ARTICLES

ANOMALOUS AGES FOR METEORITE IMPACTS AND TEKTITES

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Impact craters in the fossil record are intriguing, but even more so is the dating associated with them. The author evaluates some of these data.

With the advent of the space age and exploration of meteorite impact sites on the moon (Short 1975), an intensified search has ensued for similar impact structures on the earth. In 1968 a list of 52 craters of meteorite or comet impact had been verified, and by 1971 the list had jumped to 62, not including seven others from the U.S.S.R. (French & Short 1968, p 256-257; Millman 1971; Zotkin & Tsvetkov 1970). Subsequent to these listings, reports from Russia called to light the two largest terrestrial craters identified to date, Ishim and Popigay impact structures, with diameters of 350 km and 70-80 km respectively (Masaytis et al. 1972; Zeylik & Seytmurdtova 1974). Very recently the discovery of the world's largest known Quaternary crater was announced (Dietz & McHone 1976). Located in Siberia some 600 km from the nearest recent volcanoes, its nearly perfect circularity 18 km in diameter has been studied both by satellite and ground observation. The catalog of Canadian craters of confirmed meteoritic origin has been brought to 21 with the recent discovery of Haughton Dome on Devon Island (Robertson & Mason 1975). Several U.S. impact structures have been suggested over the years: Meteor (Barringer) Crater, Arizona (Figure 1); Kentland structure, Indiana; Japhtha Knob, Kentucky; Wells Creek Basin, Tennessee; Serpent Mound, Ohio; and Crooked Creek, Missouri (Middlehurst & Kuiper 1963). More recently, similar structures have been identified totally subsurface through drilling operations in the Williston Basin on the U.S.-Canadian border (Sawatzky 1975).

During the 1960s it was sometimes heatedly debated whether such structures were volcanic or meteoritic in origin. The most outstanding proponent of their extraterrestrial origin has been R.S. Dietz, who proposed

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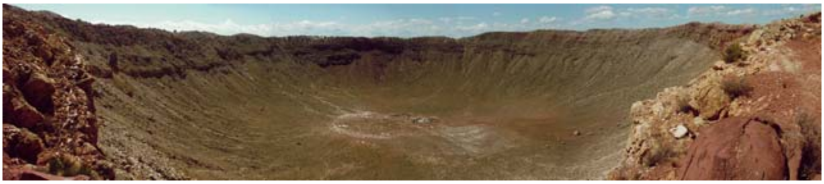

FIGURE 1. Panoramic view of Meteor (Barringer) Crater near Winslow, Arizona. This crater is 1.26 km in diameter and 174 m deep.

the term “astrobleme” (star wound), to describe them (Dietz 1963). One of the main proponents of their endogenetic origin was the late Walter Bucher, who identified them as “cryptovolcanic structures” (Bucher 1964).

The true meteoritic (or perhaps cometary) origin of these enigmatic structures has been established on the basis of several criteria. The most obvious criterion is the presence of shatter cones, conical fractures with diverging striations along the length of the cone. Orientations of the cone apices were originally in the direction of the impact object and thus served as indicators of the amount of tilt in the beds subsequent to impact, some beds even overturning (Manton 1965; Howard & Offield 1968). Many shatter-coned astroblemes have been identified since Dietz listed 17 examples (Dietz 1968). While shatter cones are easily visible to the naked eye, other effects of shock can be observed only through microscopic and X-ray studies, such as shock deformation lamellae in quartz (Carter 1965; Engelhardt & Bertsch 1969).

Two other criteria of shock impact are both high-pressure polymorphs of silica, coesite and stishovite, which can be produced in the laboratory only under extremely high pressures and fairly high temperatures (Stoffler 1971). The presence of coesite, which can be formed at pressures of 425-500 kilobars and temperatures near 1000°C, has confirmed the meteoritic origin of Lake Wanapitei Crater in Ontario (Dence et al. 1974) as well as other sites (Cohen et al. 1961). Other specialized types of melted rocks, suevite and pseudotachylite, are also key indicators of meteorite impacts (Dennis 1971; Wilshire et al. 1971).

