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Occam's Razor and Mars: Hertzian fractures, Gale and other domed and fractured craters

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Terms used in this paper can be found in Hertzian Fractures and Related Terms – A Glossary and The Physicalities of Hertzian Fractures.[1]

ABSTRACT

Gale crater is a 155 km diameter impact crater that is at its center a blend between a compound and a coved-shield-type Hertzian cone (HC). Its features include a tilted peak and dome and dual wings on the east and west in arcs running north to south which are typical of low-angle impacts that create Hertzian fractures (HF) in glass and ceramics. Gale's mound strata were laid over the years and in the flash of one meteoric impact the sub-surface cone was created. The bowl-shaped crater area eroded to a level below the original crater floor as wind quarried and dispersed the dust of the surrounding upper plane. Around the impact-compressed cone-mound of Mount Sharp (Aeolis Mons) wind forces carved out and carried away uncompressed material enlarging the bowl to reveal the lower mound. Gale Crater is now eroded well below the original surface by aeolian reduction revealing the totality of the current structure. In the future Gale crater could include a still deeper bowl and taller mound as more material is extracted. The main peak-shaped point-of-impact (POI) of Mount Sharp stands at ~5 km above aqueous and aeolian deposited crater-floor strata that is comprised of sediment rock and dunes. A larger, second point-of-impact peak stands ~20 kilometers to the north forming the main upper mound that stands above the winged ridges to the ESE and WSW. This wider dome POI area on the mound's center-north quadrant suggests at least two coincidental impacts by a fragmented projectile. Arroyos and canyons that cut through the mound hold similarities to features found in other Hertzian cones. The mound area of Mount Sharp contains the five classic features found in many HC and HF structures; point of impact, mirror, mist, hackles region and Wallner undulation lines. Yardang-shaped hillocks along the body of the mound appear to be eroded hackles as can be found on compound HC structures. Features formed by projectile impacts that are similar in shape to Mount Sharp can be found in the windshields of cars in countless mall and market parking lots around the world. Like the ding in a glass window, Mount Sharp is the structure of a common Hertzian fracture -- a projectile-impact-induced stack of compacted crystalline material. Gale is only one of innumerable and similarly created structures on Mars and other rocky planets and moons in the universe.

INTRODUCTION

Mound craters are like poorly designed sports arenas--seating on the outside with a dome over the central field of action. After the main impact blast, the mound is where the action took place and the rimming bowl is where transition and egress proceeds at a leisurely pace. Domes in craters are HC positive segments of Hertzian fractures and can contain the five main Hertzian features; point of impact, mirror, mist, hackle and Wallner lines as shown in figure 17. The overburden contains the mold section of the HF as shown in figure 1. The initial crater is a small tip-of-the-iceberg occurrence. Hertzian fractures in themselves are neutral; the void between the cone and the mold. The cone segment is many times larger than the inverse of the crater with fractures running deep into the target material, figure 29. As erosion progresses the original crater erodes into an expanding, downward and widening circle while surrounding strata are washed, worn or blown away along the lines of the fracture. Though the term Hertzian fracture was not used, Thomas J. Ahrens experiments with impacts of sandstone and granite display this structure. Cross-sectional cuts of these studies show the crater hollow above a vastly larger HC section of stone.[2] The mound remains less effected by erosion and therefore intact due to compression during impact. It is be similar to compressed hammer or planer marks on wooden boards after processing. The blade-beaten, compressed fibers resist the sanding process if no sanding block is used.[3] It is suspected that in aqueous strata the impact area creates fracturing beyond the crater walls the way oil and gas shale is "fracked" in North Dakota oil fields. It weakens the annular rock and promotes rapid erosion. Variation of central peak and domes in craters are variations of erosion or spall evacuation of surface material around the HC.

[1] Byous, James D., *The Physicalities of Hertzian Fractures*, and *Hertzian Fractures and Related Terms – A Glossary*, A.T. Dowd Research, AAtR Publishing, Savannah, Ga. 2013.

[2] Huirong Ai (with Thomas .J. Ahrens), *Shock-Induced Damage in Rocks: Application to Impact Cratering*, pp 115-116, Figure 5.2b. Caltech, 2006, and LaSalvia, J.C., McCuiston, R.C., Fanchini G., McCauley, J.W., Chhowalla, M., Miller H.T., and MacKenzie, D.E., *Shear Localiztion in a Sphere-Impacted Armor-Grade Carbide*. 23RD INTERNATIONAL SYMPOSIUM ON BALLISTICS TARRAGONA, SPAIN 16-20 APRIL 2007, pp 1331-1334, figures 1a,1b and figure 4.

[3] Bob Flexner, *Rules for Sanding Wood*, Popular Woodworking Magazine, April 8, 2008, and *Preparing Wood For Finish*, August 2010, The Finishing Store.com.

Multi-ring craters are in the same manner created except that the spinner and POI are comminuted and flattened out to the laminae on the radius of the POI.

Since primitive times Hertzian fractures, also know as conchoidal fractures, were used to sharpened edges of lithic blades and points. Their creation uses the same principle of physics that forms conical fractures in planets and moons when a speeding bolide strikes a planetoid surface. In a spear point, HF's are created by using an indenter applied with angular pressure on a point of rock to create hollowed fluted sections, figure 10. The body of the blade is the equivalent of overburden and the flute is the mold (negative) section of the fracture. The partial cone (positive) section is shed in the process and is discarded. In ceramic dentures and glaciated-granite rock surfaces "flutes" can be found after a tooth slides along a ceramic denture implant or rock boulders in glaciers, figure 2 and 3, grind along granite walls and planes to create chatter marks.[4]

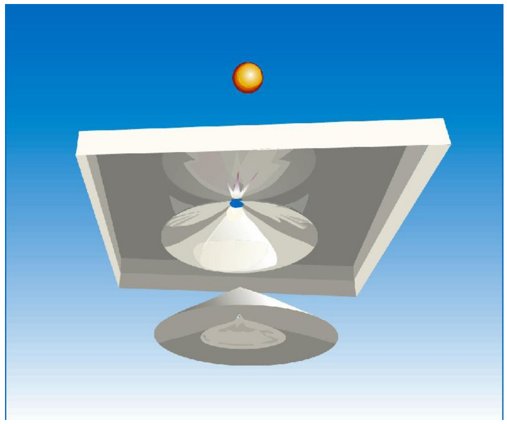

Figure 1 *Diagram of a Hertzian fracture. The overburden is the main sheet. The projectile strikes the pane and creates a cone shown below the mold (void) in the overburden. If the impact is of high velocity the cone is fragmented but retains its shape*

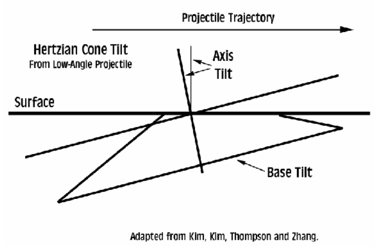

Figure 2 *Diagram adapted from Kim et al showing axis tilt in HF in ceramic and glass material due to low angle compression..*

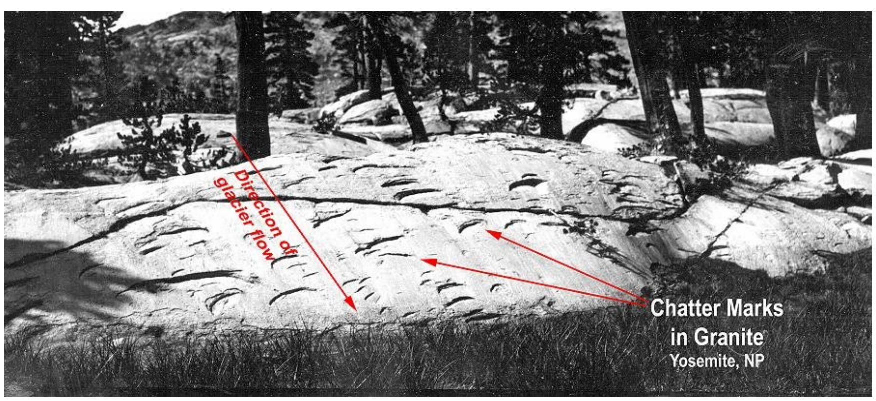

Figure 3 *Chatter marks, semi HC's, created by boulders being dragged across the surface of the granite creating tilted Hertzian fractures. Transient boulders serve as indenters creating results as described by Kim et al in ceramics and glass studies. The angle of the indenter or projectile pressure determines the angle of the HC. Gale Crater is a sample of a tilted HC.*
Photo, G.K. Gilbert USGS 1903.

