in Henbury glass with a Ni/Fe ratio of 0.0120 whereas Preuss gives 940 p.p.m. nickel and 47,000 p.p.m. iron for a Ni/Fe ratio of 0.02. Using the analyses of Hey for the meteorite[6] in Table One, one gets a Ni/Fe ratio of 0.078. In the process of vaporization of the meteorite, capture of nickel-iron spherules, and dissolution in the glass, nickel seems to be lost. When one corrects for the original iron content of the sandstone from which the glass was made, the ratio of Ni/Fe using Ehmann's data for the glass is 0.025; using Preuss's data, it is 0.036. The possibility that nickel is fractionated in the vaporization of meteorites deserves further study.

According to recent work of Goel and Kohman,[8] the Henbury Craters are

[7] W. D. Ehmann, The Abundance of Nickel in some Natural Glasses, Geochim. et Cosmochim. Acta 26, 489 (1962).

[8] P. S. Goel and T. P. Kohman, Cosmogenic Carbon-14 in Meteorites and Terrestrial Ages of "Finds" and Craters, Science 136, 875 (1962), and Nuclear Chemistry Research at Carnegie Institute of Technology, 1961-62, Progress Report, June 1, 1962, p. 37.

Table One

Chemical Analyses of Henbury Glass and Sandstone (Ref. 6)

Element as Oxide	Henbury Black Glass	Henbury Sandstone	Element	Henbury Iron Meteorite
SiO_2	68.88	86.71	Fe	93.04
Al_2O_3	5.60	3.84	Ni	7.26
Fe_2O_3	8.46	2.84	Co	0.22
FeO	7.92	0.46	Cu	0.044
MgO	2.03	0.90	Cr	nil
CaO	2.51	1.00	Pt	trace
Na_2O	0.03	0.13	S	0.06
K_2O	1.43	1.15	Insoluble	0.06
MnO	0.05	0.005		
TiO_2	3.64	0.32		
NiO	0.28	nil		

4,700 years of age or less while the Odessa Craters are 6,300 years or older. Boxhole Crater is 5,400 ± 1,500 years old.

Lake Bosumtwi (Ashanti Crater) is an isolated lake in Ashanti province near Kumasi in Ghana. The lake is 8 kilometers in diameter lying in the bottom of a crater with a diameter of about 10.5 kilometers rim to rim. The inner slopes of this pleistocene crater are steep, and a continuous rim, 91 to 183 meters above the general ground level, encircles the crater. The depth of the crater from the lowest portion of the rim to the bed of the lake is 46 meters. The flat bottom of the lake suggests an explosion crater. No meteorite material has been found in the area, although abundant glass is present. Littler[9] and co-workers have discovered

[9] J. Littler, J. J. Fahey, R. S. Dietz and E. C. T. Chao, Coesite from the Lake Bosumtwi Crater, Ashanti, Ghana. Abstracts, 74th Annual Meeting, The Geological Society of America, Cincinnati, Ohio, Nov. 1961, p. 94A.

coesite in a small portion of breccia from this crater. These workers found twisted vesicular glass (N about 1.47) as inclusions in the prevalent glass (N about 1.507). Occurrence of glasses of varying refractive index in breccia and presence of coesite substantiate the suggestion of Maclaren[10] that this

[10] M. Maclaren, Lake Bosumtwi, Ashanti, Geogr. Journ, London, 78, 270 (1931).

is a meteorite crater. Only one small piece of material has been available in this country from Lake Bosumtwi. Detailed work awaits availability of additional research material.

The Ries of Nordlinger, Ries Kessel or Ries Basin has been shown by Shoemaker and Chao[11] to be a structure of impact origin. The crater is about

[11] E. M. Shoemaker and E. C. T. Chao, New Evidence for the Impact Origin of the Ries Basin, Bavaria, Germany, J. Geophys. Research 66, 3371 (1961).

28 kilometers in diameter and is a basin lying between the Franconian and Swabian plateaus in the south of Germany. A breccia called suevite is

scattered throughout the basin and contains glasses of varying composition even in a single specimen. Coesite and stishovite have been found in the sintered rocks in the suevite as well as lechatelierite. The presence of the two high pressure paramorphs of silica make a volcanic origin impossible for the Ries. Petrographic studies and chemical analyses of the glasses present at the Ries are now being undertaken at the U. S. Geological Survey.