Lunar exploration has confirmed another unique feature of astroblemes, whether terrestrial or lunar; namely a central uplift area which occurs only in the larger impacts (Cohen et al. 1961). This uplift can be easily observed in such confirmed impact sites as the Wells Creek Basin, Tennessee, where Ordovician strata have been raised 750 m, and the Sierra Madera of Texas, where Permian rocks have been uplifted 1200 m (Wilshire & Howard 1968). Associated with central uplift is the actual forcing of adjacent strata inward and upward accompanied by intense brecciation of the uplift area (Wilshire et al. 1971).

The dating of the meteorite impact events is one of the most intriguing aspects of this study, since it has application in determining the frequency of meteorite impacts both on earth and on the moon (Baldwin 1971). The tremendous pressures (425-500 kilobars with coesite) and the high temperatures (1000°C with coesite and 400° with stishovite formation) result presumably in a resetting of the potassium-argon and the fission-track radiometric clocks.

Examples of the resetting of the clocks are numerous. The Charlevoix structure, Canada, has K-Ar ages of 372 million years (m.y.) and 342 m.y. for impactites and 335 m.y. for pseudotachylites. Impactites and pseudotachylites are unique rock types that are good indices of impact. The rubidium-strontium age of the same rocks is 1280 m.y., suggesting that the Rb-Sr clock was unaffected by the impact (Rondot 1971). Mistastin Lake, Labrador, shows a K-Ar age of 202 m.y. for shocked rocks and 1340 m.y. for an area outside of the shock zone (Taylor & Dence 1969). In Mauritania, the Tenoumer Crater has a vast age gap between shocked and unshocked rocks. The K-Ar ages of unshocked Precambrian basement rocks are 2010, 1770, and 1820 m.y., while the shocked rocks that were melted by impact show K-Ar ages of 2.4, 2.6, 4.2 and 9.2 m.y. (French et al. 1970), a reduction in magnitude of up to 10^3. The Rb-Sr clock for the same basement rocks reads 2400 and 2440 m.y. while for the shocked rocks it shows slightly reduced ages of 2000 and 1800 m.y.

In rare cases two different radiometric clocks have been reset synchronously. The Gosses Bluff structure, Australia, has the main earmarks of meteorite impact (shatter cones, suevite, quartz lamellae, central uplift). The dating of sanidine, which is argon retentive, in the central uplift region shows a K-Ar age of 133 m.y. (Milton et al. 1972). A drill hole has uncovered Precambrian rocks at the base giving Precambrian ages (greater than 600 m.y.) by the fission-track method, while rock from the baked zone melted by the meteoric impact yielded a fission-track age of 130±6 m.y. (Milton et al. 1972).

In Germany the Ries-Kessel Crater has the key indices of shock (suevite, coesite, shatter cones) as well as the additional evidence of scattered erratics and glass bombs. One erratic block about 1000 kg in weight appears to have been hurled 150 km east of the crater and scattered glass bombs indicate temperatures upwards of 2000°C (Horn 1972). Many such erratic blocks are found along the Pliocene surface outside the crater area proper (Dennis 1971). Concordant K-Ar and fission-track ages of

14.8 and 14.0 m.y. respectively are used to date the impact event. Brecciated Mesozoic rocks (Triassic and Jurassic) are found within the crater while undisturbed upper Miocene rocks fill the basin of the crater up to 300 m deep. According to the current geological time-scale (Harland & Francis 1971, p 33), the upper Miocene began 12 m.y. ago; thus the stratigraphic evidence is stated as correlating remarkably with the radiometric dating of the Ries event.

The confirmed meteorite crater at Gosses Bluff, Australia, indicates upturned Ordovician, Devonian and Carboniferous rocks overlying Pre-cambrian undisturbed rocks. Shock pressures are estimated at several hundred kilobars based upon the presence of the high-pressure polymorphs of silica. In contrast volcanic activity produces pressures of just a few kilobars at the most. For instance the 1956 eruption of Bezymianny was calculated at three kilobars based upon erratics thrown up to 30 km (Milton et al. 1972). The Charlevoix cratering event has shattered Ordovician rocks, which may have been deposited both before and after the event (Rondot 1971). According to the current geological scale (Harland & French 1971), the Ordovician period came to an end 435 m.y. ago, while the mean age of the Charlevoix Crater is published as 380 m.y. The discrepancy is usually attributed to argon escape.