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[4] Kim, J.-W., Kim, J.-H., Thompson, V.P., Zhang, Y., *Sliding Contact Fatigue Damage in Layered Ceramic Structures*, Department of Biomaterials and Biomimetics, New York University College of Dentistry.

This semi-cone is caused by the inertia of the projectile transferring energy into the material, slanting the formation of the cone and fracture. The cone's base tilts along the trajectory of the impacting projectile the way light refracts below the surface of glass or water. At very low velocity and angles >10° above the glass surface, the projectile can bounce off with a small amount of scuffing or by creating a circular fracture and/or a front side semi-cone. Around 20° to 30° the tilted cone can form below the surface. Spinning and rotation of a projectile will also affect the slant and shape of a cone in glass studies, therefore it is suggested that spinning bolides or fragments of bolides will have some influence on those feature in rock. Front side semi-cones can also be created in by low velocity projectiles as seen in figure 4.

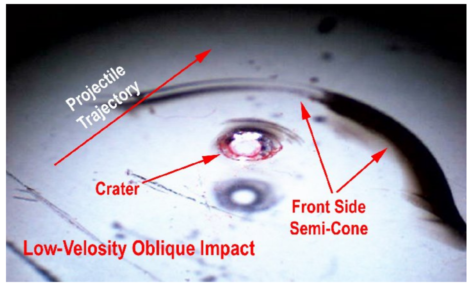

Figure 4 *A low-velocity oblique impact in soda lime glass displays a front-side semi cone.*

Methods for HF creation

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.[5] Velocity was adjusted by distance from the target, 7.62cm to 1 meter. 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 generally from 45º to 60º and also true vertical at 0/360º.

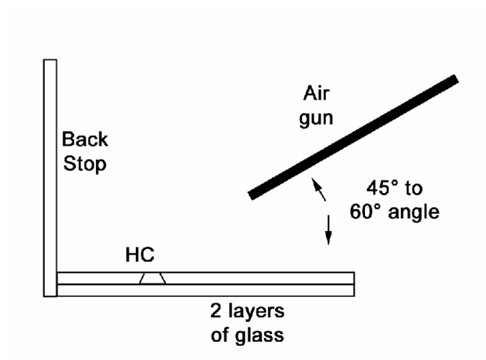

Figure 5 *Configuration of impact sample set.*

GALE CRATER

Configured in a sloping plane between the Naochian Age highlands' southern region and the Hesperian Age lowlands northern edge, 155 km Gale Cater has a ~4% south to north grade due the regional tilt. The crater sits directly on the transition line between the two. Contrary to the tilt of the overall crater, the cone has a ~7% dip toward the south at a radius of 30 km from Mount Sharp's central peak. The combined slope difference between the crater rim and the mound tilt equals ~11%. The peak itself has a similar tilt at ~7% to ~10% toward the south. This difference is within the sample evidence for cone sub-surface, full-cone tilt in sliding indenter on glass studies by Kim, Kim, Thompson and Zhang. Lesser angles create partial-cone chatter marks as mentioned above. However, as mentioned, rotation of projectiles can create variances in cone tilt in glass HC's as well creating problems for establishing causation.

Sedimentary rock makes up the whole of Mount sharp in Gale Crater. It stands ~5 km above a water and aeolian deposited flat of sinuous ridges, dark-colored basalt dunes, squared bluff and meteor-peppered terrain. In the center of the crater is the main peak that creates POI #1. The second and largest bolide-fragment-created POI is directly to the north, the upper mound.[6]

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

[6] A small, eroded and possibly Gale-related impact lies 123 km, 334° NNE from the peak of Mount Sharp. It has a south-to-north impact trajectory with a rim-to-rim measurement of 28 km. This partially-buried crater has an evenly slanted floor with the strike

Wing-shaped appendages lie to the east and west of the central points of impact. Uniform, eroded hackle features stripe the southern slopes in the form of yardang or drumlin-like mounds, figure 6. The term yardang is used by Armstrong and Bell and others[7] and replicate large and small Hertzian features described as hackles and feather hackles in the Byous publications*, Hertzian Fractures and Related Terms – A Glossary* and *The Physicalities of Hertzian Fractures*.[8] These features are similar to hackles on compound HC's as well as winged and buttressed samples as seen in figures 6, 7, and 8. They are formed when the smooth mirror portion of a HF changes direction downwardly in a "ripping" of the two faces of the HF, the cone and the mold, as energy pulls them apart. Other fractures throughout the mound taking on the appearance of arroyos and canyons appear to be tensional fractures as are found in compound Hertzian cones. When a projectile strikes the target material the inertia in the direction of travel pulls the material creating wing-like fractures, crab fractures or crab cracks that sometimes take on the appearance of the legs of the crustaceans. They are much like a wake through the material as the impact point is compressed and pulled along the trajectory like a finger pulling on congealed gelatin.

The trajectory of the Gale impactor was from south to north at ~N7.5°E at a low angle. The projectile was fragmented into at least two segments, Figure 37. The first segment struck the surface creating the peak in the center of the dome. The second and largest struck just to the north and slightly to the west creating the northern upper mound. The history seen in sedimentation of Gale mound is the history before the crater was formed by impact. The cone is a compressed record of multiple surfaces as sediment was laid down over the years, thus agreeing with Milliken, et al in the events of the sedimentation of the landscape. The central upper mound is composed of near-surface strata at the time of impact and relatively little erosion when compared to the surrounding and outward growing crater walls.

There are differing hypotheses on the formation of Mount Sharp in Gale Crater. They vary from water to wind to tectonic uplift. Water is described as a possible building source of the mound's growth through spring deposits in Rossi, et al.[9] Water is also described as a depositional source for building strata as described by Milliken, Grotzinger and Thompson.[10] Descriptions of wind creation are found in Kite, Lewis, Lamb, Newman and Richardson*,*[11] and tectonic actions are suggested by Kraft and Christensen.[12] The latter three have elements that agree in part with this paper's assertion.

Aeolian processes are responsible for the creation of Gale mound strata. But that course of action was before the bolide impact. After the impact the process was instrumental in the denudation of the outer crater material probably combined with ejection of materials during the impact, the inverse of the Kite, et al, hypothesis. The mound shape was not deposited by wind; the outer-crater overburden was carried away by wind to reveal the mound shape. The material in Mount Sharp is the same country rock that makes up the surrounding strata albeit compressed and is a typical Hertzian cone with comparatively little erosion on the surface of the mountain. Many, if not most of the Hertzian physicalities are still present on the slopes; mirror, hackles, feather hackles, Wallner lines and others. For an overview of current hypotheses consult Anderson and Bell. Volcanic contributions to Gale Crater will be addressed in the Volcanism section of this paper and agrees in part with Kraft and Christensen.

~87° and a dip ~8%. The floor tilt could be aeolian deposited, but the angle is similar to that of the larger Gale Crater to the SSE. A 13 km by 16 km mound to the south of the small crater appears to be a remnant of the southern crater rim.

[7] Ryan B. Anderson and James F. Bell III, *Geologic mapping and characterization of Gale Crater and implications for its potential as a Mars Science Laboratory landing site*. Department of Astronomy, Cornell University, MARS, The International Journal of Mars Science and Exploration.

[8] Byous, James D., *The Physicalities of Hertzian Fractures*, and *Hertzian Fractures and Related Terms – A Glossary*, A.T. Dowd Research, AAtR Publishing, Savannah, Ga. 2013.

[9] Angelo Pio Rossi, Gerhard Neukum, Monica Pondrelli, Stephan van Gasselt, Tanja Zegers[1], Ernst Hauber, Agustin Chicarro Bernard Foing, Large-scale spring deposits on Mars?, *Large-scale spring deposits on Mars?,* Journal of Geophysical Research: Planets (1991–2012), Volume 113, Issue E8, August 2008. "We present a large-scale spring hypothesis for the formation of various enigmatic light-toned deposits (LTDs) on Mars. Layered to massive LTDs occur extensively in Valles Marineris, chaotic terrains, and several large craters, in particular, those located in Arabia Terra… Internal unconformities and evidence of large temporal hiatus (e.g. in Gale crater bulge) are consistent with an intermittent or multistage process, e.g. supply of water from the subsurface. In this hypothesis, the presence of interbedded eolian deposits could not be excluded locally."