Wabar Craters in the "empty quarter" of Saudi Arabia were discovered by H. St. J. B. Philby in February, 1932. There are at least two craters, one 100 meters in diameter and another 50 X 40 meters in diameter. During a visit in 1960, Dr. Virgil Barnes, of the University of Texas, found that the smaller crater had been completely filled with sand. This indicates that the craters are probably not too old. The meteorite producing the craters is a medium octahedrite containing 7.3% nickel. Figure 1 illustrates the black glass from Wabar Crater. The pieces show shaping by atmospheric friction and contain small magnetic spherules resulting from vaporization of most of the meteorite. Examples of this glass are shown in Figure 2. In addition to the black glass, there is a less abundant white, partially fused glass. Table Two gives a comparison of the chemical analyses of these two glasses taken from Spencer's work.[6] In comparing the analyses, it is evident that the white glass is produced by melting of the desert sandstone or sand. The temperature was great enough to volatilize some of the silica and enhance the alumina, etc. No nickel-iron from the meteorite seems to be present according to the analysis. However, in the case of the black glass, abundant nickel and iron are present in the glass. Ehmann[9] found 1270 p.p.m. of nickel and 54,200 p.p.m. iron present in the Wabar glass with a nickel-iron ratio of .023, whereas the ratio in the meteorite is 0.080 based on Hey's analysis given in Table Two. In order to compare the nickel and iron in spherules

Figure 1

Several small pieces of Wabar silica-glass collected by Dr. Virgil Barnes. The glass contains numerous bubbles and inclusions of nickel-iron spherules. Shocked, white sandstone inclusions are high in the high pressure silica paramorph, coesite.

Figure 2

A photomicrograph of a small piece of Wabar Crater glass containing several nickel-iron spherules. The large spherule has a diameter of 58 microns in one direction and 61 microns in another. The smaller spherule to the right of the large one is 21 microns in diameter. The spherule to the left is 17 microns in diameter. The remaining spherules range from 3 to less than a micron in diameter. These metallic spherules are shiny, and the surfaces are as fresh as when formed.

Table Two

Chemical Analyses of Wabar Glass and Sandstone (from Ref. 6)

Element as Oxide	Wabar White Glass	Wabar Black Glass	Wabar Sandstone	Element	Wabar Iron Meteorite
SiO_2	92.88	87.45	92.06	Fe	92.00
Al_2O_3	2.64	1.77	2.80	Ni	7.30
Fe_2O_3	0.23	0.28	0.60	Co	0.22
FeO	0.53	5.77	0.19	Cu	0.037
MgO	0.47	0.60	0.45	Cr	nil
CaO	1.46	1.90	1.19	Pt	trace
Na_2O	0.42*	0.39	1.03	S	0.11
K_2O	1.61*	0.58	1.04	Insoluble	0.20
MnO	0.01	0.01	0.01		
TiO_2	0.12	0.15	0.12		
NiO	nil	0.35	nil		

*Separation of alkalis probably inaccurate according to M. H. Hey, the analyst.

enclosed in the glass to the ratio in the meteorite, one needs to separate them and analyze them separately. The black glass will be difficult to analyze for dissolved nickel-iron because of the difficulty in separating all the minute spherules contained in it.

Impact-Glasses Associated with Craters with No Evidence of Meteoritic Material in the Glass or Surrounding the Explosion Site.

The tests that a crater is produced by impact of a metallic body are:

(1) quadratic relationship of depth to diameter of crater indicating it was produced by explosion.[12]

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[12] R. C. Baldwin, The Face of the Moon, The University of Chicago Press (1949) p. 128-153.

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(2) presence of rim composed of overturned strata and/or breccia and possibly glass and fragments of meteorite. All explosion craters of young age will have rims.

(3) association of nickel-iron meteorite fragments or nickel-iron spherules with crater. Large pieces of meteorite, if present, have always been found outside of an explosion crater and are probably arranged in a definite strewn-field of meteorite fragments.

(4) presence of breccia in crater.

(5) presence of silica-glass in breccia if crater is in silicate material. The glass and breccia may contain small pieces of partially melted meteorite as well as metallic spherules.

(6) The root structures of ancient craters may be exposed. These will show a central uplifted portion containing shatter cones and breccia. Structures of this type are not discussed in this paper, as no glass has been found in these ancient explosion structures as yet.

(7) presence of coesite[13] or stishovite[14] produced by high pressure

[13] E. C. T. Chao, E. M. Shoemaker, and B. M. Madsen, First Natural Occurrence of Coesite from Meteor Crater, Ariz., Science 132, 220 (1960).

[14] E. C. T. Chao, J. J. Fahey, J. Littler and D. J. Milton, Stishovite, A Very High Pressure New Mineral from Meteor Crater, Arizona. J. Geophys. Res. 67, 419 (1962).

shock wave on impact in addition to (1) and (4) and (5). Canyon Diablo, Wabar, Lake Bosumtwi, the Ries Kessel and Holleford craters have all yielded coesite.

