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Comparitive Hertzian Features in Glass and Rock

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ABSTRACT

Plates of 5mm soda-lime glass were impacted by 5mm steel projectiles traveling at velocities of ~30 to ~91 m/s at angles between 45º and 60º -- 0/360º being vertical. Impact features were recorded and compared to bolide impact characteristics in craters on Earth, the Moon and Mars. Hertzian cone (HC), ring cracks, wall fracturing and comminuted landscapes were examined in photographic comparisons to determine physical likenesses and differences and to view potential changes in projectile velocity and angle and their effect in variances on crater features. They were then viewed beside known meteor impact craters for comparison. Sub-crater features in glass were studied and noted for future comparison to possible like characteristic in rock. Then, Hertzian fracture (HF), cone and mold (HFM) characteristics were recorded and studied for circ and parenthesis shaped features found in craters.

INTRODUCTION

We report that fracture traits in sheet-glass craters above Hertzian fractures having similar structure and crater-diameter-to-circ ratio comparison to erosional features in craters formed by bolide impact. Examples of craters created by projectiles connected to Hertzian fractures in glass and ceramics display similar circular and semi-circular anomalies (CSA) within crater wall and floors as are found in bolide impact craters shown below. In many glass examples these features are found throughout the Hertzian cone segment

Hertzian fractures in glass, rock and ceramics have been studied by multiple disciplines and in many fields. Nomenclature for impact features vary in past studies. This study was undertaken to compare features in impact similarities, primarily in glass and rock. However, examples from reports on ceramics, metal, ballistics armor and dental materials provided insight. Undocumented features heretofore were unnamed so necessity dictated that they be examined and named in a glossary. An attempt to consolidate terms used in the publication can be found in, *Hertzian Fractures and Related Terms – A Glossary.* [1]

EXPERIMENTS

In most studies a standard, conventional air gun was used to propel 5 mm steel balls into plats of 5 mm thick soda-lime glass. Surfaces were not sanded or abraded to promote crack formation. Tests angles varied and distances from barrel tip to garget to adjust trajectories and muzzle velocity. All muzzle velocities are estimated for distances of 7.6 cm to 122 cm and range from ~30 to ~91 meters per second.

RESULTS

Craters in glass demonstrated circular and semi-circular anomalies (CSA) in both micro and macroscopic records. Close distances, 7.6 mm, created comminuted crater floors that varied from fine, micrometer sized grains to circular features dominating an estimated two to one. Impacts from distances around 122 cm created solid crater floors with fractured crater walls.

Unlike bolide impacts, velocity and mass of steel sphere and glass impacts are far too low to produce explosive forces. However similar features are present in comparison. CSA features were labeled “circs” if complete or near complete and labeled “parenthetic” (P) when divided or if displaying a single arc. Parenthetic refers to the parenthesis-like shape of the semi circular features.

Glass samples observed did not very in color or shading unless dye was applied. CSA samples observed at Middlesboro, Kentucky demonstrated visible differences in circ-center shading and in depth and angularity of parenthetics as well as crystalline formation, dikes, joint and concaved and convexed elements.

With further study CSA features may be found to be taxonomically similar to the base and truncated apical areas of shatter cones. Preliminary study suggests that energy is diverted around voids or drives heterogeneous

[1] Byous, J., contributions by Ruddy, D.P. and McCormick, K.H *Hertzian Fractures and Related Terms – A Glossary*, AAtR Publishing, 2013.

or underlying material into target material to generate their formation.

METHODS

For studies below 45 m/s a standard steel yoke and arm support sling was used. In studies between 45 to 91 m/s samples were created with a conventional air rifle.[2] Velocity was adjusted by distance from the target, 7.62cm to 121cm. Both release systems were hand held to allow for rotational variances in steel ball projectiles. Sling samples were found to be primarily on Y axis rotation while air rifle samples exhibited multi-rotational impact evidence. Two to three layers of glass were used to allow confined fractures for viewing of samples from the base. Angles varied from 45º to 60º from true vertical at 0/360º. Images were recorded with micro and macro-photographic lenses on Nikon and Olympus digital cameras.

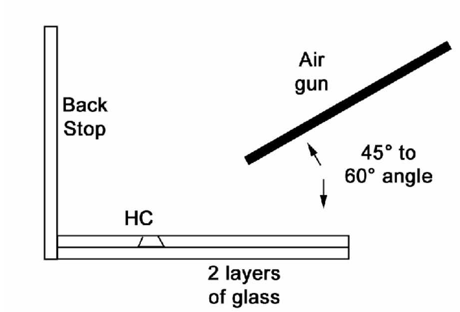

Figure 1 *Method for creating Hertzian fractures in glass.*

GLASS SAMPLES

Hertzian fractures have been studied by various fields. It was named for German physicist Heinrich Rudolf Hertz who described the feature in 1882. Until recently Hertzian fractures were divided into five segments:

1. The crater at the point of impact.
2. The mirror area where the fracture is a smooth, annular and transitional "bulls eye" band around the crater.
3. The mist, a finely defined and faintly viewable annular band around the mirror segment, is viewable in glass but hard to define in rock and opaque materials.
4. The hackle area is where ray-flower-petal-like fractures spread across an annular section.
5. Wallner lines are the wavy undulations in HC's that are created when sound waves (P-waves) bounce back and slightly change the direction of the fracture as it forms in the crystalline material.[3]

Hertzian fractures are divided into three distinct segments. First, the Hertzian fracture is created – the space or separation between the positive body of the Hertzian cone and the negative body of the Hertzian mold. To date the latter has been referred to as a Hertzian fracture. But the mold and fracture are two distinctly different aspects during formation. The mold is a portion of the overburden. In glass it is the entirety of the pane or sheet. In rock, metal or ceramics it is the area surrounding the crater but above and around the cone and fracture.

Hertzian fractures can contain many more features. A few can be seen in figure 2. Compound fractures add complexity to the standard attributes seen in this image. Variations in projectile speed and mass change facetal characteristics of the HF when energy transfer surpasses elastic and plastic tolerances in the target material. Directional spin of the projectile may add a third factor to the equation. At this point fragmentation and segmentation occurs. Areas may fracture into a pile of angular parts that are described by L.C. Forde, et al, as, "A three-dimensional jigsaw" puzzle.[4] Laminae, "hackle flakes," often form annularly to create an onion-peel-like formation around a center core. Occasionally multiple layers of laminae overlap around the center segment. CSA features may be found in any of these divisions.

Circs, circular features, complete or near-complete will appear in most glass/projectile crater walls. Partial circs, "parenthetics," can also be found. Parenthetic are called such due to their parenthesis shaped features in and on craters and cones.

Hertzian fracture facetal features divide into multiple components, most of which are part of the cone:

1. Overburden, the area around the crater and cone but divided from the cone by the fracture.
2. Crater, includes the crater wall and floor.
3. Mirror. More than one mirror section may be present.
4. Spinner. A segment of the mirror section of a crushed cone that has separated from lower body.[5]

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[2] An official 50-year commemorative Red Ryder carbine-action two-hundred-shot range model air rifle.

[3] Henry P. Kirchner, James W. Kirchner, *Fracture Mechanics of Fracture Mirrors*, Ceramic Finishing Company, State College, Pennsylvania 1979.

[4] L.C. Forde, W.G. Proud, S.M. Walley, *Ballistic Impact Studies of A Borosilicate Glass (BIS)*, Fracture and Shock Physics Group, Cavendish Laboratory, Cambridge UK. "Eventually we would expect the glass to be heavily fragmented (comminuted). However,this fragmented material will initially be locked together like a three-dimensional jigsaw. Plate impact experiments give clear evidence that this material exhibits a finite shear strength for some time after the initial impact although the spall strength is zero."

[5] "Spinning top," used by Ball and McKenzie in *On the low velocity impact behaviour of glass plates,*A. Ball and H.W. McKenzie, Dept of Materials Engineering, Univ of Cape Town, South Africa. 1994.