[10] Milliken, R. E., Grotzinger, J. P., Thomson, B. J., *Paleoclimate of Mars as captured by the stratigraphic record in Gale Crater* Geophysical Research Letters, Vol. 37, 2010.

[11] Kite, E.S., Lewis, K.W., Lamb, M.P. Newman, C.E., Richardson, M.I. *Possible role for slope winds in forming Gale Crater's mound (and other sediment mounds on Mars): The slope wind enhanced erosion and transport hypothesis.,* 44th Lunar and Planetary Science Conference, 2013. And, Growth *and form of the mound in Gale Crater, Mars: Slope wind enhanced erosion and transport*, Geology, 2012.

[12] Kraft, M.D., Christensen, P.R., *Techtonic formation of Mount Sharp, Gale Crater*, Mars, 44th Lunar and Planetary Science Conference, 2013.

Gale Crater configuration

Gale Crater mound is a composite Hertzian cone containing many physical features commonly found in like Hertzian fractures in glass. Glass HC's are fairly simple due to its consistent homogenous makeup. Rock, however with ample heterogeneities can be complicated to decipher and predict. Glass HC's are like snowflakes, no two are exactly alike. Those in rock have their deviances augmented. As mentioned above, Hertzian features in surface cratering were addressed in the paper *Comparative Hertzian features in glass and rock (impact craters.)*[13] This paper deals with the physicalities of sub-surface HC's in glass and their similarities to features found on the Gale Crater mound.

For this study we divide the Gale Crater Mound into four near-equal quadrants, north, west, south and east as shown in figure 6. Overall the mound is in the shape of a tilted, wing-buttressed, shield-shaped HC, figure 7, as described above. The north segment contains the two points of impact. The first bolide fragment struck to form the peak of Mount Sharp in the manner as can be found when a pedestal is formed when a projectile strikes the flat surface of glass as seen in Figure 28. In these instances the energy is transferred downward for a short distance before it turns outward moving at the speed of sound in the target material. After the creation of the point-of-impact (POI) pedestal and the HF feature, the mirror segment is created as the wave smoothly moves outward as the inertia from the projectile continues to force the cone down.

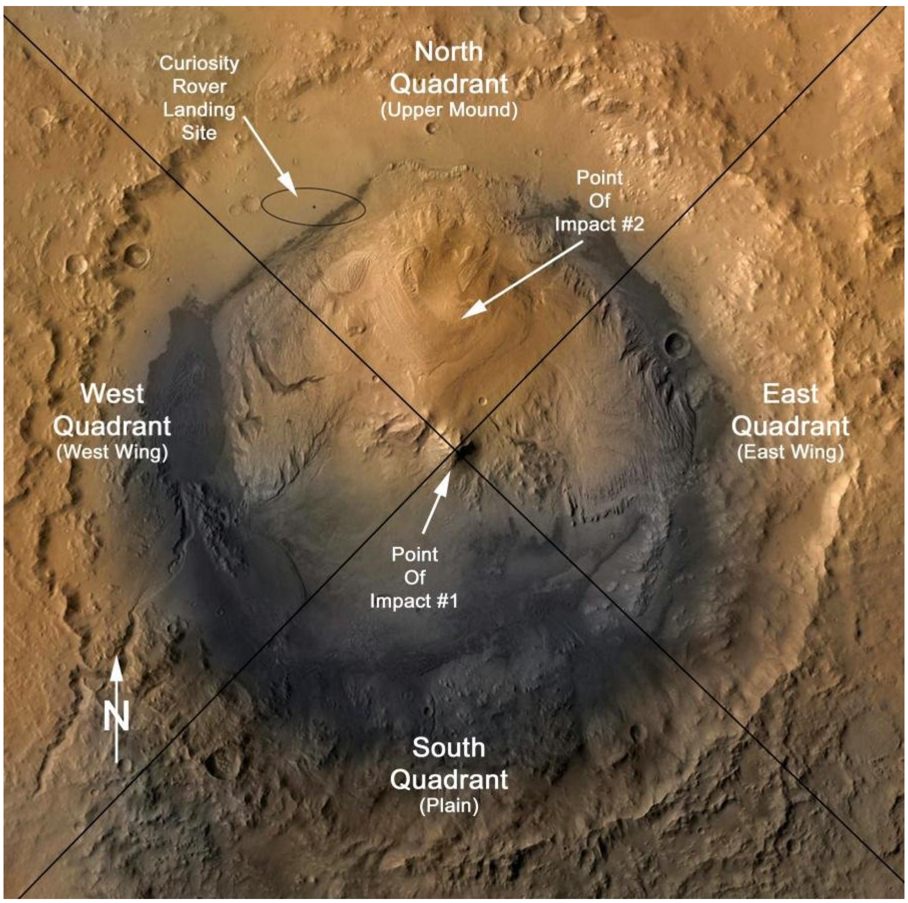

Figure 6 *Gale Crater divided into four quadrants, North, West, South and East.*

[13] http://dowdresearch.academia.edu/JamesByous or http://www.dowdresearch.org/ComparitiveFeatures.html

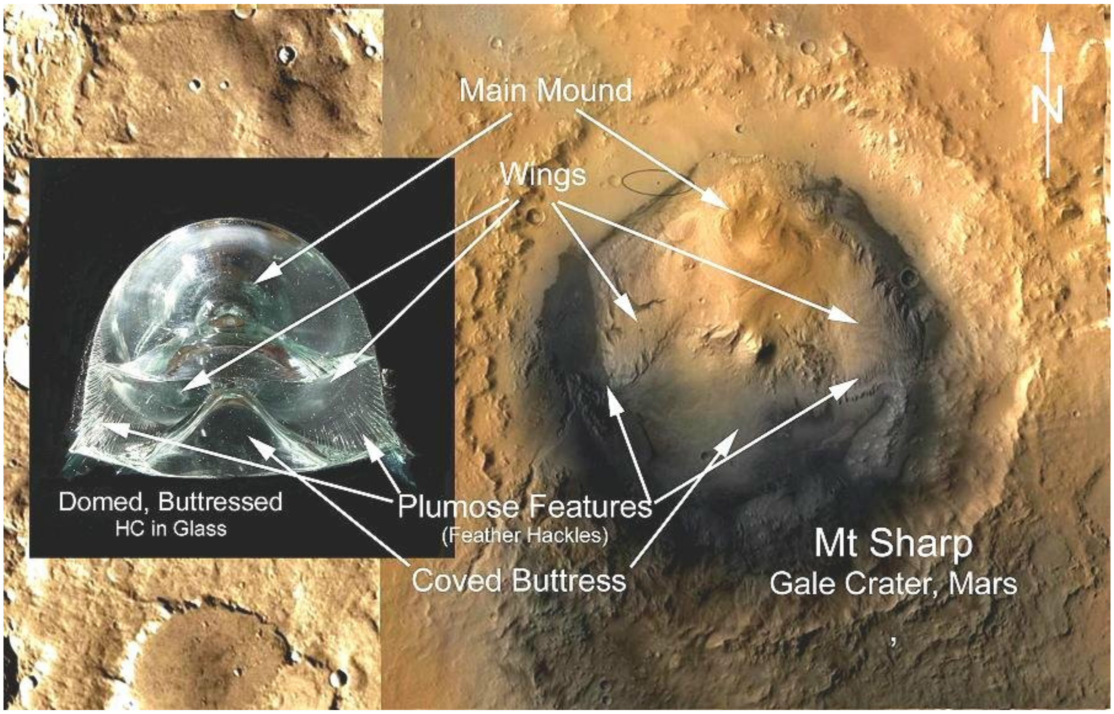

***Figure** 7 Gale Crater compared to a shield-shaped HC with a winged buttress at bottom.*

The shape and physicality of an HC is determined by the target mass, projectile mass, projectile velocity and projectile trajectory. In low-velocity impacts the cone material is forced beyond its elastic boundary into the plastic zone as inertia of the impact travels downward and outward. The moving fracture is pulled away from the POI and overburden by the compressing cone. In high-speed, high velocity bolide impacts the inertial force is augmented by the resultant explosion created by the compression of the projectile. Variances in the speed, mass and constitution of the target then determine if the cone is pulled from the overburden smoothly or if it begins "ripping" to forming mist and hackle features as described in Buehler and Gao in *Modeling Dynamic Fracturing Using Large-Scale Atomistic Simulations*.[14] In the Gale impact this action began the formation of the HC microseconds before the secondary impact created the larger, forward, upper section of the mound. When the second bolide fragment struck near-simultaneously with the first, the fracturing converged to form the totality of peak and upper mound areas. Near-simultaneous convergence of HF's can be seen in the Scot's Jump illustration in HC glossary. The differences between the two types are similar in result of form.