Such findings have dynamic implications from a creationist viewpoint. If these astroblemes as mentioned are indeed the products of meteorite impact (the evidence points in that direction); if the cratering event actually reset the radiometric clocks (the resetting of two independent clocks synchronously seems to suggest this); and if fossiliferous strata were involved in the cratering event (here the evidence is unequivocal), then the creationist is faced with an ultimatum offering two alternatives:

1. He accepts the radiometric readings at face value, and thus he must accept the existence of life for at least as long as 450 m.y., when the oldest confirmed cratering event is said to have occurred in fossiliferous strata;
2. He rejects the usual interpretation of radioactive-age measurements, thus maintaining harmony with the Scriptural view of life extending back only a few thousand years.

Either the radiometric dating interpretations must be in error, or the interpretation of these fossiliferous rocks as products of the Noachian flood is in error. Which alternative is the correct one? We turn to tektites for further information.

Tektites are small glassy objects usually sculptured into distinctive shapes and whose origin has sparked one of the more heated controversies of twentieth-century space science. The glass has been generally ascribed to an impact origin, but it has been debated whether the impact was on earth, on the moon, or on some other planet. The debate was most intense through the 1960's, but the tide turned away from the lunar origin after the Apollo moon landings: "The Apollo lunar missions provide critical evidence which refutes the hypothesis of lunar origin of tektites" (Taylor 1973). Tektites are now firmly linked with terrestrial meteorite impacts which have splashed this molten glass into particular geographical ranges, called strewn-fields. Each strewn-field has provided samples of harmonious composition as well as harmonious radiometric dates (Table 1).

TABLE 1

Potassium-argon ages of tektite strewn fields.

(Adapted from Barnes VE. 1967. Tektites. International Dictionary of Geophysics 2:1516).

TEKTITE TYPES	NUMBER OF SPECIMENS	K-AR AGES (10^6 yrs)
Australites	6	0.68-0.76
Bediasites (Texas)	6	33.7-35.0
Georgia tektites*	3	33.7-35.0
Indochinites	4	0.71-0.73
Ivory Coast tektites	1	1.3
Javanites**	3	0.72-0.73
Moldavites (Germany)	8	14.4-14.9
Philippinites	5	0.68-0.73

*Includes Martha's Vineyard tektite.
**Includes one billitonite and a specimen from Borneo.

The most clear-cut case of a common origin for an astrobleme and nearby tektites is the Bosumtwi Crater (Ghana) and the Ivory Coast tektites. The presence of coesite, suevite and shatter cones indicates that this is an impact crater (Schnetzler et al. 1966). Glass from the crater itself and from the Ivory Coast strewn-field 300 km to the west shows concordant K-Ar and fission-track ages of 1.3 m.y. (Schnetzler et al. 1966). Samples from both localities also lie on the 1970 m.y. Rb-Sr isochron, while no other tektites — either Australian, European, or North American — lie on the same isochron (Durrani 1971). An analysis of uranium, thorium, and potassium content shows very close correlation between the two areas (Rybach & Adams 1969). Of these Ivory Coast tektites, it is stated that the "identification of these, as derived from the country rocks at the Bosumtwi Crater, appears well established" (Taylor 1973).

The European tektites, known as moldavites, have often been linked with the Ries-Kessel Crater, which has been dated (as noted previously) between 14.0 and 14.8 m.y. Moldavites have a strikingly similar age range of 14.4-14.9 m.y. (Table 1). Chemical analysis of the two areas has failed to turn up a genetic relationship, so that it is now questioned whether moldavites have been derived from the Ries (Taylor 1973). Recent evidence points in the direction of a "swarm" of meteorite impacts at the time of the Ries event, thus linking moldavites with associated craters (Horn 1972).

The Australian tektites, known as australites, have not been linked with any parent crater. In nearby Tasmania another type of glass which is compositionally related to tektites, known as Darwin glass, has now been linked with the Darwin Crater (Gentner et al. 1974). Further search may uncover a source for Australian tektites.