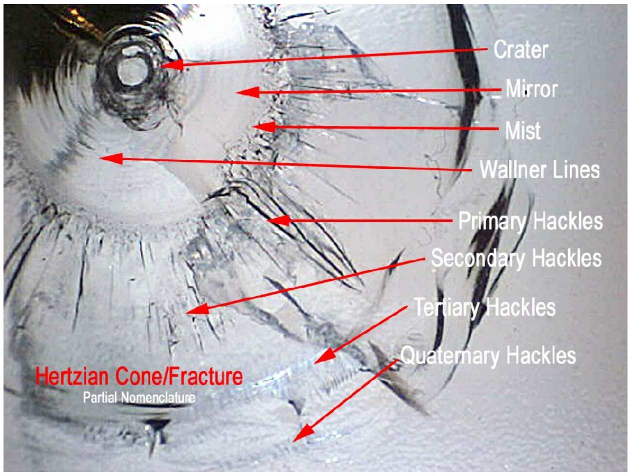

Figure 2 *A partial list of possible Hertzian fracture traits sequence. Additional features are created when Hertzian cones are fragmented.*

5. Mist. The finely fractured segment between the mirror and hackle sections.
6. Hackle. The region or regions where radial fracture lines may or may not penetrate and divide laminae. There may be several annular hackle sections in the progression from the crater to the outer base of the cone.
7. Wallner lines. They may be found in or near all sections of Hertzian cones or molds.
8. Laminae. Radially-lined hackle segments that "peel" from a central core when crushing of the cone occurs.
9. Terrace. Sections of a cone that have slumped into terrace-like transitions after overburden has been removed.
10. Flange. Thinning of the outer cone base or laminae to form an undivided annular projection.
11. Hackle flake. A lamina with hackle features that has separated from the main cone.
12. Triangulate segment. Triangle shaped features within a hackle flake that exhibit inverted V shape fractures.
13. Lobe. A segment along the flange which protrudes and is divided radially from the main line of the flange.
14. Cone core. An inner cone within the total cone underlying the laminae.
15. Feather Hackles are fine hackles resembling plumes or the edge of a bird feather.

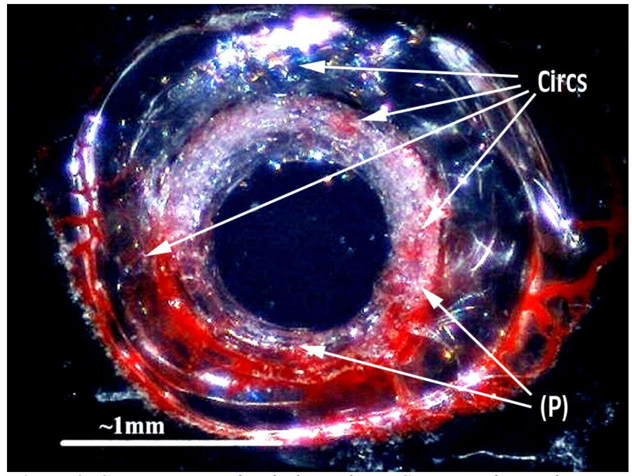

Figure 3 *Crater in stained soda-lime glass. Circs are observed in crater wall and border area. Parenthetics are faintly visible in the crushed wall area. The crater floor is unfragmented in this sample.*

CIRCS AND PARENTHETICS

Circular features are present in many craters and cone structures in glass suggesting that a crushing wave force radiates in circular patterns or cells from the point of impact downward with rebounding waves from the base or from heterogeneities. In figures 3 and 4 circs and parenthesis shaped, "parenthetics" can be seen in a crater and lamina. In the former dye has seeped into voids and show both annular fractures and interior fractures within circs. In samples at 1:00 and 3:00 the dye has penetrated single crushed circs.

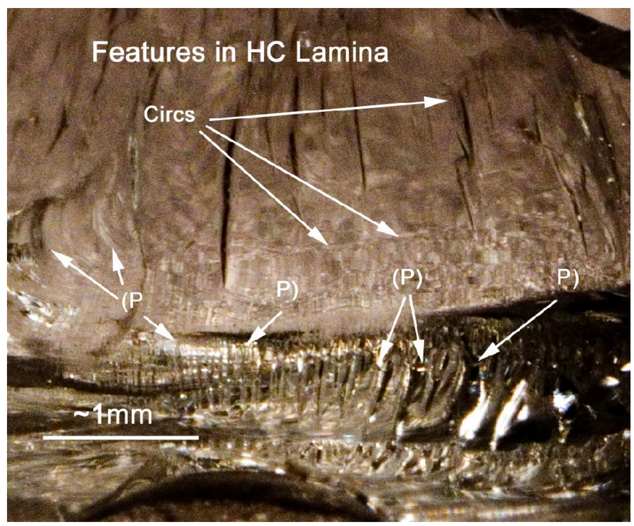

Figure 4 *Parenthetics, crescent feather hackles, are observed in a lamina of glass shed from a Hertzian cone. Some parenthetics are obvious while others are slight. The two at far left are in a conchoidal fracture on the inside of the flake and appear to be Wallner lines.*

Within the flake hackle lines in figure 4 circs and parenthetics can be seen near the boundary formation of the flange. Just above the fine, feather hackles are the circular to ovate features and within the feather hackles are the semi-circular parenthetics. Coding for parenthetics are, right only = P), left only = (P and complete parenthesis forms = (P)

Crushed Hertzian Cones

When a low-velocity projectile strikes glass the cone can form partial or complete cones as illustrated in the dome-shaped cone in figure *5*. The transition of energy moves smoothly from the crater and arcs to the base or back plane

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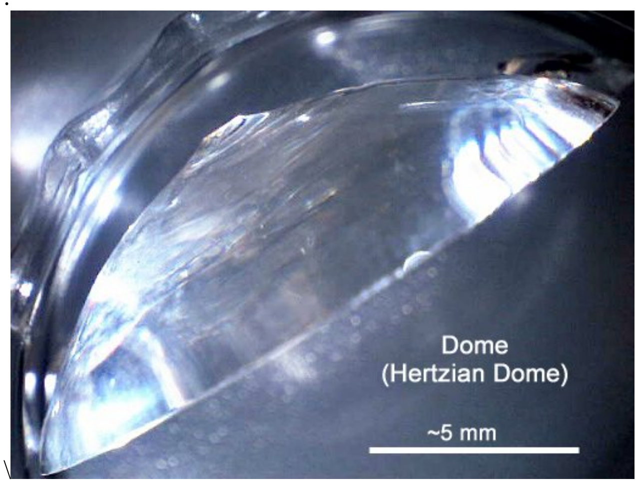

Figure 5 *A simple, dome-shaped Hertzian cone or "Hertzian dome" created by a low-velocity projectile. It contains the crater floor and pedestal at top. It exhibits some Wallner lines seen around the pedestal, but other features are not present.*

When an impact force is sufficient to crush a glass cone it will generally crush from the base to the top. The spinner may remain intact (figure 6) while the lower section divides into laminae and fragmented segments. Often, but not always, the crater floor will comminute while the spinner remains relatively undamaged.

In crushed compound cones the structure appears to be fragmented from the crater to the base. The spinner shatters, as inertia forces the ceiling down laminae are formed and divided into hackle flakes that display intra-dispersed mirror, mist, hackle and Wallner lines along with triangulate segments under exfoliated laminae.

The base of the crushed compound cone (figure 7) often has lobed and irregular flange sections that break away from the main body when overburden is removed. Likewise, crater floors may be comminuted or totally fragmented so it does not maintain provenance when the overburden has been lifted.

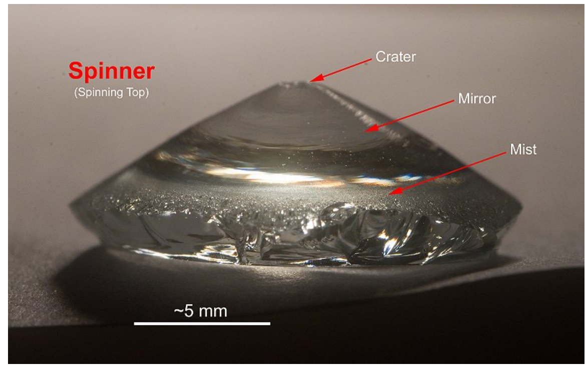

Figure 6 *An intact spinner without comminution in the crater.*

In these instances, as is the case in figure 6, only the base fragments while the spinner, from crater to mirror to mist forms as a solid unit. In all such occurrences the center base is shattered and layers of laminae are may be formed.