North Quadrant and mound area

Glass HC point-of-impact physicalities and their similarities to the upper mound of Gale Crater can be seen in figure 7. Here one can observe tensional fractures in glass and the corresponding features of the Upper mound. Between POI-1 and the POI-2 upper mound one can observe sweeping lines forming triangular, tension-wake areas. Tensional wakes are similar to the wake of a boat's stern as it moves and displaces water. The water converges at the transom to form a "V" or triangular shape within an outward forming and inverted "V". In water the bow of the vessel forces energy waves to the sides in the same manner as a projectile forces the glass or rock material around the point of impact. In transparent glass "crab fractures," leg-like fractures, form along the edges of the shifting target material as inertia pull the material beyond the elastic boundary. In opaque materials these features are obscured but can be seen overall in the shape of the winged segments of the lower mound. Based on the center of the angle of the triangular-shaped tension (transom) wake the trajectory of the projectile was ~N7.5°E.

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[14] Buehler, Marcus J., Gao, Huajian, *Modeling Dynamic Fracture Using Large-Scale Atomistic Simulations*, http://web.mit.edu/mbuehler/www/Teaching/IAP2006/dynamic-fracture_buehler-gao-Dec13.pdf.

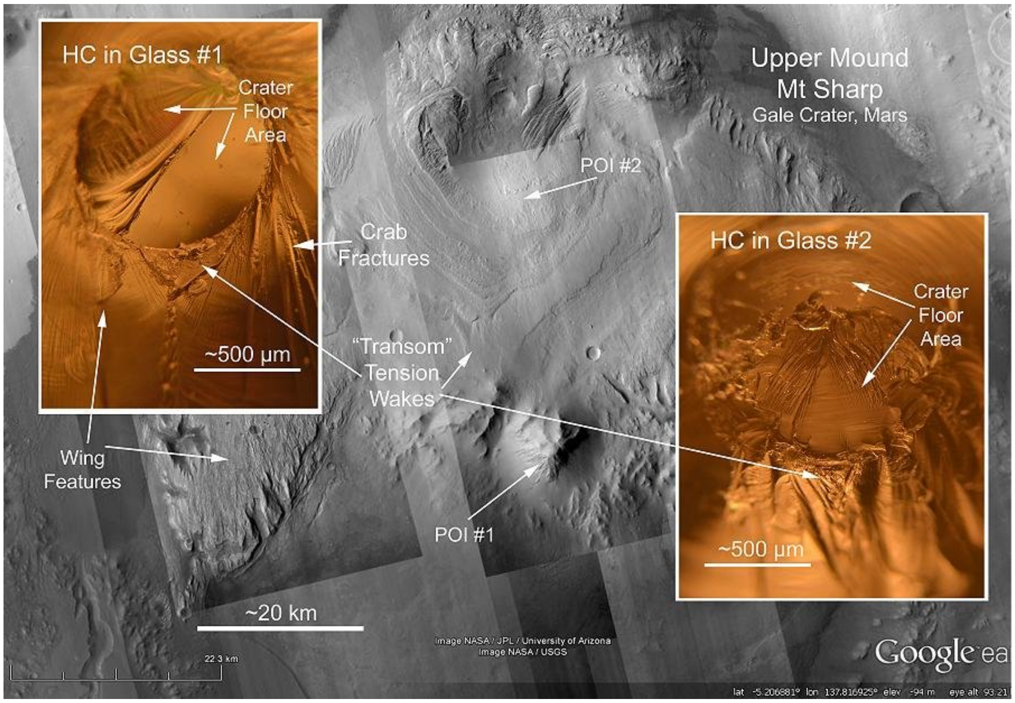

Figure 8 *Comparisons in Points of impact on two soda lime glass samples and the upper mound of Gale Crater. Tension features are evident in all three looking like the wake behind the transom of a boat. The projectile forces the impacted area along the trajectory causing tension bulges and fractures in the wake. Wing-like fractures form along the edges of the POI area that in some specimens resemble crab legs or the outward forming wakes along the gunnels of a moving boat. Gale crater appears to have two POI's created by a fractured, segmented bolide. The projectile trajectories are from the bottom of all three frames.*

At the northern edge of the mound is a couloir-like depression situated within the slope shown in figures 8, 9 and 10. This feature is similar to, and appears to be, a flute-void created by the impact of the projectile. Archaeologists usually refer to these as conchoidal fractures. They are tilted semi-HC's. Similar features can be found in lithic blades and stone tools. It appears that here the percussion of the projectile/indenter fractured the mound in a manner whereby erosional forces now reveal the flute segment. Over the years the flake segment was reduced and sloughed off. It may be possible that the fragmented core will be found in the comminuted rock at the base of the slope. The angle and depth would be consistent with like stone-blade features. During Gale's secondary impact the diverted rock mass served as the indenter, creating the flute.

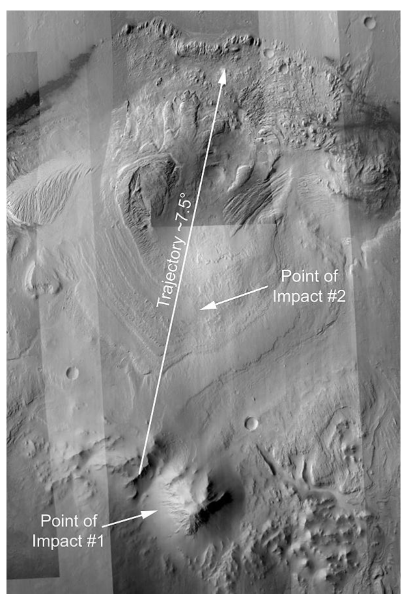

Figure 9 *The trajectory and angle of the couloir on the north side of the upper mound area.*
The gap appears to be a "flake" that was created during impact like the depressions on a lithic blade.

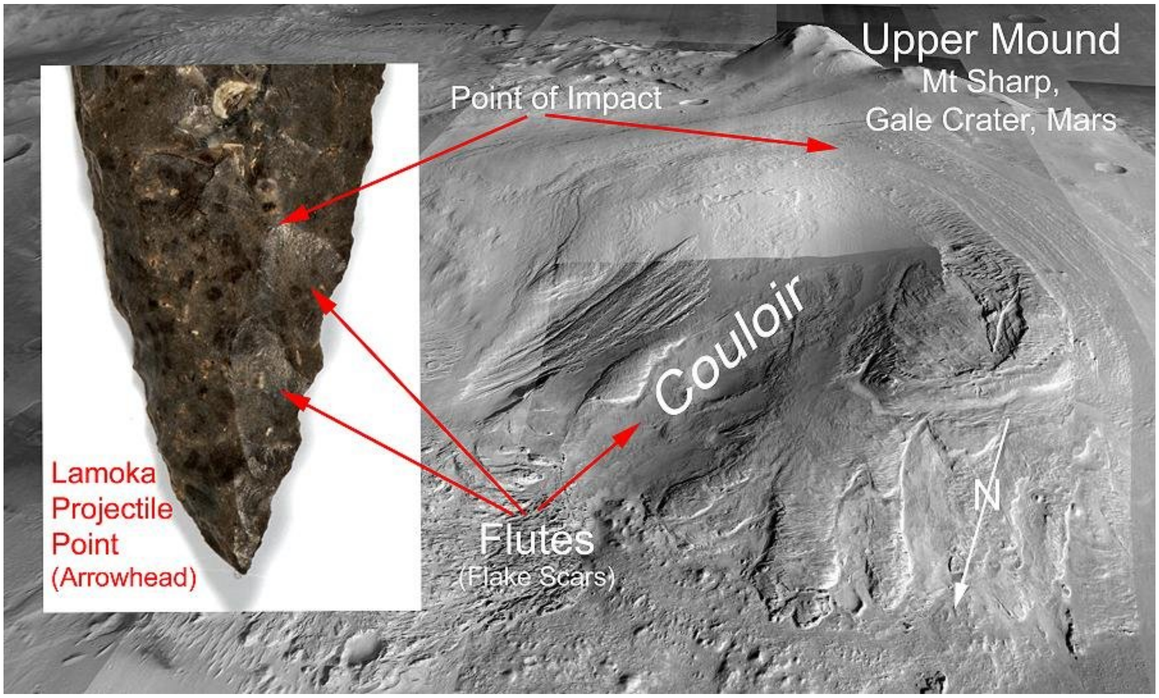

Figure 10 *Gale Crater's upper mound compared to a Lamoka projectile point. The couloir and the blade flutes were created by angled pressure at their upper points. (Lithic point image by PAR via Creative Commons Attribution/Share-Alike License.)*

Lobate features

Along the edges of the couloir are lobate features that stretch from the upper mound toward the crater floor. These are described by Anderson and Bell as mound skirting that has eroded into lobe-shaped features. However, similar features are found in HC samples as shown in figure 11 can be found with a like, proportional purlieu. They are sub-surface features just below the plane of the cone and could be related to the Gale Mound features.