The tests above are listed in this section to emphasize the mystery at present associated with Aouelloul Crater discussed in this section. All known meteorite explosion craters, with which a meteorite has definitely been associated, have been produced by metallic bodies. This is logical when one considers that non-metallic bodies would suffer space erosion to a much greater extent, and statistically more large-sized metallic bodies might be expected after erosion by space dust and even earlier during collisions in the asteroidal belt (if one accepts this region as the main source of meteorites).

However, there is always the possibility that compact silicate bodies large enough to produce an explosion crater still exist in space and occasionally collide with the earth. The well-known periodic meteor showers intersecting the earth's orbit are mute but colorful evidence that comets still in recent millenia have intersected the ecliptic in the earth's orbit; and, in some instances, the comet head must have impacted on the earth. It has recently been suggested by a Russian scientist that the Tunguska River event of June 30, 1908, in Yeniseisk, Siberia, was caused by the impact of a small comet.

Aouelloul Crater, 280 meters in diameter, is located in Mauritania in in the Western Sahara Desert at lat. 20° 15' N. and long. 12° 41' W. This explosion crater has abundant glass present with no evidence of meteoritic material having been found. Cassidy[15] has searched the area with a mine

[15] W. A. Cassidy, personal communication.

detector without locating any meteoritic material. The glass is so prevalent around the crater that even sand samples received from Cassidy have abundant fine splinters of glass present. This glass was, without doubt, formed by the forces producing the crater. Although no meteoritic material has been found in the glass, Ehmann[9] finds 260 p.p.m. of nickel and 14,000 p.p.m. iron for a Ni/Fe ratio of 0.019. This ratio is higher than that for Henbury glass and only slightly lower than that of Wabar glass.[6] It is very likely that traces of nickel-iron dissolved in the glass. No metallic inclusions have been found in this glass, as is the case with Henbury, Wabar and Meteor craters. These latter craters have meteoritic material associated with them however. The Ries glass and Lake Bosumtwi glasses have not as yet been closely enough examined to exclude the possibility of metallic spherule inclusions. Further study of Aouelloul glass may also yield enclosed spherules in the glass. However, thorough examination of several samples in this laboratory have yielded no positive results. Uneven streaks of ferric color are present in this bubbly glass. A. M. Reid of this laboratory has observed crystalline quartz grains to be present in this glass, confirming the earlier findings of Smith and Hey.[16] The relict quartz attests to its short time at

[16] W. C. Smith and M. H. Hey, The Silica-Glass from the Crater of Aouelloul, Bull. Inst. Francais d'Afrique noire, 14, 762 (1952).

high temperature. It was most probably produced by shock-impact with little or no melting. Analyses[16] of Aouelloul glass and sandstone are given in Table Three.

Table Three

Chemical Analyses of Aouelloul Glass and Sandstone (Ref. 16)

Element as Oxide	Glass	Glass	Glass Average	Sandstone	Sandstone	Sandstone Average
SiO_2	86.92	86.10	86.51	95.30	92.00	93.65
Al_2O_3	6.47	5.05	5.76	1.85	2.75	2.30
Fe_2O_3	1.16	1.45	1.30	0.45	0.75	0.60
FeO	1.72	1.45	1.58	0.05	0.05	0.05
MgO	0.32	1.50	0.91	0.40	0.90	0.65
CaO	0.55	0.90	0.72	0.80	0.70	0.75
Na_2O	0.23	0.05	0.14	0.20	0.20	0.20
K_2O	2.05	2.05	2.05	0.10	1.00	0.55
MnO	0.04	0.05	0.04	0.02	0.06	0.04
TiO_2	0.49	0.60	0.54	0.55	0.45	0.50
NiO	0.019	0.025	0.022	nil	nil	nil

The increase in ferric ion as well as total iron and the presence of nickel in the glass and not in the sandstone indicates clearly that nickel-iron has been added to the sandstone during glass formation. The large increase of potassia in the glass is hard to understand, as one would expect to have volatilization of potassia during the formation of the glass.

Further field work at this crater is needed in order to understand the nature of the object producing it.

Impact Glasses Containing Little or No Aerodynamic-Shaping and Not Associated with any Known Crater.

Tektites as a group will be excluded from this section although there are shapeless tektites found in Cambodia, Viet Nam, Laos and Thailand along with the better-known aerodynamically-shaped tektite glasses according to a recent investigation.[17]

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[17]K. Pitakpaivan and V. E. Barnes, Origin of Muong Nong-Type Tektites, Abstracts 43rd Annual Meeting, American Geophysical Union, April 1962. p. 111.