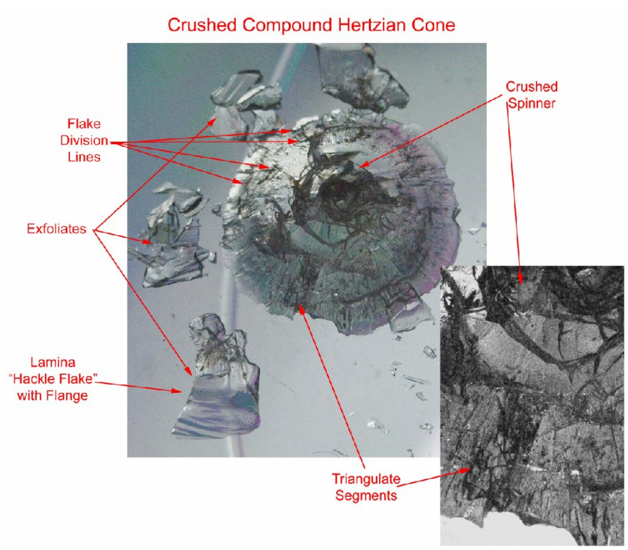

Figure 7 *A crushed compound cone including triangulate segments.*

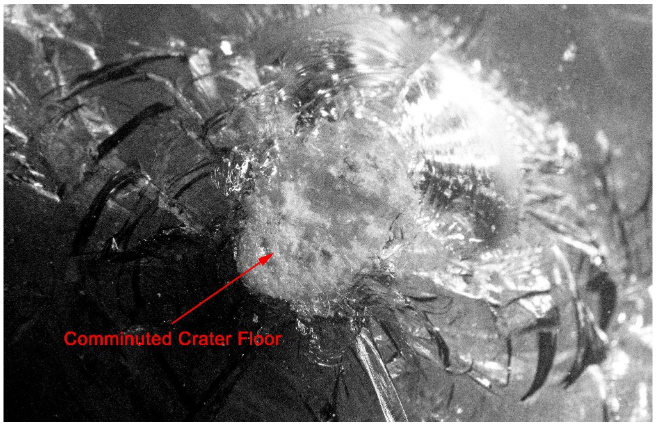

Figure 8 *A comminuted crater floor with overburden in place.*

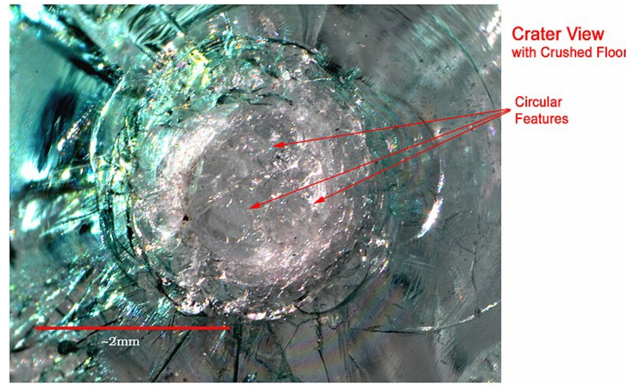

Figure 9 *Circular features are found in the floor and walls of this crater in soda-lime glass.*

GLASS AND ROCK COMPARISON

Circs in Crater Floors

Glass studies show circular features in ~5 percent of samples, all of which were from higher velocity impacts. Crater floors crushed by the steel-ball projectiles generally displayed three to four main circular features among comminution. The crater floor in figure 9 shows a remarkable similarity to aerial view of Haughton Impact Crater, figure 10, on Devon Island in Nanavut, Canada. The glass sample has a diameter of ~2mm while Haughton Crater measures around 11.5 km.

Linear and circular features in Utah's Upheaval Dome show similar, less-distinct circs. (See appendix) They are located on the monocline above the crater. Here features indicate circular microfractures that collects moisture for plant growth. In areas that are predominately rock, plants grow in joints, fault and along microfractures where roots are provided with sources of water. They are found throughout the structure of Upheaval Dome and the surrounding area. Arced watershed can also be seen with the plants.

Samples forming plant "dot-to-dot" circs can be found in figures 13a & 13b. Highlighted in red they show arcs of botanical life in the surrounding rock. Images from Google Earth, June 6, 2006 are used in the example.

Sample location A is located 0.59 km (0.37 mi) aerial distance to the northeast of the parking loop and 0.67 km (0.42 mi) by trail. Coordinates: 38.430170 -109.919441.

Sample location B is located to the southeast of the parking loop opposite the ridge. It is 0.7 km (0.43 mi) aerial and a 1.5 km (0.71 mi) hike from the parking loop. Coordinates: 38.421541 -109.918669.

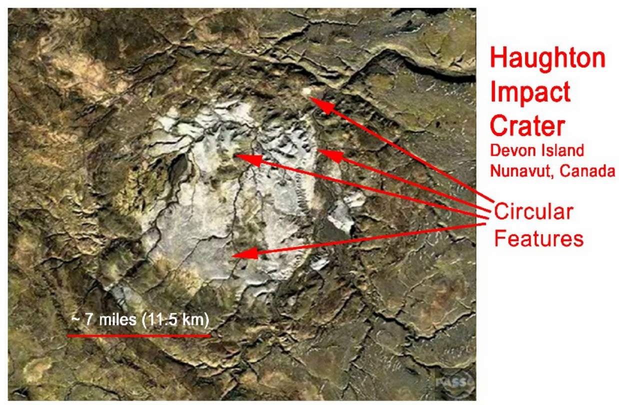

Figure 10 *This satellite image of Haughton Crater reveals circs in the crater floor with proportional diameters similar to the glass crater in figure 9.*

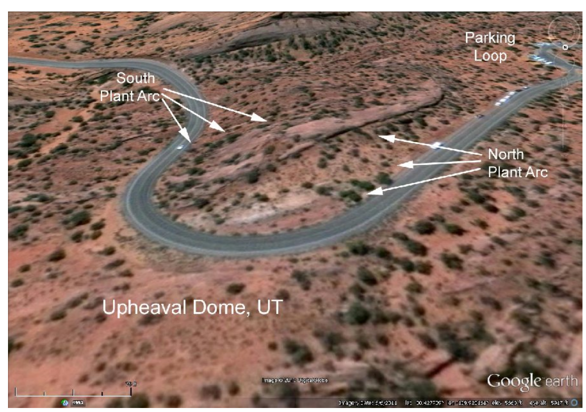

Figure 11 *An oblique view of the road curve into the Upheaval Dome parking loop from the north. The circ creates a semi-conical rise in the bend of the road.*

Figure 12 *Note the circ opposite the road curve 0.7 km from the parking loop at Upheaval Dome. The plant circ is visible as a corresponding arc to the road that follows the contour. Coordinates: 38.427432° -109.923140°. Virtual altitude:6583.*

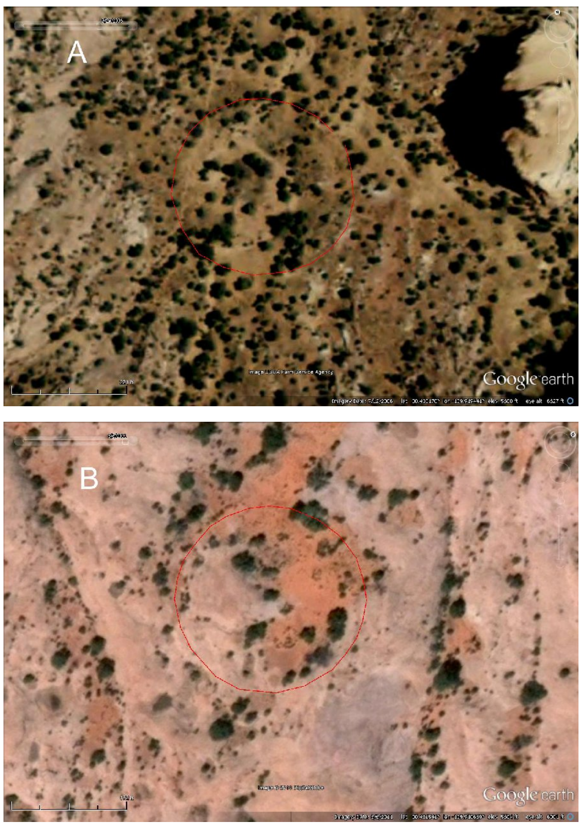

Figure 13 *Upheaval Dome samples of circs with plant growth and wash features marked in red. Google Earth photo 11a coordinates: 38.430170 -109.919441. Virtual eye altitude: 6381. Other plant arcs can be seen in the frame of the images. Google Earth photo 11b coordinates: 38.421541° -109.918669°. Virtual eye altitude:6627 ft.*

A third circ location easily accessed is at the last turn toward the parking look. Here the slope resembles a partial Hertzian cone. The road follows the contour of the base while plant arcs form on both sides of the ridge in figures 12 & 13. It is accessed after a short 0.7 km (0.1 mi) hike from the parking area.