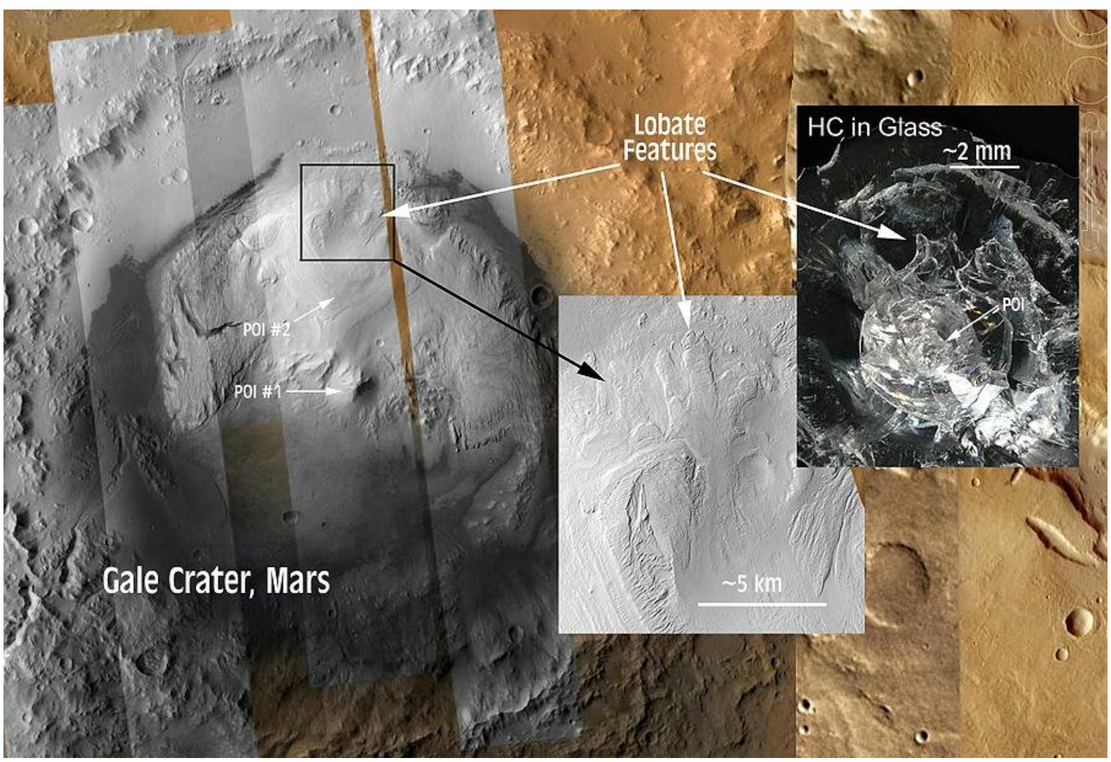

Figure 11 *Lobes on the north slope of Gale mound are similar to those found in partially crushed Hertzian cones shown in insets.*

Western Quadrant and northwest mound base

Step structures are found along the northwestern base and are consistent with similar features in HC's. Near the Curiosity Rover landing site are terraced benches that stretch from that location to the chasm that is sometimes called Gale's "Grand Canyon" in the southwest section. These are similar to features found in many compound HC's when the overburden has been removed. Steps and undulations are created by pressure wave (P-waves) as they bounce from lower strata during cone creation. They are instrumental in forming undulations and terraces since they change the course of the HF as it moves outward and downward. In some samples undulations were present before overburden removal. In others annular laminae slumped when overburden was detached. The laminae align in an onion-peel configuration from samples having only one set of annular layers to others with several overlapped layers. The HC shown in the upper left of figure 12 shows a compound HC with two major laminae steps and smaller hackle-lamina segments dispersed around the base. In glass these laminae may be pulled away from the main body of the HC displaying in some samples an inner core or a crushed core that has been described as a three-dimensional jig-saw puzzle.

Along the edges of the steps are yardang-like ridges. These correspond to the lower flange boundaries of many compound HC's. Comparative images seen in figure 12 show the corrugated step areas of a glass HC and the similar structure of the lower terraces of Gale mound. These forms of hackles are commonly found on the edge of compound or crushed HC extremities, figure 13. The edge of the lamina plate (hackle plate) also corresponds with the line of Gales "Grand" canyon on the western slope marking the division of laminae plates. As seen in the illustration the uniform hackle lines end at the fracture juncture on both the glass sample and on the Gale mound.

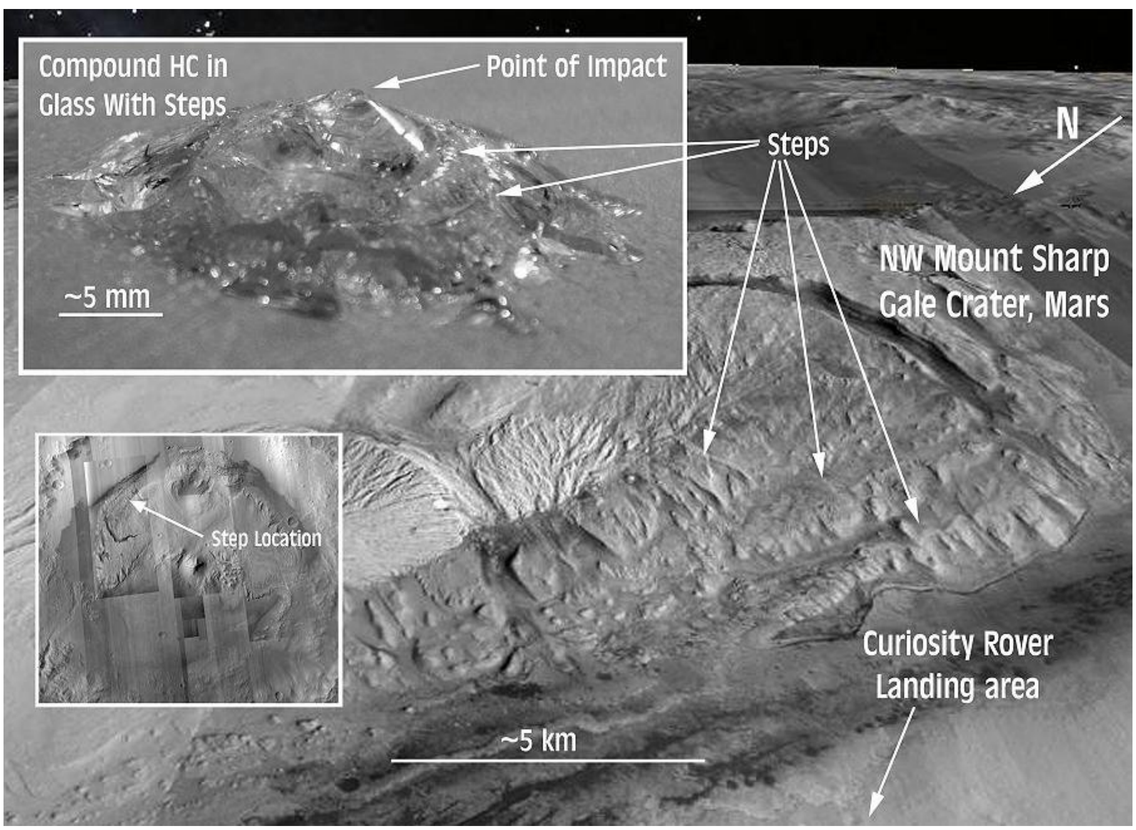

__Figure 12__ Steps in Gale mound are compared to a crushed HC shown in the top inset. The location is near the Curiosity Rover landing area. The areas have hackled, yardang-like features running radially from the point of impact.