Darwin glass was first brought to the attention of the scientific world by Loftus Hills,[18] a geologist in Tasmania. It was first found on Ten-Mile

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[18]L. Hills, Darwin Glass, Tasmania Geological Survey Record No. 3 (1915) p. 1-9.

Hill in the Mt. Darwin range on the surface or in the upper few centimeters of detrital material. The glass occurs on the hill between the altitudes of 260 and 380 meters above sea level. No glass was found above 380 meters at this location. At other locations, the glass was never found above this altitude. However, it occurs at Flannagan's Flat, west of Mt. Darwin at about 150 meters above sea level. No recent acid volcanic rocks are present in Tasmania younger than tertiary age, and none are near the areas where the Darwin gla was found. It has been suggested that the occurrence only at 400 meters or below is due to the glaciation at higher altitudes in early pleistocene time.[19] It is assumed that the glass was thrown onto the glacier where it

[19]T. W. E. David, H. S. Summers and G. A. Ampt, The Tasmanian Tektite--Darwin Glass, Proc. Roy. Soc. Victoria 39 (N. S.) II, 167 (1927).

was gradually transported to the ice margin. A piece of Darwin glass weighing 20.9 grams is shown in Figure 3. Table Four gives two analyses for Darwin glass.

Recently we have discovered coesite to be present in Darwin glass, which indicates it is produced by meteorite or comet impact.[20] The presence of

[20]A. M. Reid and A. J. Cohen, Coesite in Darwin Glass, J. Geophys. Research 67, 1654 (1962).

tourmaline[20] and quartz indicates that it is from terrestrial material. A crater or eroded remains of one should exist somewhere near Mt. Darwin in Tasmania to account for the presence of this impact glass.

The evidence for the terrestrial origin of Libyan Desert silica-glass has been discussed in a recent paper.[21] This glass was discovered in 1932

[21]A. J. Cohen, The Terrestrial Origin of Libyan Desert Silica-Glass. Phys. Chem. Glasses 2, 83 (1961).

by P. A. Clayton during an expedition into the southwestern corner of Egypt. The glass occurs in an oval area, between latitudes 25° 2' N and 26° 13' N and longitudes 25° 24' E and 25° 55' E, measuring about 130 km. N-S and 53 km. E-W. The glass was found on the surface or embedded in reddish, sandy loam. None was found on the dunes except that transported by early man as evidenced by its having been chipped. It was found that the germanium contents of the sands and silica-glass are similar. The red earth is too high in gallium to be a source of the glass.[21] Table Five gives analyses of the

Figure 3

A specimen of Darwin glass weighing 20.9 grams. This is the largest single piece known to the author.