Caltech Study

Thomas J. Ahrens of California Institute of Technology (Caltech) was a leader in the study of projectile impacts in rock. His experiments were among the first to study how impact craters were created. His studies included elastic properties of small specimens at high pressure, shock metamorphism of natural materials and hundreds of other published examples.[6]

In the publication Figure 1 image A shows a small cylinder of Coconino sandstone after an impact by a flying disk.[7] Within the spall are circular fractures and features. To the right of the frame concentric circular fractures can be seen. These mimic circular features on the walls of impact craters in rock and glass.

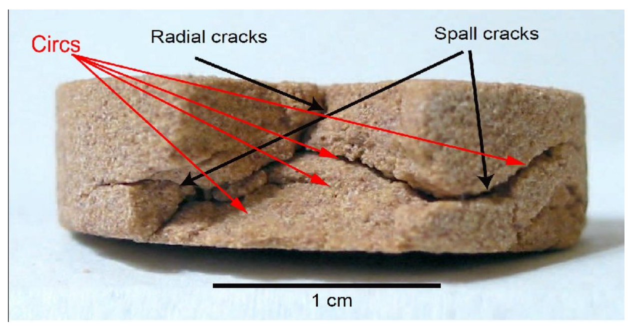

Figure 14 *Circs appear in Coconino sandstone after impact by a flying disk. This sample was from experiments by T.J.Ahrens, et al at, California Institute of Technology,Pasadena CA. Red portion added. Image: T.J. Ahrens, Caltech.*

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6 Connect With Caltech obit: "Thomas J. Ahrens, the Fletcher Jones Professor of Geophysics… His research also included planetary impacts and the formation of craters and planets." - See more at: http://www.caltech.edu/content/thomas-j-ahrens-74#sthash.DaH48rJb.dpuf and http://www.fas.harvard.edu/~planets/sstewart/ahrens/.

7 *Dynamic tensile strength of terrestrial rocks and application to impact cratering* by Huirong-Anita AI and Thomas J. Ahrens, Lindhurst Laboratory of Experimental Geophysics, Seismological Laboratory, California Institute of Technology,
Pasadena, California, 2004

Additional Images of Circs in Craters.

Figure 15 *India's Lonar Crater is shown with faint plant arcs and washes along the southern rim. Coordinates: 19.97670° 76.505633°. Virtual elevation: 2995 ft. Image date: May 26, 2007.*

Figure 16 *The same image as figure 15 but without lines.*

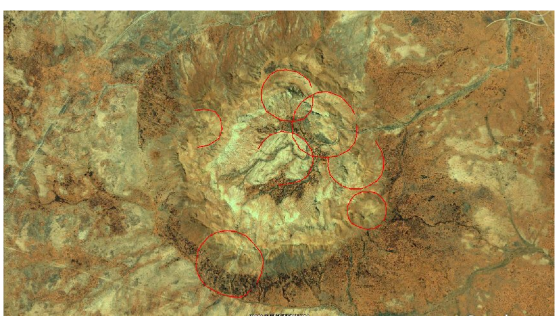

Figure 17 *Gosses Bluff, Australia with lines marking some circs.*

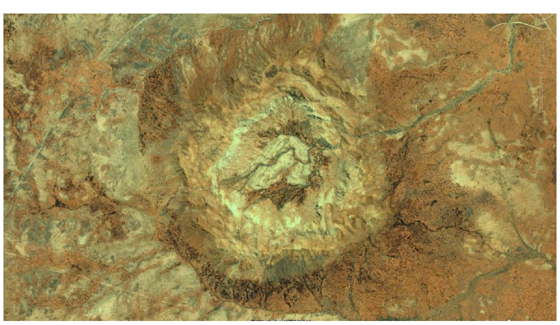

Figure 18 *Gosses Bluff without lines. Coordinates: -23.817836° 132.306827°. Images: NASA, Google Earth.*

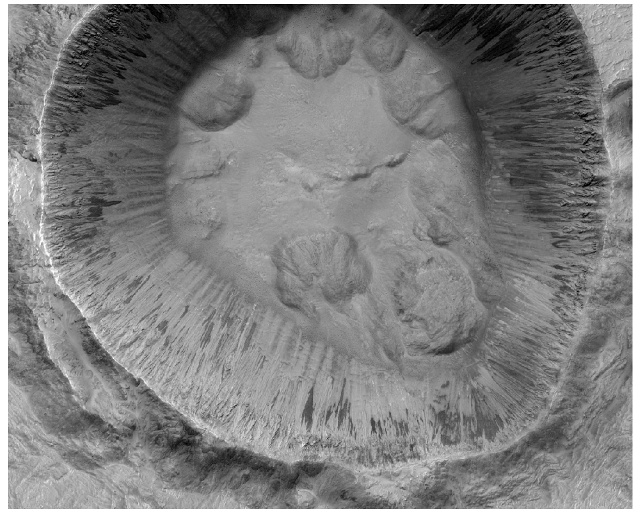

Figure 19 *Central circular lobes in an unnamed fresh crater south of Isidis Region, Mars. NASA/JPL/Arizona State University image ESP_014412_1780.* [8]

Parenthetics

In Middlesboro, KY ground leveling in Roselawn Memorial Garden revealed CSA and parenthetic features as are shown on below in figure 23, image A, with features outlined in image B. Photo C shows an overlapping "flap" of sandstone with an edge to "V" contact depth of ~8 inches. Another smaller, shallower overlap is shown to the right of the box. The overlap displays possibilities of Hertzian cone-shaped microfractures creating the circs in this location.

A complete circ can be seen in the upper left quadrant of images A and B. Most circs, as can be seen in all images, form features shaped like parenthesis symbols on a keyboard. For purposes of the study the features are dubbed parenthetics. Locations of double parenthetics are labeled (P), single right are listed, P), and single left are coded (P.[9]

Impact crater walls display parenthesis-like features above the alluvial fans along the outer crater floor. Alluvium forms a lower arch as is typical in these locations. But beyond the lower bounds of the alluvium rivulets continue to arc as can be seen in the photo of Barringer Crater in Arizona, figure 21, Parenthetics also appear in the rock above the fans indicating fracturing or microfracturing during crater evacuation.

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[8] http://hirise.lpl.arizona.edu/ESP_014412_1780.

[9] Byous, J., Grubb, W., field study, April, 2008 Middlesboro, KY.