Whereas Australian tektites show concordant radiometric ages clustering around 0.7 m.y. (Table 1), their stratigraphic ages show a far different picture. Edmund Gill, of the National Museum of Victoria, Melbourne, in working the Port Campbell area of western Victoria has uncovered 14 australite samples *in situ* above the hardpan soil zone which has been dated by the radiocarbon method at seven locales, the oldest being 7300 radiocarbon years (Gill 1965). Charcoal from the same level as that containing specimen 9 yields a radiocarbon age of 5700 years. The possibility of transport from an older source area has been ruled out. Since the "Port Campbell australites include the best preserved tektites in the world ... any movement of the australites that has occurred...has been gentle and has not covered a great distance" (Gill 1965). Aboriginal implements have been discovered in association with the australites. A fission-track age of 800,000 years and a K-Ar age of 610,000 years for these same australites unavoidedly clashes with the obvious stratigraphical and archaeological interpretation of just a few thousand years.

A similar study was done on australites from the Lake Torrens Plain, South Australia (Lovering et al. 1972). They are found abundantly and in an excellent state of preservation from the Lake Torrens Formation, which has been carbon dated between 16,000 and 24,000 years B.P. Transport from a nearby Pleistocene source has been ruled out for several reasons. Nearest Pleistocene outcrops are 15-25 km away, and tektites have been found in "modern" sand dunes which are part of the Lake Torrens

Formation, showing that they could not have been washed into a wind-blown deposit. "As the excellent preservation of most of the australites indicates that they have undergone negligible transport since their infall, it is concluded that the australites fell into the dune field sometime between about 24,000 and 16,000 B.P." (Lovering et al. 1972).

In answer to the suggestion that there could have been two episodes of australite falls, the one recent and the other at 800,000 years, the australite distribution pattern is marshalled as evidence for just one australite fall (McColl & Williams 1970). "Hence, geological evidence from the Australian mainland is at variance, both as to infall frequency and age, with K-Ar and fission-track dating" (Lovering et al. 1972). Commenting on the above findings by Lovering and his associates, the editors of the recent book *Tektites* state that "in this paper they have built an incontrovertible case for the geologically young age of australite arrival on earth" (Barnes & Barnes 1973, p 214).

Based on Australian data, the K-Ar and fission-track dates of all tektites are suspect. Artificial tektite glass with the same chemical composition as natural tektites has been produced in the laboratory with the startling results that the apparent K-Ar ages range from zero to over 1 m.y. (when supposedly the radiometric clock had been reset to zero). "The data indicate that the assumption of complete loss of ^{40}Ar may not be completely valid, and that the interpretation of K-Ar dating as applied to tektites may need reevaluation" (Clark et al. 1966). Another study of certain natural tektites shaped like wheels also indicates that a partial resetting of the K-Ar clock must have occurred. Discrepant K-Ar readings are found between the cores and the flanges of the same australites, the flanges consistently suggesting a greater age (McDougall & Lovering 1969). If the K-Ar ages for tektite glass are shown to be unreliable, then could it be that such ages for related meteorite impact events are also not trustworthy?

A look at radiometric dating of particular meteorite craters validates the suggestion of a partial resetting of radiometric clocks, such as the Manicouagan, the W. Clearwater Lake and the Brent Craters of Canada. The. largest astrobleme in the western hemisphere, the Manicouagan-Mushalagan Lakes structure, has been intensely studied and dated by the K-Ar method, perhaps more intensively than any single structure to date (Wolfe 1971). The radiometric ages show a wide scatter, depending on the various points from which the readings are taken. In general the ages of the impact event focus on two points, 210 m.y. and 300 m.y., and the evidence is clear-cut for a meteorite impact origin — shatter cones, pseudo-tachylite, breccias, and a gradation of shock effects with depth — in this

60 km-wide structure. But a closer examination of the ages show that they drop as low as 190 m.y. and reach as high as 371 m.y. for totally shocked rocks. An even wider range is suggested when a single independent reading of 169 m.y. taken independently from the same structure is considered (Wanless 1968). A slightly shocked anorthosite gives an age of 532 m.y. and unshocked anorthosite five miles away gives an age of 932 m.y. The latter would be considered as the reading prior to impact. Fission-track ages of 208 and 36 m.y. were obtained on separate samples (Fleischer & Price 1968), thus indicating a partial resetting of the radiometric clocks. The anomalous figure of 36 m.y. has not been adequately explained, but is dismissed as erroneous.