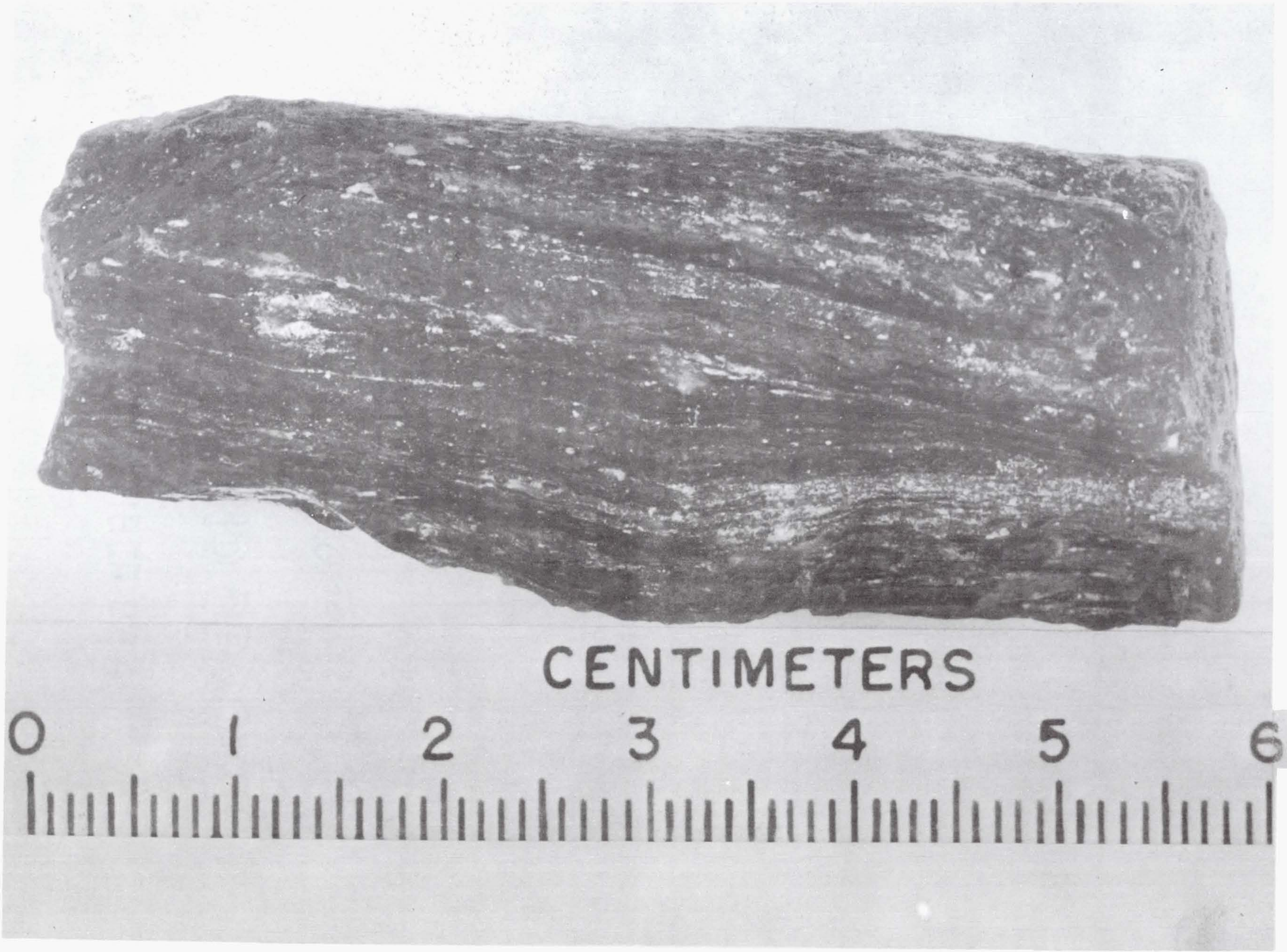

Table Four

Chemical Analyses of Darwin Glass (Ref. 19)

Element as Oxide	Smoky Grey, Full of Vesicles	Pale Greenish Grey, Many Vesicles
SiO_2	86.34	87.00
Al_2O_3	7.82	8.00
Fe_2O_3	0.63	0.19
FeO	2.08	1.93
MgO	0.92	0.82
CaO	0.05	nil
Na_2O	0.15	0.14
K_2O	0.87	0.99
MnO	nil	nil
TiO_2	0.52	0.51
ZrO_2	0.11	tr (?)

silica-glass taken from the work of L. J. Spencer.[22] Figure 4 illustrates a

[22] L. J. Spencer, Tektites and Silica-glass, J. Mineral. Soc. 25, 425 (1939).

piece of silica-glass from the Smithsonian Institution collection. The dark striations on the left side trailing downward and to the right are spherical inclusions of cristobalite. Angular grains of quartz are also present.

The author earlier concluded that the Libyan Desert silica-glass was produced by melting of the desert sand. The large size of the glass fragments and their lack of aerodynamic shaping would indicate a crater in the vicinity of the silica-glass area. It may be completely covered with drift sand. The low nickel content of the Libyan glass, 3.3 p.p.m. according to Ehmann,[23]

[23] W. D. Ehmann, Nickel in Tektites by Activation Analysis, Geochim. et Cosmochim. Acta 19, 149 (1960).

suggests that a friable stony meteorite or comet produced the glass. The impact was such that most of the melting was near the surface, as it appears that the glass was produced from the desert sand and not the red Nubian sandstone. If Libyan Desert silica-glass were produced by a nickel-iron meteorite, one would expect glass similar to that found at Wabar Crater.

Aerodynamically-Shaped Green to Brown Glasses Containing Only Silica-Glass and Ni-Fe Spherules as Inclusions.

This section includes a brief discussion of the fascinating glasses known as tektites. Figure 5 illustrates the five general types or shapes found in tektites from Czechoslovakia, known as moldavites. These are boats spheroids, ablate spheroids, droplets and hollow cylinders. As can be seen in Figure 5, the moldavites are transparent and light green in color. This color is due to the low ferrous iron content.