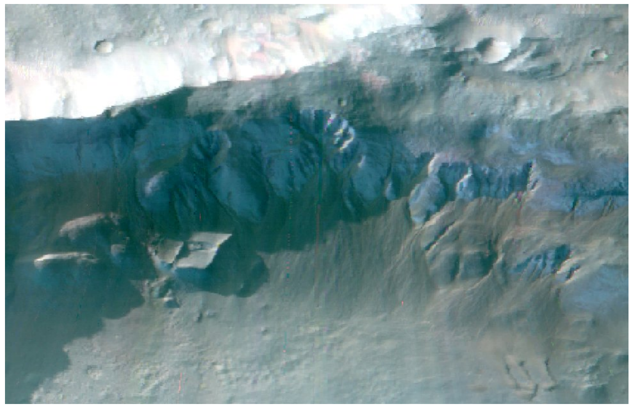

Figure 20 *Parenthetics are seen in the center of the frame on this NASA image showing part of a crater rim in the Terra Sirenum region, Mars. Image. Mars Coordinates: Near 38.9° south latitude, 195.9° east longitude*

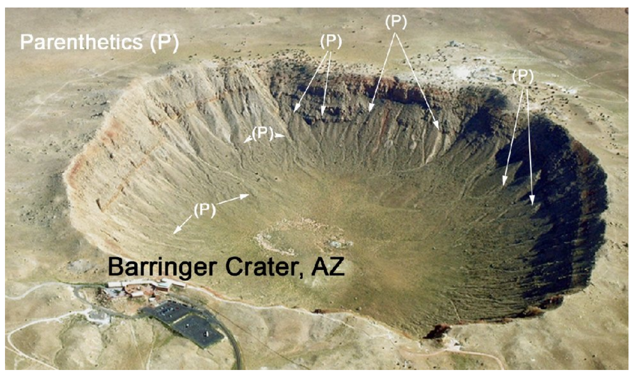

Figure 21 *Parenthesis-shaped arcs in wall rocks and floor of Barringer Crater, Arizona. Coordinates: 35.028071° -111.023196° Image: Shane.Torgerson creative commons Wikipedia.*

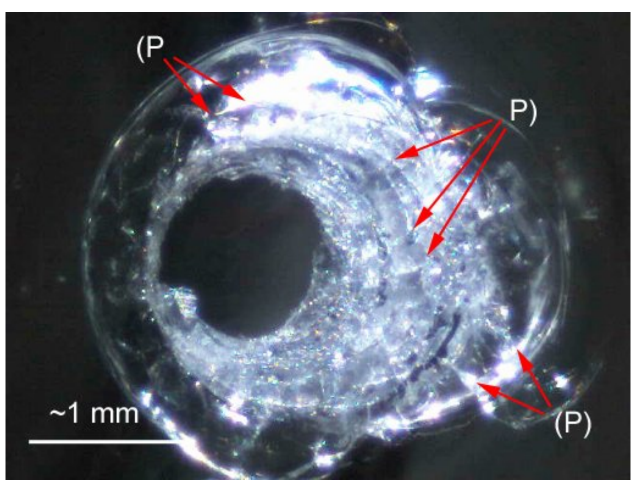

Figure 22 *Crater in soda-lime glass showing parenthetics.*

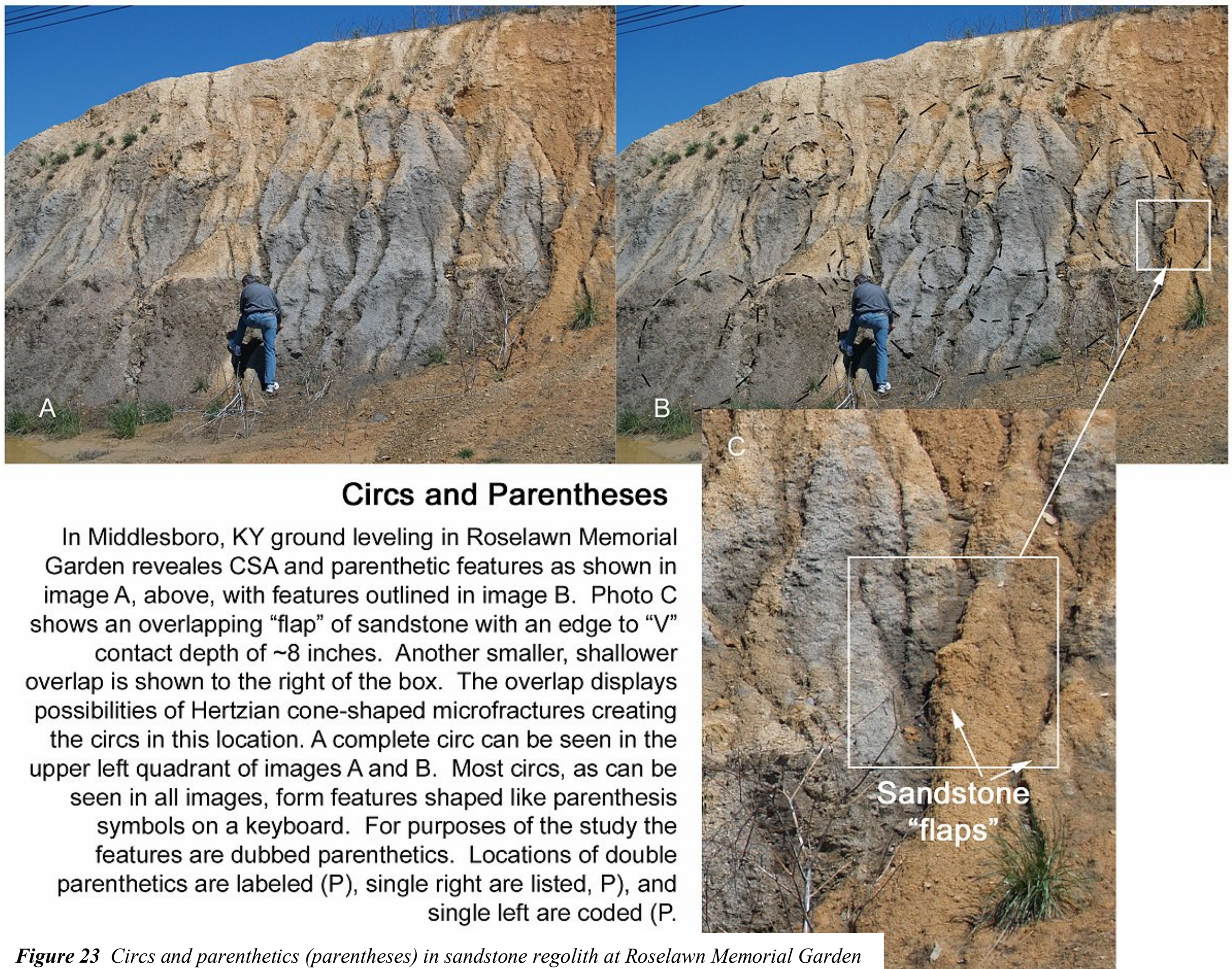

Figure 23 *Circs and parenthetics (parentheses) in sandstone regolith at Roselawn Memorial Garden NE of the center of the city and of the central uplift. Coordinates: 36.628273° -83.704949°.*

The false-color photo of the Mars crater Endurance at right was made by a panoramic camera on NASA's Mars Exploration Rover Opportunity in 2004. It shows mineral changes between materials in the Endurance crater rim. The color cyan indicates basalts, dark green shows iron oxide and basaltic mixtures, reds and yellows denote dusty material containing sulfates. Along the jointed face parenthetics can be found. Ironically, the center-left section contains fractures that replicate the symbol for facing arch parenthetics, (P). The image was not altered other than cropping to show detail.[10]

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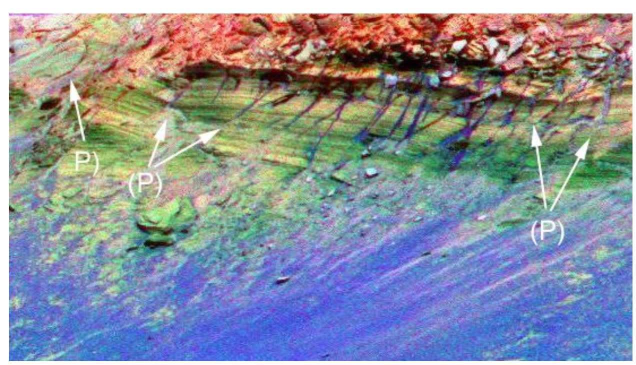


Figure 24 *False color image of Image: NASA/JPL/Cornell*

[10] : http://photojournal.jpl.nasa.gov/catalog/PIA06013

HAMMER MARKS IN ROCKS

Hammer marks is a term used for lightly concaved or convexed, circular or crescent shaped features in rock that resemble depressions and ridges made by a hammer on metal or rock. Shown in figure 25, they are found in rocks at Middlesboro crater, Kentucky and in images of Apollo missions on the Moon on Tracy's Rock (figure 26) in an area of bolide impact. Individually they appear to be similar to shallow Hertzian fractures as are found in projectile studies. Their formation can be explained in softer material studies. Woodworking examples of hammer impressions in soft fiber woods illustrates the concaved features. Fiber erosion via hand sanding without a sanding block will produce a convexed bulge due to harder, compressed fibers. The latter are formed in the same manner as Hertzian fractures in crystalline material.