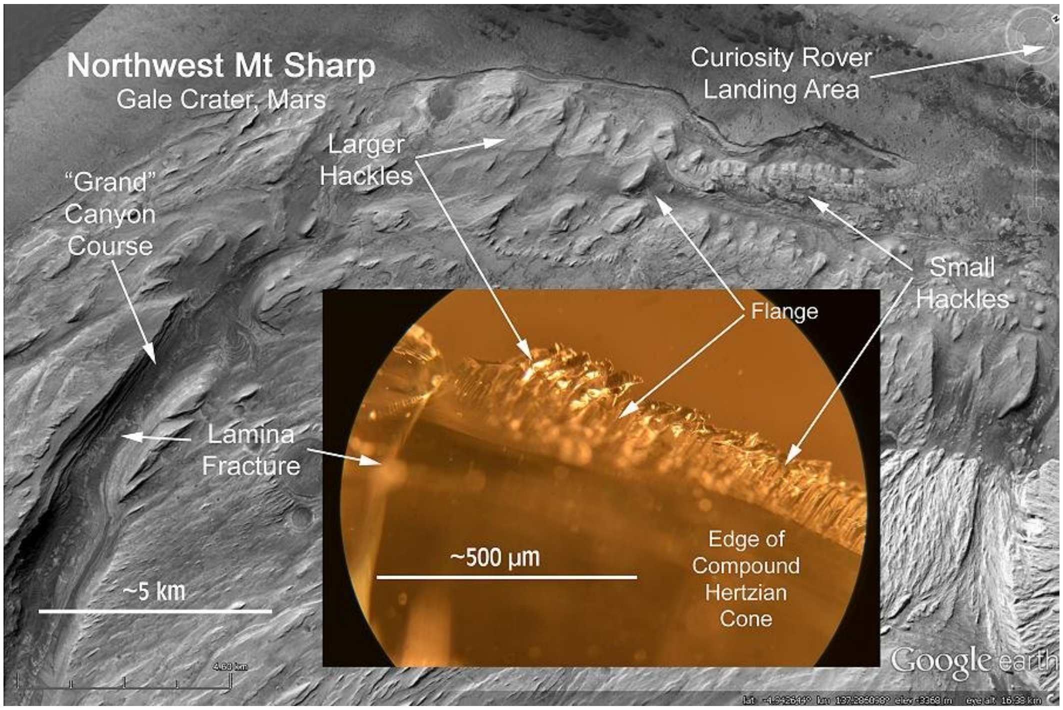

Figure 13 *Here a hackled flange of a Hertzian cone is shown in comparison to the steps in that are divided into the west and north quadrants of Gale Crater. These are features are often found along the bottom edge or flange of an HC near stratification divisions in layered glass. Here the similarities are striking with a lamina-edge fracture approximating the canyon course on the crater mound with hackles lining the lower slope where the mound intersects with the crater floor.*

Inverted riverbed

Dubbed the "Inverted Riverbead" in the HIRISE image PSP_009149_1750, an image of the lower base region of the mound, has similar features to thickened hackles along the base of Hertzian cones. These can be compared in the inset images found in figure 14. It is believed that the base flange is thinned to its blade-like shape where P-waves bounce faster thinning the flange outward. The waves react to like dribbling a basketball, the bounce rate increases as the ball is forced in to a shorter and lower bounce pattern. At these junctures the upper edge of the flange sometimes thicken with small hackles along the leading rim as seen in figure 14d2. This appears to be the case of the "inverted riverbed" since it lies on a slope above the trough with a dip of ~18° and appears to be a continuation of the base flange fracture line that can be seen in figure 14 running between insets B and C as it snakes along the lower-mound terrain.

Plumose feature

The plumose or feathery section of the western slope is reminiscent of feather hackles found in HC structures. In glass these are macro to micro features that form in varied regions and levels within the form. Two HC samples in glass are compared to the feathery features of the Gale mound in figure 15. All show dendritic structuring short distances from the point of impact. All three samples also contain V-shaped, calyx-like formations around the spinner section of the cones. The corresponding yardangs mentioned in Anderson et al and others can be seen as hackles on the glass samples. Feather hackles should be considered as taxonomically related to shatter cones since energy fractures the target material into branched segments during impact. The plumose features on Gale mound are separated by a canyon that runs from the mid level to the crater floor. This divisional line could be a lamina edge as is found in the glass samples and is similar to the "Grand" canyon farther to the south along Gale mound. Dendritic patterns on the mound originate from differing angles, the northern plume from the northeast and the southern plume from the northwest. This difference in direction is conducive to directional patterns found in HC's. With their orientation along the edge of the impact area these features may also be forms of tensional "crab" fractures.

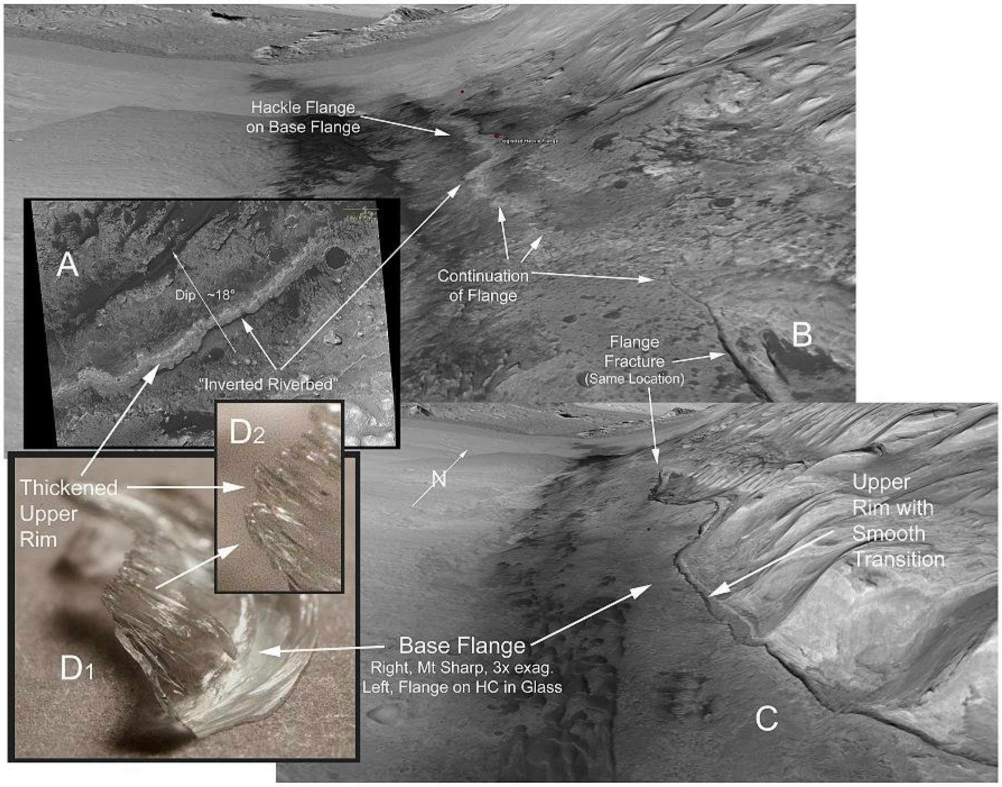

Figure 14 *The "Inverted Riverbed" (inset A) as described by the University of Arizona's Lunar and Planetary Laboratory HIRISE image PSP_009149_1750. It is found along the western base area of Gale Crater near the Curiosity Rover landing. The line in image C running lower-right upward appears to be the upper edge of the base flange. In our samples flanges often hold thickened upper edges as seen in images D1 and D2. The"riverbed" is situated on a slope about -4210 meters, 250 meters above a trough floor that parallels its course around the mound.*