Tektites are natural silica-glasses high in both silica and alumina. Their compositions are similar to igneous rocks from which alkali has been

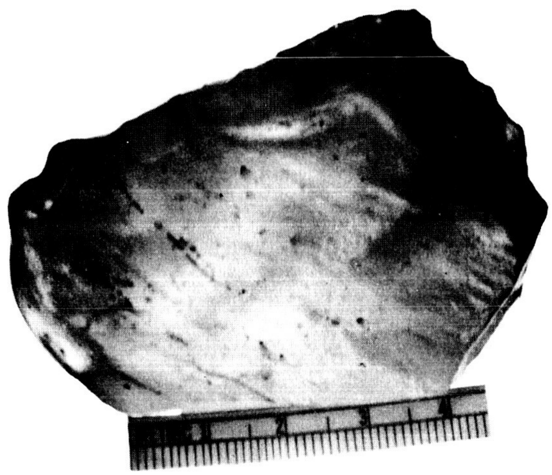

Figure 4

A specimen of Libyan Desert silica-glass showing rows of spherules of cristobalite inclusions from upper left to lower right.

Figure 5

Moldavites, tektites from Czechoslovakia, are almost 15 million years old. These green glasses are found in the shapes above from left to right and top to bottom: boat shape (rare), spheroid (common), droplet (fairly common), ablate spheroid (common) and portion of a hollow cylinder (rare).

Table Five

Chemical Analyses of Libyan Desert Glass (Ref. 22)

Element as Oxide			
SiO_2	97.97	98.44	97.58
Al_2O_3	0.91	0.49	1.54
Fe_2O_3	0.54	0.53	0.11
FeO	0.24	-	0.23
MgO	0.01	0.01	trace
CaO	-	0.30	0.38
Na_2O	0.33	-	0.34
K_2O	0.02	-	nil
MnO	-	-	trace
TiO_2	0.21	0.25	0.21
NiO	0.032	0.016	trace

vaporized. The temperatures reached were so high as to transform most of the ferric to ferrous iron. Their low water content makes a volcanic origin impossible. The tektites are of at least three different ages. The oldest are found in Texas and Georgia in the United States, and one has been found at Gay Head on Martha's Vineyard, Massachusetts. The American tektites all date between 33 and 35 million years old. Compositions of three North American tektites are given in Table Six. The high silica-high alumina contents account for the stability of these glasses through tens of millions of years. The moldavites are almost 15 million years old. It has been suggested that these tektites were produced by the asteriod or comet producing the Ries Kessel and thrown into Czechoslovakia.[24] This

[24] A. J. Cohen, A Semi-Quantitative Hypothesis of Tektite Origin by Asteroid Impact, J. Geophys. Research 66, 2521 (1961).

hypothesis was greatly strengthened by the age dating of Ries Kessel impact glass[1] which was found to have the same age as the moldavites by potassium-argon dating. The Ivory Coast tektites have been related to Lake Bosumtwi Crater in Ghana. Confirmation of this suggestion awaits dating of the Ivory Coast tektites and Bosumtwi impact glasses.

All tektites other than the moldavites, the North American and the Ivory Coast tektites are about 610,000 years old.[25] These younger tektites

[25] W. Gentner and J. Zähringer, The Potassium-Argon Ages of Tektites, J. Geophys. Research 65, 2492 (1960).

are found widely scattered in Southeast Asia including Thailand, Cambodia, Laos, North and South Viet-Nam, Hainan Island, Tan-Hai Island, Philippine Islands, Billiton Island, Java, Borneo, etc. It has been recently suggested that all these tektites may result from an asteroid impact in southeastern Thailand.[26]

Table Six

Chemical Analyses of Three North American Tektites

Element as Oxide	Martha's Vineyard, Mass.[27]	Empire, Georgia[27]	Muldoon, Texas[28]
SiO_2	80.6	80.54	81.31
Al_2O_3	11.3	11.21	10.96
Fe_2O_3	0.4	0.33	0.15
FeO	2.2	2.40	2.29
CaO	0.7	0.61	0.50
MgO	0.7	0.65	0.53
Na_2O	1.1	1.16	1.50
K_2O	2.4	2.38	2.17
MnO	0.05	0.05	0.03
TiO_2	0.5	0.43	0.53

[27] R. A. Clarke, Jr. and M. K. Carron, Comparison of Tektite Specimens from Empire, Georgia and Martha's Vineyard, Massachusetts, Smithsonian Miscellaneous Collections 143 No. 4, 1 (1961).

[28] V. E. Barnes, Significance of Inhomogeneity in Tektites, Int. Geol. Cong. Report of 21st Session Norden XIII, 328 (1960).

[26] A. J. Cohen, Asteroid-Impact Hypothesis of Tektite Origin III. The Southeast Asian Strewn Fields, COSPAR, Third International Space Science Symposium, Washington, In Press, May 1962.