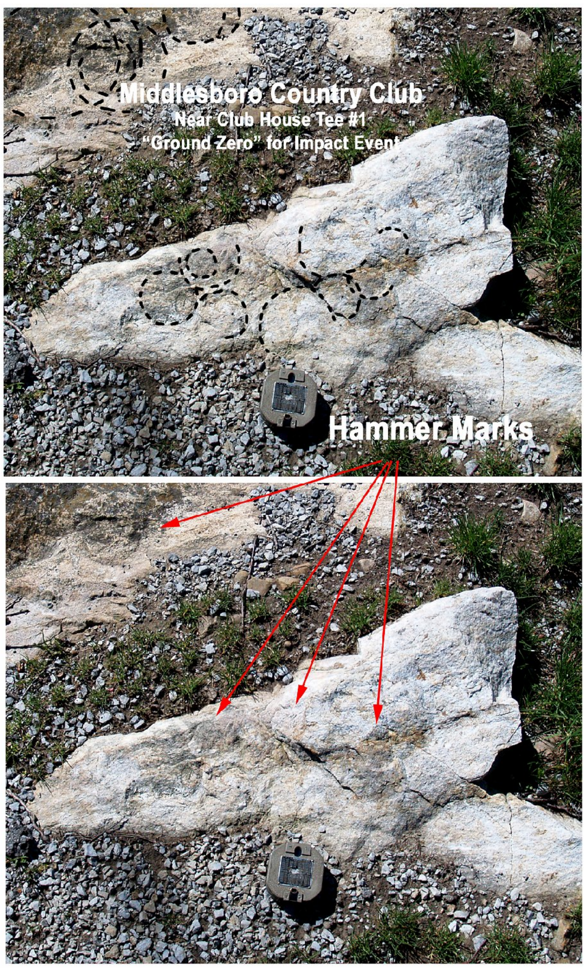


Figure 25 *Circular and ovate features in rocks having similar features to the marks of a hammer are found here in Middlesboro impact crater, Middlesboro, KY. This rock is found near the club house on the first tee of the Golf course. Above circs are outlined in the top image showing locations in lower image. Hammer Marks are lightly concaved or convexed circular or crescent shaped features that resemble depressions and ridges made by a hammer on metal, wood or rock.*

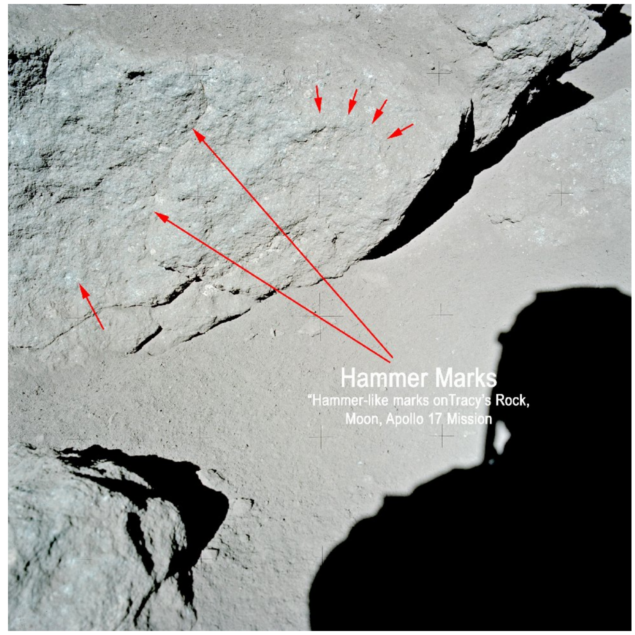


Figure 26 *Hammer Mark features in the Moon bolder named Tracy's Rock by the Apollo 17 crew. Hammer-mark-like features can be seen in other Moon images from several missions. NASA photo AS17-140-21477HR.*

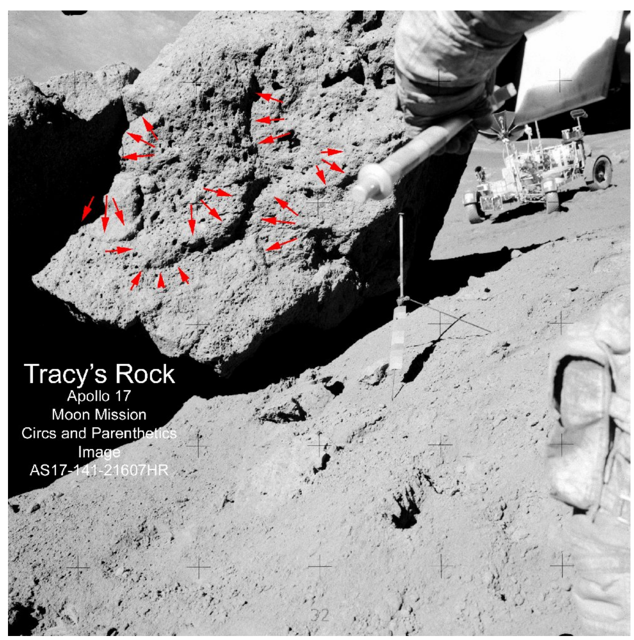
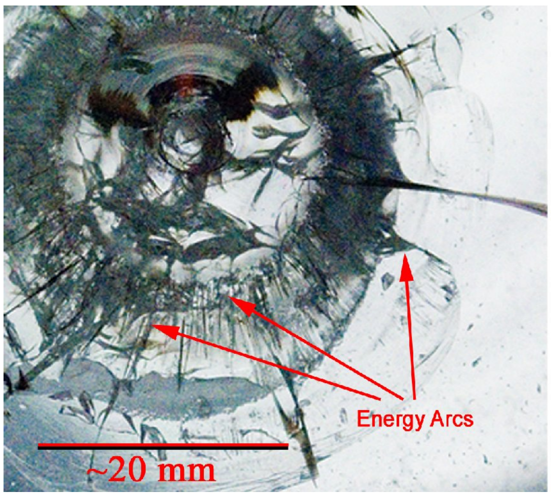


Figure 27 *Tracy's Rock, Apollo 17 Moon mission.* *Circs and parenthetics are found on most sides.*

FRACTURE AND BLAST SIMILARITIES

Energy dispersal in glass Hertzian fractures bear a resemblance to ground stains at above-ground nuclear test sites as seen in figure 28. Both initiate at a central point and display radial line separated by arced features. It appears that when energy is displaced outward from the central point of impact or blast it concentrates in these locations.

These cellular segments tracts are traceable in glass



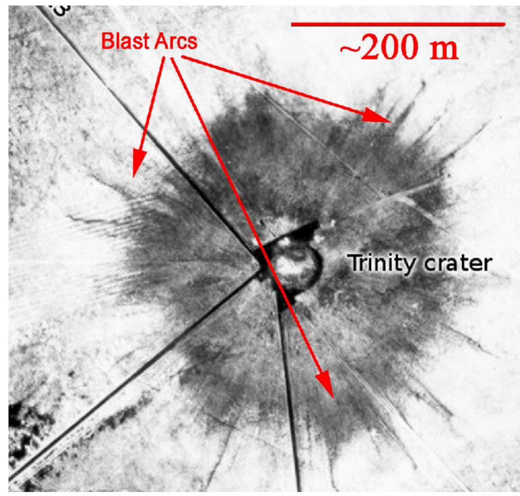


Figure 29 *Arced and rayed fractures in a Hertzian cone replicate blast scars on the ground at the site of the Trinity nuclear test.*