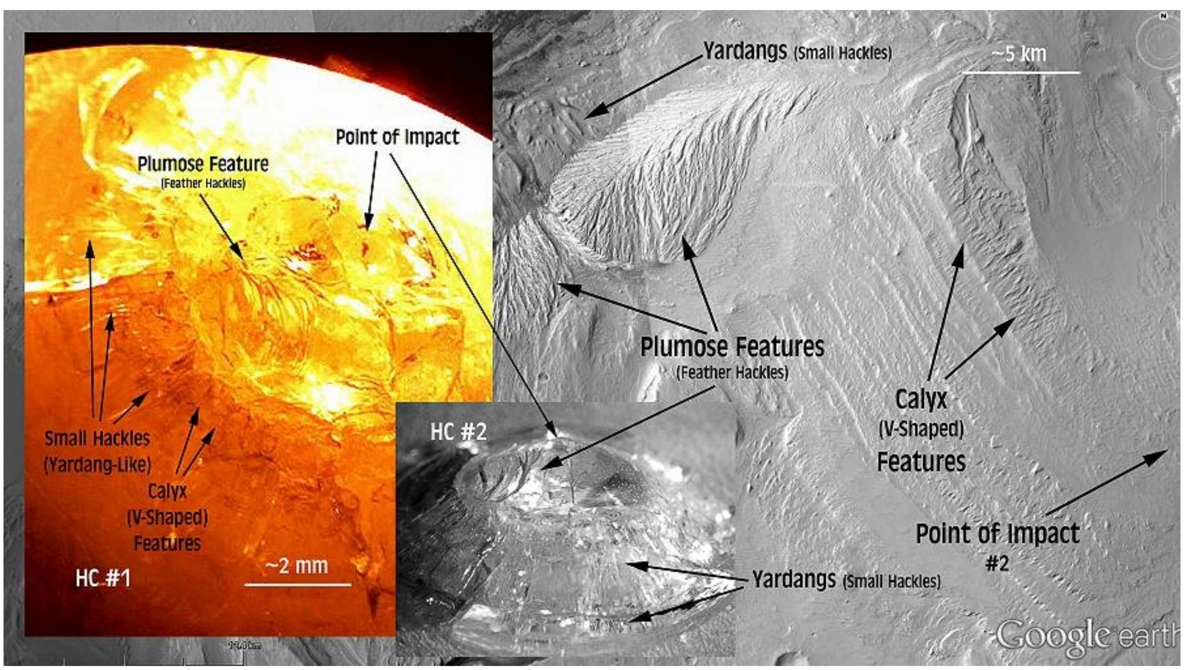

Figure 151 *Plumose features (feather hackles) can be seen in the inset images of Hertzian cones. They are created during impact and can be found on many levels within the HC. Similar features appear on Gale mound in the western quadrant above the stepped section. Calyx-shaped "V" formations can be seen around the POI on Gale mound and on the glass cone in the left inset.*

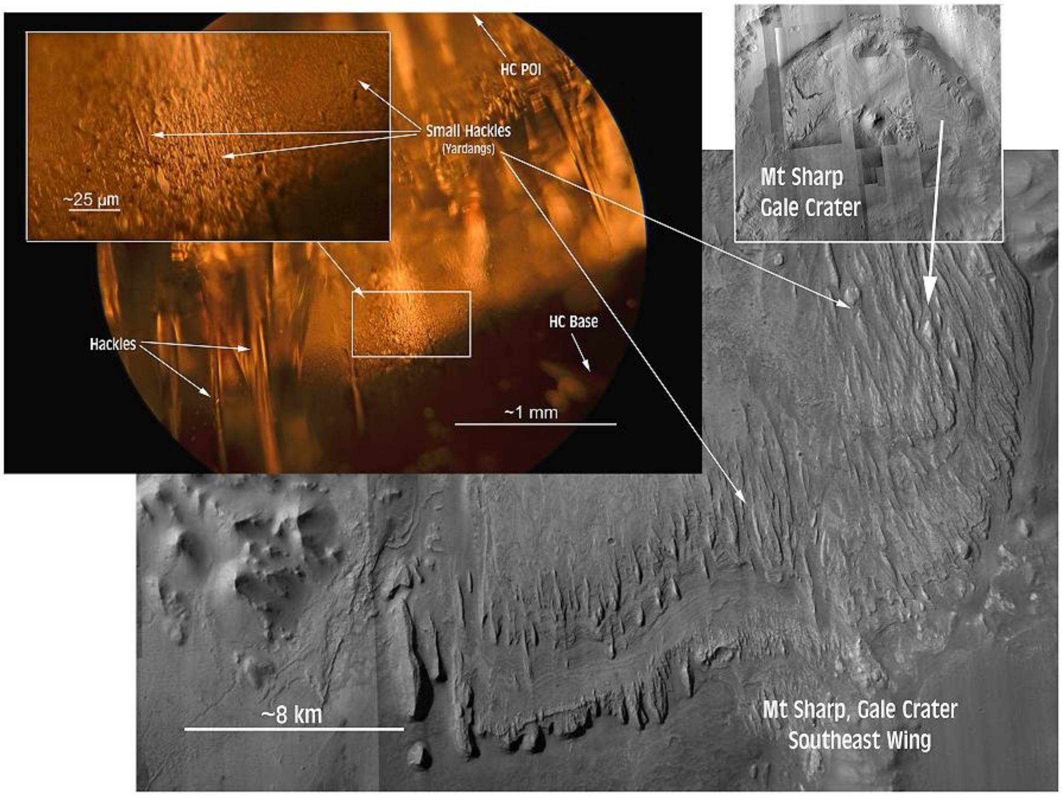

Figure 162 *Yardangs on the eastern wing of Gale Crater are shown in the main lower image. Hackles in a glass HC, upper left, show similar features. These are created during formation of the cone when inertial compression forces directional changes in the radiating fracture. Compare the main lower image above to the wing of a shield cone in glass shown in figure 5.*

Eastern Quadrant

Yardangs and wings

Hackles form in several ways. In classic HC formation hackles are designated to the finger-like divisions on the outer band of the cone and mold. They can, however, form in other ways as demonstrated in feather hackles. Faint and tiny hackles also form at the edge of the mist band between the mirror and hackle sections. These yardang-like mounds are comparative to the yardangs on the wing sections of the Gale mound. Figure 16 compares the yardang-like hackles in a glass HC to the yardangs found on the southwest wing of the mound. Like their counterparts on the northeast slope they also form in stepped terraces, though less prominent. When compared to the wing segments shown in the comparison in figure 17. The likeness is striking.

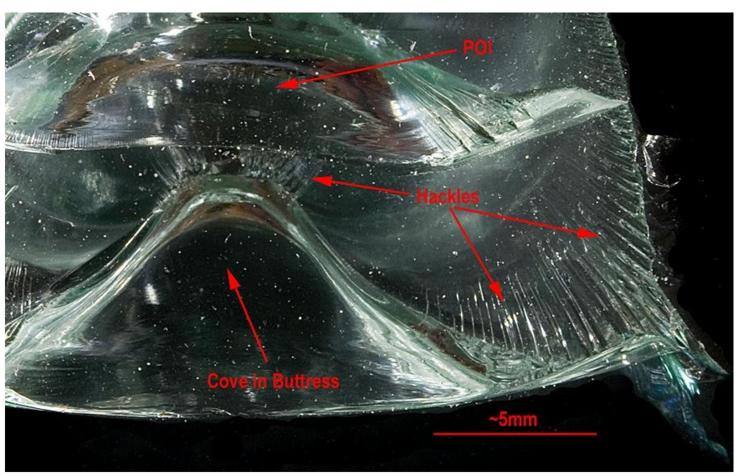

Figure 17 *A section of a shield-shaped HC in glass with similarities to the mound in Gale Crater.*

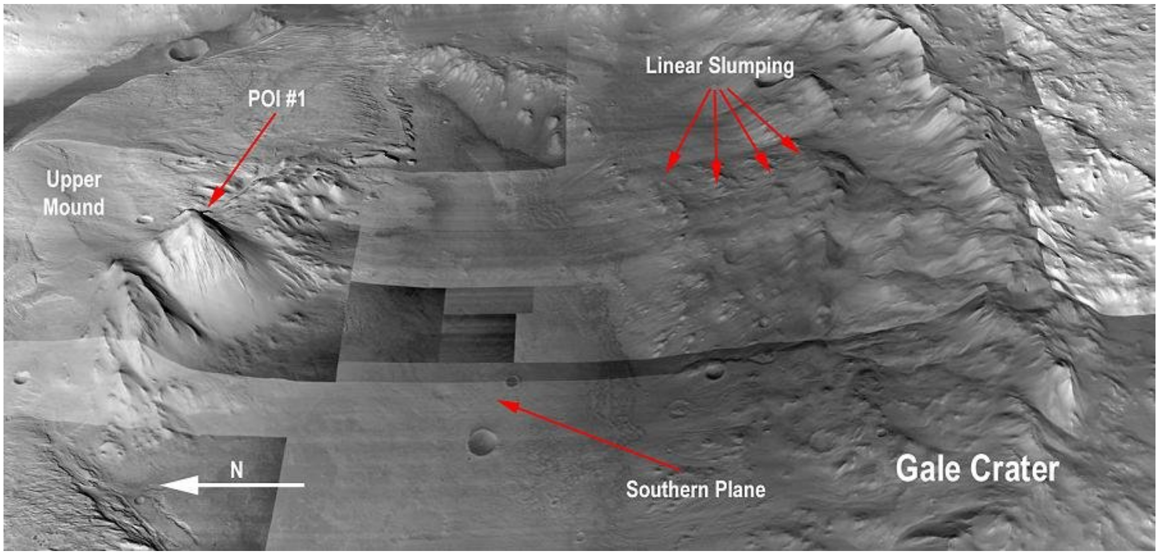

Figure 18 *An oblique view of the southern quadrant and plane of Gale Crater. Linear slumping can be seen in the center right of the frame suggesting outward erosion through concentric fractures in the original fractured overburden terrain.*