In addition to the Southeast Asian tektites, there are large numbers of tektites of the same age covering about the southeastern two-thirds of the Australian continent. These tektites have undergone two periods of melting, one upon their formation by impact and the second upon re-entry into the atmosphere. Figure 6 shows an australite that was found two and a half miles east of Port Campbell township, Victoria. The front side shows a spiral figure melted into the glass upon flat re-entry. The glass was probably rotating slightly. The back side of the australite shows a flange of glass that flowed back after being melted by friction with the atmosphere. The flange surrounds the original portion of the sphere. It has been suggested that the origin of australites is a crater in Antarctica.[29]

[29] A. J. Cohen, Asteroid-Impact Hypothesis of Tektite Origin, II. The Australian Strewn Fields, Program, Forty-Third Annual Meeting, American Geophysical Union, Washington, April, 1962, p. 112.

For many years, the only inclusions known in tektites were silica-glass and other glass inclusions forming separate phases in the tektite glass groundmass. Figure 7 is a shadowgraph of a polished section of an Ivory Coast tektite. Inhomogeneity is observed in the glass matrix as well as numerous small elongated bubbles. In addition, several wiggly inclusions of lechatelierite are seen. These are probably grains of fused quartz. It is probable that tektites are transformed from crystalline to amorphous solids by the shock wave of the impacting body. When the pressure becomes low enough, the amorphous solid then melts while being ejected from the site of impact.

Recently, metallic spherules have been observed in tektites from the

Figure 6

Australite (tektite) showing two periods of melting. A sphere of glass produced on asteroid (or comet) impact is thrown out of the atmosphere. Upon re-entry, the leading side melts, giving spiral shape (on left). The back side (on right) shows flange of secondary glass surrounding original sphere. This tektite has about half of the flange missing. Scale is in centimeters.