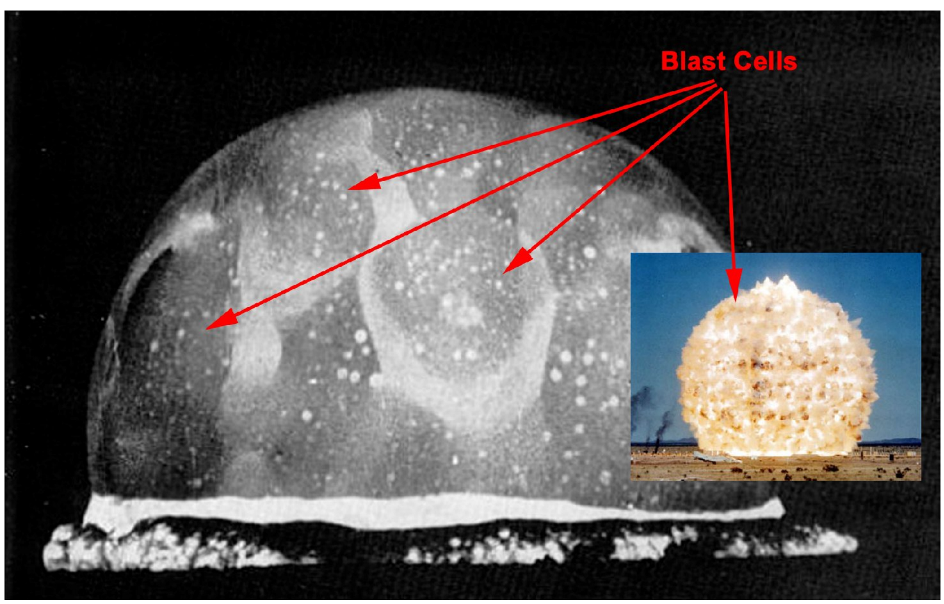


Figure 28 *Cell shaped bulges in some above-ground nuclear test could be indicative of causation for circ and parenthetic formation in impact craters.*

fractures and burn scars on the ground after blasts. Images of nuclear tests as shown in figure 29 appear to form dispersal cells in some test images. However not all above ground test show these uniform dispersal features. This attribute could account for circs and parenthetic formations in HC, HF and in glass and rock craters.

CONCLUSIONS

Circular features are found across the globe. Some are obvious, others are faint and unnoticed. Few papers have been written on these faint, indistinct features. Under closer observation they are abundant in impact locales. Photomicrographs show circular features in impacted glass in association with Hertzian fracture, cone and mold properties. Similar features in macro and mega environs display like features. The question to now ask is, “Are these reliable, indicative indicators of bolide impacts?” At present it is believed that they are created by pressure and sound waves within the crater and cone during impact. Future studies may provide more data for examination. Similar features appear in blast nuclear test sites and could provide information for future studies.

ACKNOWLEDGEMENTS

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References Cited

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AI, H., Ahrens, T.J., Dynamic tensile strength of terrestrial rocks and application to impact cratering, Lindhurst Laboratory of Experimental Geophysics, Seismological Laboratory, California Institute of Technology, 2003.

Ball, A., McKenzie, H.W., On the low velocity impact behaviour of glass plates, Dept of Materials Engineering, Univ of Cape Town, South Africa, 1994.

Byous, J.D., Hertzian Fractures And Related Terms – A Glossary, A.T. Dowd Research, AAtR Publishing, Savannah, GA, 2013.

Connect with Caltech, News, Obituary, Thomas J. Ahrens.12/10/2010. http://www.caltech.edu/content/thomas-j-ahrens-74.

Forde, L.C., Proud, W.G., Walley, S.M., Ballistic Impact Studies of A Borosilicate Glass (BIS), Fracture and Shock Physics Group, Cavendish Laboratory, Cambridge UK, 2009.

High Resolution Imaging Science Experiment (HIRISE) Arizona State University, http://www.uahirise.org.

Kirchner, H.P., Kirchner, J.W. Fracture Mechanics of Fracture Mirrors, Ceramic Finishing Company, State College, Pennsylvania 1979.

Photojournal, NASA Jet Propulsion Laboratory, California Institute of Technology, http://photojournal.jpl.nasa.gov.

Bibliography

Ahrens, T.J., Xia, K., Cokert, D., Depth of Cracking Beneath Impact Craters: New Constraint for Impact Velocity, Seismological Laboratory 252-21, Institute of Technology, Pasadena, CA, Guggenheim Aeronautics Laboratory 105-50, Calif. Institute of Technology, Pasadena, CA.

Arizona State University, Mars Odyssey THEMIS Archives, http://themis.asu.edu/.

Baratoux, D., Melosh. H.J., The formation of shatter cones by shock wave interference during impacting, Laboratoire Dynamique Terrestre et Plane¤taire, Toulouse, France, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, 2003.

den Toonder Jaap M.J., A General Introduction To Fracture Mechanics and Mechanical Strength of Materials, Or: Why do things break and what can we do about it?, Unclassified report, Philips Electronics, 1998.

Doquet, V., Ben Ali, N. A., Constantinescu Laboratoire de mécanique des Solides, CNRS, Ecole Polytechnique, 91128 Palaiseau cedex, France. Crack paths in a borosilicate glass under triaxial loading.

Ernstson, K., Rampino, M.R., Hiltl, M., Cratered cobbles in Triassic Buntsandstein conglomerates in northeastern Spain: An indicator of shock deformation in the vicinity of large impacts, Geology, The Geological Society of America, 2002.

Frank, F.C., Lawn, B.R., H.H. Wills, On the theory of Hertzian fracture, 1966, Physics Laboratory, University of Bristol.

French B. M. Traces of Catastrophe: A Handbook of Shock-Metamorphic Effects in Terrestrial Meteorite Impact Structures. LPI Contribution No. 954, Lunar and Planetary Institute, Houston. 120 pp, 1998

Holsapple, K.A., Theory and equations for "Craters from Impacts and Explosions", 2003.

Korteniemi, J., Aittola, M., Ohman, T., Raitala, J., Floor-Fractured Craters On the Terrestrial Planets – The Martian Perspective, Astronomy, Physical Sciences, University of Finland, Department of Geosciences, Division of Geology, University of Oulu, Finland.

Kumar, P.S., Kring, D.A., Impact fracturing and structural modification of sedimentary rocks at Meteor Crater, Arizona, 2008, Journal of Geophysical Research, Vol. 113, E09009, doi:1029/2008JE003115, 2008.

Meintjes-Van Der Walt, L., Shattering the silence: How glass analysis speaks, Academia.edu, 2005.

Miyamoto, A., Murakami, Y. The Morphology of Hertzian Cone in Plate Glass by Projectile Impact, The Society of Materials Science, Japan, Vol. 49, No.8, pp867-872, Aug. 2000

NASA Jet Propulsion Laboratory, California Institute of Technology Image Archives, Arizona State University, http://www.jpl.nasa.gov.

.Ori1, G.G., Baliva1, A., Large Bulges at the Center of Impact Craters on Mars, IRSPS, Universita' d'Annunzio, Viale Pindaro, Pescara, Italy.

Sagy, A., G. Cohen, Z. Reches, and J. Fineberg (2006), Dynamic fracture of granular material under quasi-static loading, J. Geophys. Res., 111, B04406, doi:10.1029/2005JB003948.

Walley, S.M., Historical review of high strain rate and shock properties of ceramics relevant to their application in armour, Advances in Applied Ceramics, Institute of Materials, Minerals and Mining, 2009.

Walley, S.M., Field, J.E., The contribution of the Cavendish Laboratory to the understanding of solid particle erosion mechanisms, Physics and Chemistry of Solids(PCS) Group, Cavendish Laboratory, University of Cambridge, Cambridge, UK.