The W. Clearwater Lake structure offers a similar pattern. The fission-track age of 34 m.y. is distinctly discordant with the two K-Ar ages obtained, 285 and 300 m.y. (Fleischer & Price 1968). It has been suggested that the solution to this discrepancy is that excess radiogenic argon was retained, as is sometimes the case with pyroxenes, in spite of high shock pressures (Bostock 1969). The anomalies between the fission-track and the K-Ar ages occur in both the Manicougan and Clearwater impact structures and both involve a range of $^{1}/_{100}$ in magnitude.

The Brent Crater, Ontario, is the most revealing, since we now have 34 dated samples from 12 drill holes, thus ranking with the Manicouagan in terms of number of readings (Hartung et al. 1971). Within a narrow 15 m zone the K-Ar ages drop significantly from a 770 m.y. average as found well below the melt zone to a 380 m.y. average next to the melt zone. Ages from within the melt zone itself are generally lower yet, the six samples showing ages of 321, 332, 339, 340, 354, and 414 m.y. The stratigraphic age of the meteorite impact event is lower Ordovician, since middle Ordovician as well as upper Ordovician fossils have been found in a series of *undisturbed* flat-lying sedimentary beds filling the crater bowl (Lozej & Beales 1975). As noted previously, current estimates place the end of the Ordovician at 435 m.y. which does not harmonize with the K-Ar ages of a lower Ordovician impact event ranging between 320-350 m.y. Hydrothermal enrichment of potassium following the cratering event has been suggested to explain the anomalous ages in the melt zone (Currie 1971), but it has been pointed out that there is little evidence for alteration, neither is it likely that sanidine, which is resistant to argon loss, could have been affected by K-enrichment (Shafiqullah et al. 1968). It is strange that the generally accepted date for the Brent cratering event is a minimum of 414 m.y. B.P. (Hartung et al. 1971), a figure which is based on just one sample out of six from the melt zone. The problem of anomalous ages in these Canadian astroblemes can be solved by one common means, and that is retention of excess argon from the older age (770 m.y.) in spite of the high pressures and temperatures involved. The real ages would be much lower than apparent ages. The former should be reduced to only a few thousand years.

Evidence is continually mounting for incomplete loss of argon in igneous rocks, thus inflating radiometric ages far beyond the actual (Hebeda et al. 1973; Dallmeyer 1975; Armstrong et al. 1975). Comparison of nuclear explosion effects with meteorite impacts is indicating also a partial resetting of the fission-track and K-Ar clocks (Fleischer et al. 1974; Naeser & Faul 1969; Hartung et al. 1970). Two different channels of evidence, the one from meteorite impacts and the other from tektites, both unite in a common solution positing a partial resetting of two key radiometric chronometers. By extension it is quite possible that igneous intrusives, such as batholiths and dikes, as well as volcanic lava flows and ash falls, have experienced only a partial resetting of the radiometric clocks. That possibility must be studied.

SUMMARY

The manned space landings on the moon, the missions of Apollo 11-16, have sparked a keen interest in the study of impact craters, both lunar and terrestrial (Baldwin 1971). This is already becoming one of the most intensely studied facets of lunar exploration, and the earth becomes a convenient laboratory for an understanding of meteorite impact effects (Short 1975). The Apollo missions have spurred a world-wide search for new impact sites as well as the confirmation of suspected sites. The amount of data being amassed is vast (Freeberg 1969). Conclusions reached are bound to have reverberations in creationist circles. One of the most ironic outcomes of the lunar space probe which began as an attempt to uncover the evolutionary origin of the moon is that it has provided data that show the terrestrial evolutionary time-scale to be in serious question. This probe has clearly ruled out the theory of a lunar origin for tektites and has confirmed their terrestrial origin. Major tektite falls in Australia in strata as young as 5700 years old according to radiocarbon dating have called in question both the fission-track and the K-Ar methods of dating which assign these identical tektites an age of about 700,000 years. Impact age anomalies as great as 100-fold for Canadian craters likewise call in question the validity of the K-Ar and fission-track age interpretations and also the associated stratigraphical age. Even with a high energy, high pressure event, such as meteorite impact, the radiometric clocks are in most cases only partially reset.