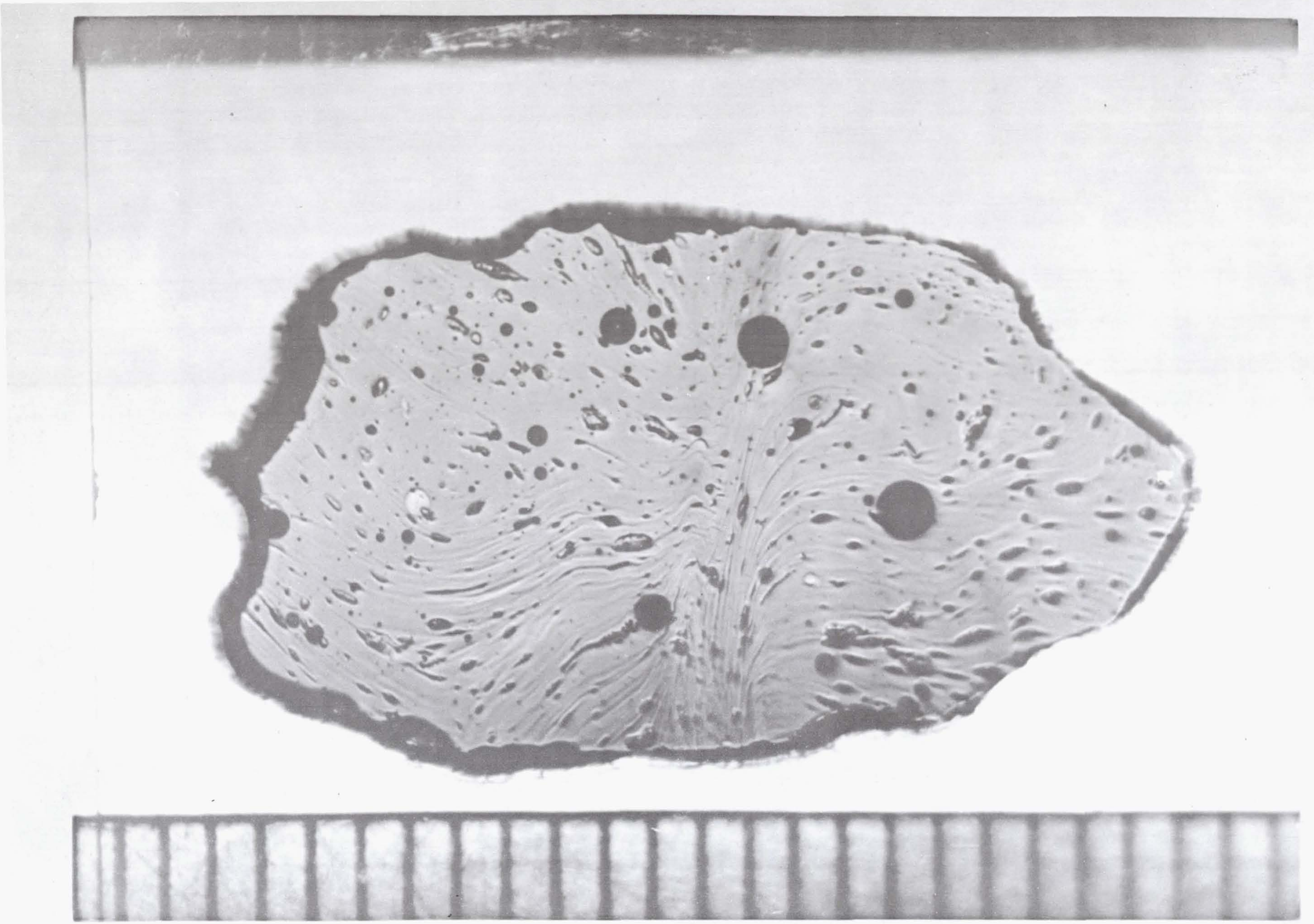

Figure 7

Shadowgram of a section cut through the center of an Ivory Coast tektite. The scale divisions are in millimeters.

Isabela district of Luzon in the Philippines.[30] The authors of this paper

[30] E. C. T. Chao, I. Adler, E. J. Dwornik, and J. Littler, Metallic Shperules in Tektites from Isabela, Philippine Islands, Science 135, 97 (1962).

suggest that this is evidence that tektites were produced by asteroidal or meteoritic impact in siliceous medium. Since only the tektites from Isabela have been known to contain iron-nickel spherules and the nickel contents of the spherules are rather low, there is a strong possibility that the spherules were formed from the ionically bound iron and nickel in the original minerals from which the tektites were produced. The tektite glasses appear to have been formed under reducing conditions; and, in this event, it would not be unusual to reduce some of the iron and nickel to the metallic state. Space does not permit a more thorough discussion of the tektite problem in this paper.

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Mr. James Nagle of the Pittsburgh Plate Glass Company, Glass Research Center, is thanked for taking the picture shown in Figure 7.

Table 7. Impact Crater Glass

Crater	Location	Age/y.	Impacting Body	Glass	Solid Inclusions	Aerodynamic Shapes Present	Ratio Ga/Ge
Aouelloul	Adrar, Western Sahara	-	Unknown, no iron meteorite fragments	Compact lumps	Lechatelierite, no elemental Ni-Fe strained crystallites	No	7
Canyon Diablo	Coconino Co., Arizona	-	Iron meteorite; coarse octahedrite	Pumice and compact	Coesite, stishovite and elemental Ni-Fe present	Yes	3
Henbury	McDonnel Ranges, Central Australia	-	Iron meteorite; medium octahedrite	Compact and scoriaceous	Elemental Ni-Fe present; lechatelierite, quartz, zircon and limonite in scoriaceous earth	Yes	-
Lake Bosumtwi	Ghana, Africa	-	Unknown	Glass in breccia, several types	Coesite	?	-
None	Libyan Desert, Egypt	-	Unknown	Libyan Desert silica-glass	Cristobalite and lechatelierite, no elemental Ni-Fe, some Fe^{++}	Slight to No	1.5-1.6
Nördlinger Ries	Swabia, W. Germany	Miocene	Undiscovered	Yes	Coesite, stishovite, several types of glass	?	-
None	Mt. Darwin, Tasmania	-	Unknown	Darwin glass	No elemental Ni-Fe coesite and tourmaline	No	4
Wabar	Rub' al Khali, Arabia	-	Iron meteorite; medium octahedrite	Sinter, blue-colored in some specimens	Coesite, elemental Ni-Fe present	Yes	-
Tektites possibly from Lake Bosumtwi	Ivory Coast	Possibly 0.6×10^6	Unknown	Dark brown transparent	Lechatelierite	Yes	28
Unknown (tektites)	East Indies, S. E. Asia and Philippines	0.61×10^6	Unknown	Dark brown transparent	Lechatelierite and Ni-Fe spherulites	Yes	Range 14-45 Average 25
Tektites possibly from Nördlinger Ries	Czechoslovakia	15×10^6	Unknown	Light to dark green transparent	Lechatelierite	Yes	Range 36-123 Average 76
Unknown (tektites)	Georgia, Texas and Martha's Vineyard, U. S. A.	$33\text{-}35 \times 10^6$	Unknown	Light to dark green to brown transparent	Lechatelierite	Yes	42