Appendix I

Sandstone rock with Quartzite

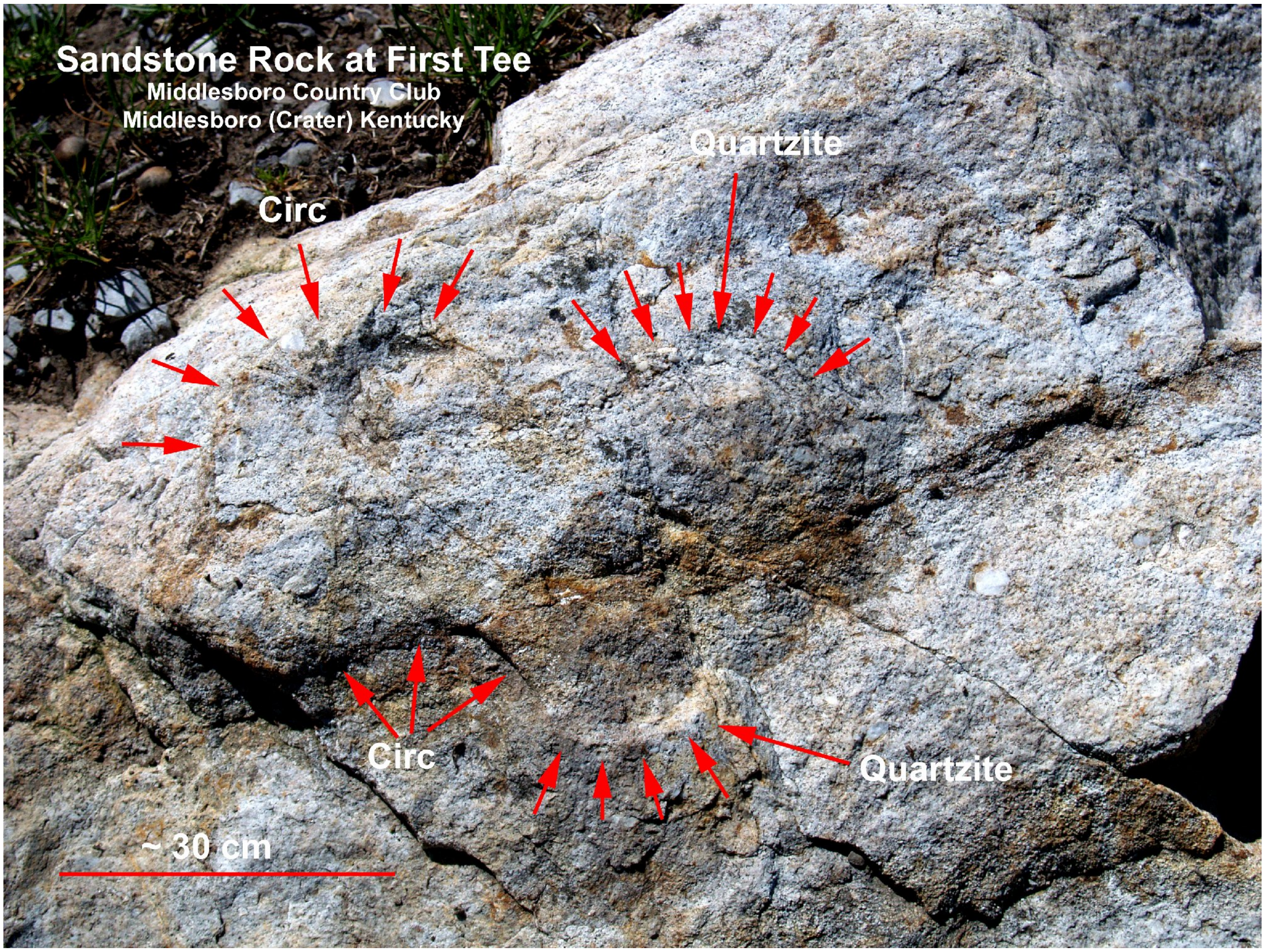

Figure 30 *This sandstone rock with Quartzite circs is next to Middlesboro Country Club's first tee, the location of the central uplift for the Middlesboro impact crater Features are similar to Tracy's Rock as seen in figure 26.. Shatter cones were found near this site by England and Roen in 1963. Shatter cones can still be found on the club grounds. Englund, K. J., Roen, J. B., Origin of the Middlesboro basin, Kentucky. U.S. Geological Survey Professional Paper 450-E, pp. E20-E22. 1963.*

Appendix II

Parenthetic Features of Upheaval Dome, UT.

Photos: Doc Searls. Creative Commons use via Wikipedia.

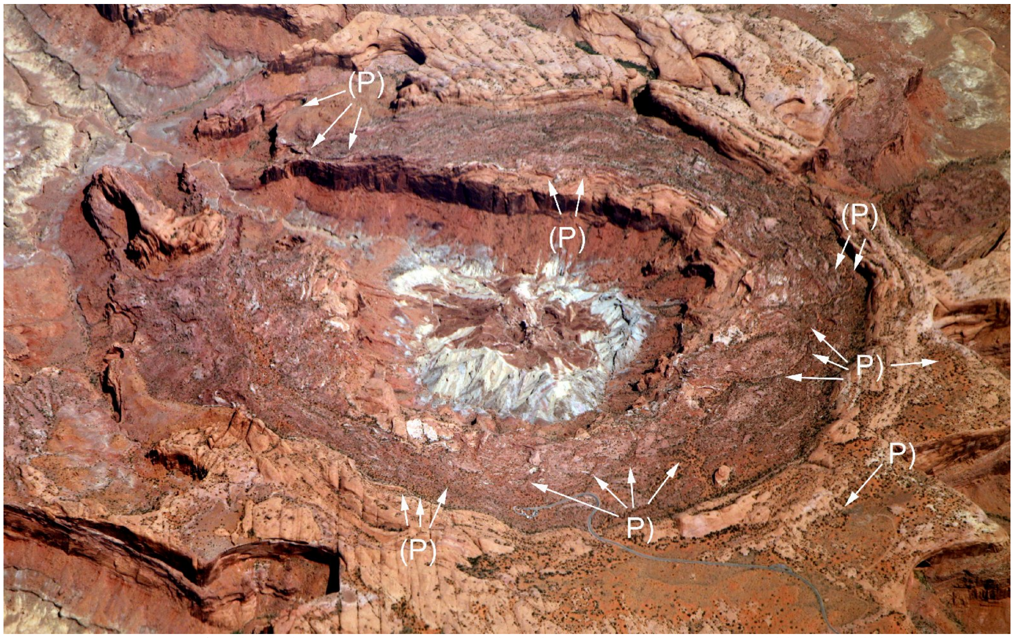

Figure 31 *Overview of Upheaval Dome, Arches National Park, UT. Parenthetics are visible around the monocline above the crater. Some appear as plant circs and others are visible as differences in opposing joint segments.*

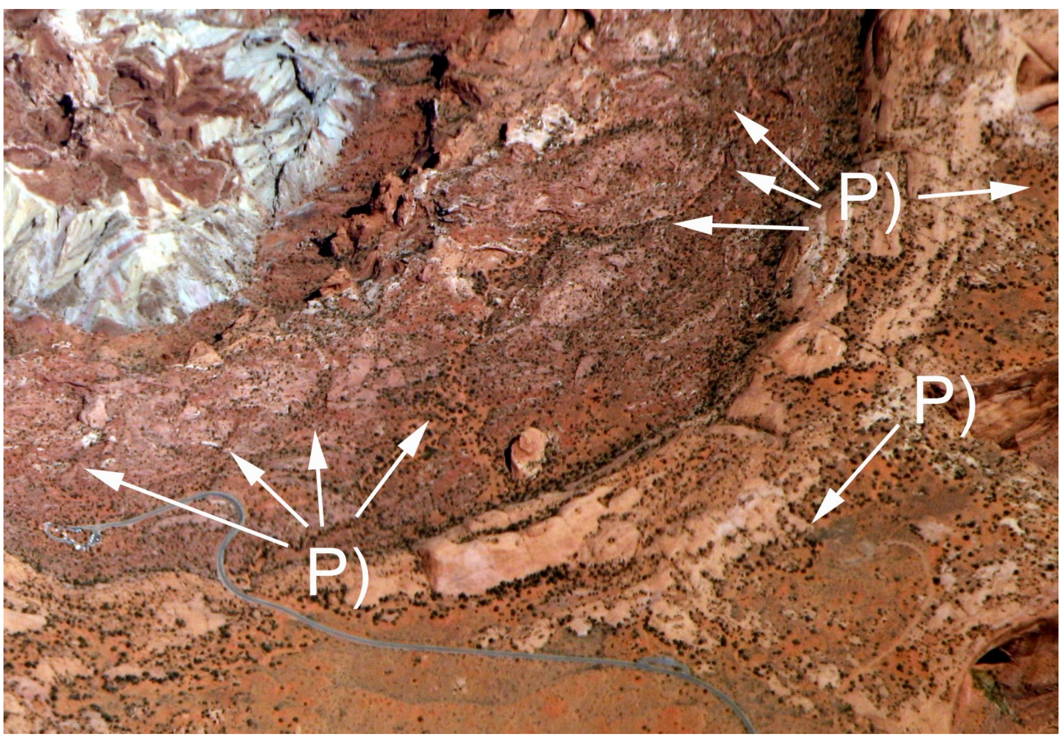

Figure 32 *A closer view of Upheaval dome's south rim with parenthetics.*