LITERATURE CITED

Armstrong RL, Leeman WP, Malde HE. 1975. K-Ar dating Quaternary and Neogene volcanic rocks of the Snake River Plain, Idaho. American Journal of Science 275:225-251.

Baldwin RB. 1971. On the history of lunar impact cratering. Icarus 14:36-52.

Barnes VE. 1967. Tektites. International Dictionary of Geophysics 2:1507-1518.

Barnes VW, Barnes MA, editors. 1973. Tektites. Stroudsburg, PA: Dowden, Hutchinson and Ross, Inc.

Bostock HH. 1969. The Clearwater Complex, New Quebec. Geological Survey of Canada Bulletin 178.

Bucher WH. 1964. Are cryptovolcanic structures due to meteoric impact? Nature 201:251-254.

Carter NL. 1965. Basal quartz deformation lamellae — a criterion for recognition of impactites. American Journal of Science 263:786-806.

Clark RS, et al. 1966. Potassium-argon ages of artificial tektite glass. American Geophysical Union Transactions 47:144.

Cohen AJ, Reid AM, Bunch TE. 1961. Coesite discoveries establish cryptovolcanics as fossil meteorite craters. Science 134:1624-1625.

Currie KL. 1971. Origin of igneous rocks associated with shock metamorphism as suggested by geochemical investigations of Canadian craters. Journal of Geophysical Research 76:5575-5585.

Dallmeyer RD. 1975. The Palisades sill: a Jurassic intrusion? Geology 3:243-245.

Dence MR, Robertson PB, Wirthlin RL. 1974. Coesite from the Lake Wanapitei CERfi Ontario. Earth and Planetary Science Letters 22:118-122.

Dennis JG. 1971. Ries structure, southern Germany, a review. Journal of Geophysical Research 76:5394-5406.

Dietz RS. 1963. Astroblemes: ancient meteorite-impact structures on the earth. In: Middlehurst BM, Kuiper GP, editors. The Moon, Meteorites and Comets. The Solar System, vol. 4, p 285-300. Chicago: University of Chicago Press.

Dietz RS. 1968. Shatter cones in cryptoexplosion structures. In: French BM, Short NM, editors. Shock Metamorphism of Natural Materials, p 367-385. Baltimore: Mono Books.

Dietz RS, McHone JF. 1976. El'gygtgyn: probably world's largest meteorite crater. Geology 4:391-392.

Durrani SA. 1971. Origin and ages of tektites. Physics of the Earth and Planetary Interiors 4:251-260.

Engelhardt W von, Bertsch W. 1969. Shock induced planar deformation structures in quartz from the Ries Crater, Germany. Contributions to Mineralogical Petrology 20:213-234.

Fleischer RL, Price PB. 1968. Fission track dating of glass from the Manicouagan Crater. American Geophysical Union Transactions 49:272.

Fleischer RL, et al. 1974. Effect of shock on fission-track dating of apatite and sphene crystals from Hardhat and Sedan underground nuclear explosions. Journal of Geophysical Research 79:339-342.

Freeberg JH. 1969. Terrestrial impact structures — a bibliography, 1965-1968. U.S. Geological Survey Bulletin 1320.

French BM, et al. 1970. Tenoumer Crater, Mauritania: age and petrologic evidence for origin by meteorite impact. Journal of Geophysical Research 75:4396-4406.

French BM, Short NM, editors. 1968. Shock metamorphism of natural materials. Baltimore: Mono Books.

Gentner W, et al. 1973. K-Ar and fission track dating of Darwin Crater glass. Earth and Planetary Science Letters 20:204-210.

Gill E. 1965. Quaternary geology, radiocarbon dating, and the age of australites. Geological Society of America Special Paper 84:415-432. Reappearing as: Gill, E. 1970. Age of australite fall. Journal of Geophysical Research 75:996-1002.

Harland WB, Francis EH, editors. 1971. The Phanerozoic time-scale: a supplement. Geological Society of London Special Publication No. 5.

Hartung JB, Short NM, Adams JAS. 1970. K-Ar analysis of rocks shocked by nuclear explosions. Modern Geology 1:279-281.

Hartung JB, Dence MR, Adams JAS. 1971. Potassium-argon dating of shock-metamorphosed rocks from the Brent Impact Crater, Ontario, Canada. Journal of Geophysical Research 76:5437-5448.

Hebeda EH, et al. 1973. Excess radiogenic argon in the pre-Cambrian Avanavero Dolerite in western Surinam. Earth and Planetary Science Letters 20:189-200.

Horn P. 1972. The Ries Kessel, Germany: an example of meteorite impact as a terrestrial geological process. Geoforum 12:91-95.

Howard KA, Offield TW. 1968. Shatter cones at Sierra Madera, Texas. Science 162:261-265.

Lovering JF, et al. 1972. Stratigraphical evidence for the terrestrial age of australites. Journal of the Geological Society of Australia 18:409-418. In: Barnes VE, Barnes MA, editors. 1973. Tektites, p 217-226. Stroudsburg, PA: Dowden, Hutchinson and Ross, Inc.

Lozej GP, Beales FW. 1975. The unmetamorphosed sedimentary fill of the Brent meteorite crater, southeastern Ontario. Canadian Journal of Earth Sciences 12:606-628.

Manton WI. 1965. The orientation and origin of shatter cones in the Vredefort Ring. New York Academy of Sciences Annals 123:1017-1049.

Masaytis VL, Mikhaylov MV, Selivanovskaya TV. 1972. The Popigay meteorite crater. The International Geology Review 14:327-331.

McColl DH, Williams GE. 1970. Australite distribution pattern in southern central Australia. Nature 226:154-155.

McDougall I, Lovering JF. 1969. Apparent K-Ar dates on cores and excess Ar in flanges of australites. Geochimica et Cosmochimica Acta 33:1057-1070.

Millman PM. 1971. The space scars of earth. Nature 232:161-164.

Middlehurst BM, Kuiper GP, editors. 1963. The moon, meteorites and comets. The Solar System, vol. 4. Chicago: University of Chicago Press.

Milton DJ, et al. 1972. Gosses Bluff impact structure, Australia. Science 175:1199-1207.

Naeser CW, Faul H. 1969. Fission track annealing in apatite and sphene. Journal of Geophysical Research 74:705-710.

Robertson PB, Mason GD. 1975. Shatter cones from Haughton Dome, Devon Island, Canada. Nature 255:393-394.

Rondot J. 1971. Impactite of the Charlevoix structure, Quebec, Canada. Journal of Geophysical Research 76:5414-5423.

Rybach L, Adams JAS. 1969. The radioactivity of the Ivory Coast tektites and the formation of the Bosumtwi Crater (Ghana). Geochimica et Cosmochimica Acta 33:1101-1102.

Sawatzky HB. 1975. Astroblemes in the Williston Basin. American Association of Petroleum Geologists Bulletin 59:694-710.

Schnetzler CC, Pinson WH, Hurley PM. 1966. Rubidium-strontium age of the Bosumtwi Crater area, Ghana, compared with the age of the Ivory Coast tektites. Science 151:817-819.

Shafiqullah M, Tupper WM, Cole TJS. 1968. K-Ar ages on rocks from the crater at Brent, Ontario. Earth and Planetary Science Letters 5:148-152.

Short NM. 1975. Planetary geology. Englewood Cliffs, NJ: Prentice-Hall, Inc.

Stoffler D. 1971. Coesite and stishovite in shocked crystalline rocks. Journal of Geophysical Research 76:5474-5488.

Taylor SR. 1973. Tektites: a post-Apollo view. Earth-Science Reviews 9:101-123.

Taylor SR, Dence MR. 1969. A probable meteorite origin for Mistastin Lake, Labrador. Canadian Journal of Earth Sciences 6:39-45.

Wanless RK, Stevens RD, Lachance GR. 1968. Age determinations and geological studies. Geological Society of America Special Paper 67-2.

Wilshire HG, Howard KA. 1968. Structural pattern in central uplifts of cryptoexplosion structures as typified by Sierra Madera. Science 162:258-261.