Gale Comparisons

Feature comparisons between Hertzian cones and Gale mound		
Features	**HC**	**Gale mound**
Impact association	X	X
Dome or cone shape	X	X
Central peak (POI)	X	X
Base tilt (low angle impact)	X	X
Winged buttress	X	X
Coved buttress	X	X
Tension wake	X	X
Lobate structures	X	X
Plumose structures	X	X
Terraces or steps	X	X
Hacklate base	X	X
Yardang-like bulges	X	X
Divisional plate lines (laminae)	X	X

Figure 19 *Comparisons of features in Hertzian cones and domed or fractured craters on Mars show many similarities..*

Southern Quadrant

This area has few HC dynamic features except for faint, possible undulations in the plane running from southeast northeast that could be interpreted as Wallner lines. This area is tilted downward as described above and would constitute the mirror segment of the cone with its flattish-sloping plane. The southernmost section is covered by dunes and slough from the crater wall.

The gentle rise from the terminus of the southern plane to the crater rim is punctuated with linear ridges that suggest wall slumping due to concentric fractures in the original topography around the crater. These concentric fractures can be found in other craters including Meteor (Barringer) Crater in Arizona as described by Kumar and Kring.[15] In estimating examples of glass HF craters and those in rock one must take into account that those in glass in our study do not have enough velocity or mass to create explosive force. Glass craters at low velocity are smaller due to the rebounding, non-fragmenting projectile and represent about 5% of the diameter of the steel ball. In bolide/rock impacts the velocity and mass magnify the crater size due to the detonation of the imploding, compressive force during contact. Therefore, more target material is removed as the crater is created. Considering this factor the boundary limit of the original Gale Crater excavation is estimated at no greater than a 33 km radius from POI #1. This would make the original crater wall just inside of the line dividing the southern plane dunes and the slope.

Conclusions on Gale Crater

Gale Crater mound features have many striking similarities to those found on Hertzian cones in glass and other crystalline materials. Both HC's and Gale Crater are of impact origin. These mega to micro similarities show formation of all five main Hertzian features, point of impact, mirror, mist, hackle and Wallner lines. They also include other intra-forming structures that include point-of-impact pedestals, secondary and tertiary hackles, terraces, base flanges and others. It must be considered that Gale mound is of impact origin and not post-impact generated.

OTHER MARTIAN CRATERS

Fractured Craters

Below are comparative images showing Martian craters next to variations of crushed and partially crushed HC's. The differences in completely crushed cones and partially crushed is dependent upon the velocity of the projectile. A smaller portion is dependent upon the mass. With our studies in glass lower velocities were created by backing the air gun away from the target. One meter was the most distant used and 10 cm was the closest. The crushed cone compared with Orson Welles Crater, figure 20, was impacted from directly overhead at ~0.3 m while the fractured glass cone in figure 21 was impacted at ~0.75 m from an angle of 30° above the plane of the glass.

Orson Welles crater

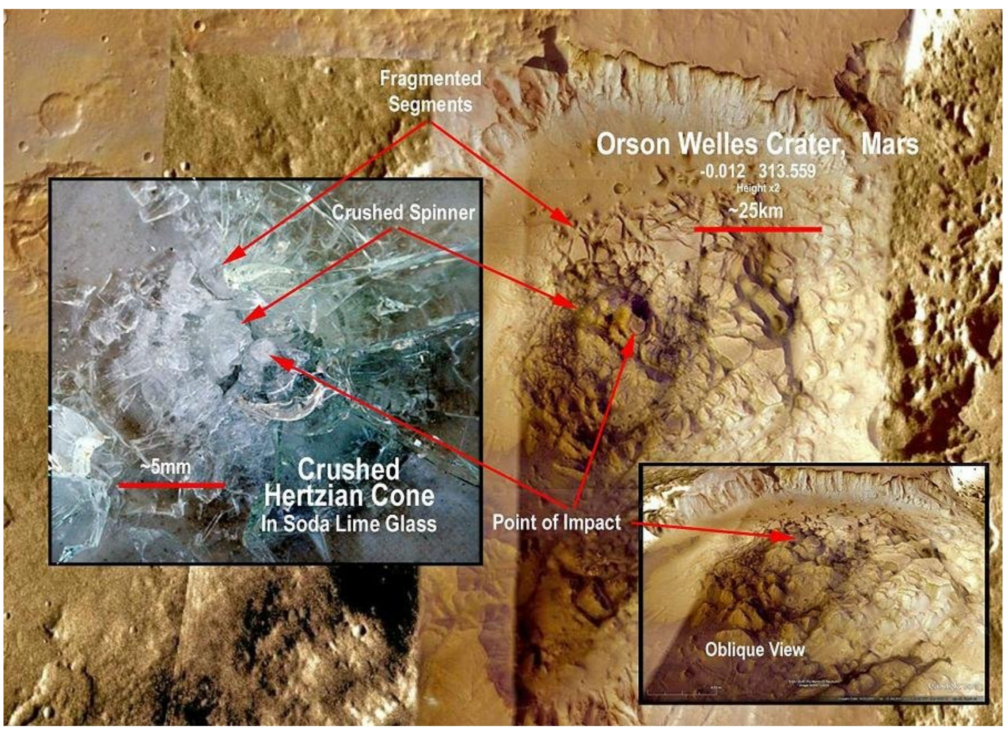

Figure 20 *Comparisons between Orson Welles Crate, Mars and crushed HC's in glass show like features. In the above comparison both have fragmented segments, crushed spinner sections and point of impact areas at center. The comparisons are self explanatory.*

[15] Kumar, P. S., and D. A. Kring (2008), Impact fracturing and structural modification of sedimentary rocks at Meteor Crater, Arizona, J. Geophys. Res., 113, E09009, doi:10.1029/2008JE003115.

Unnamed Fractured Crater, Mars

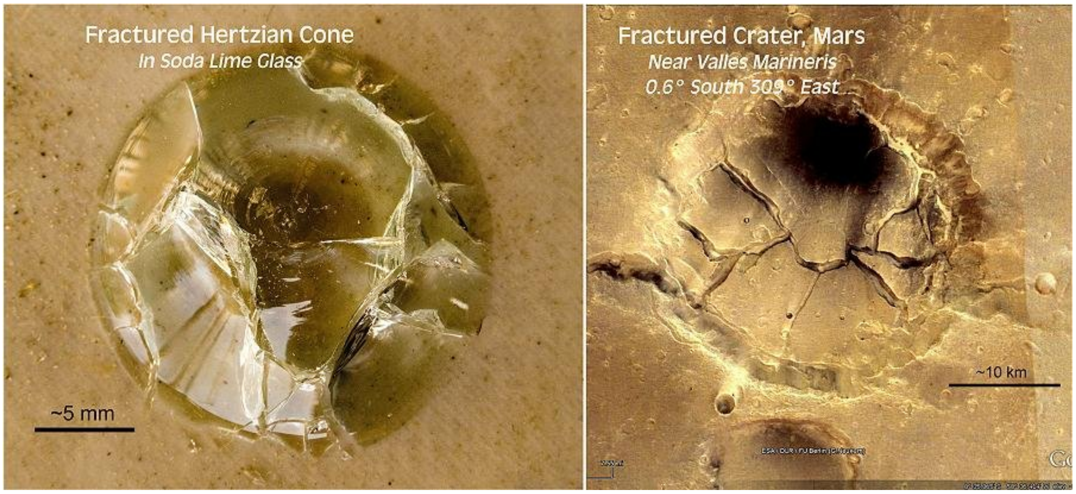

Figure 21 *Above left is a Hertzian cone created by a mid-velocity impact. On the right is an unnamed fractured crater with similar features. HC's vary in fragmentation with the velocity and mass of the projectile. Such should hold for planetary impacts.*

52 km Floor Fracture Crater, Mars

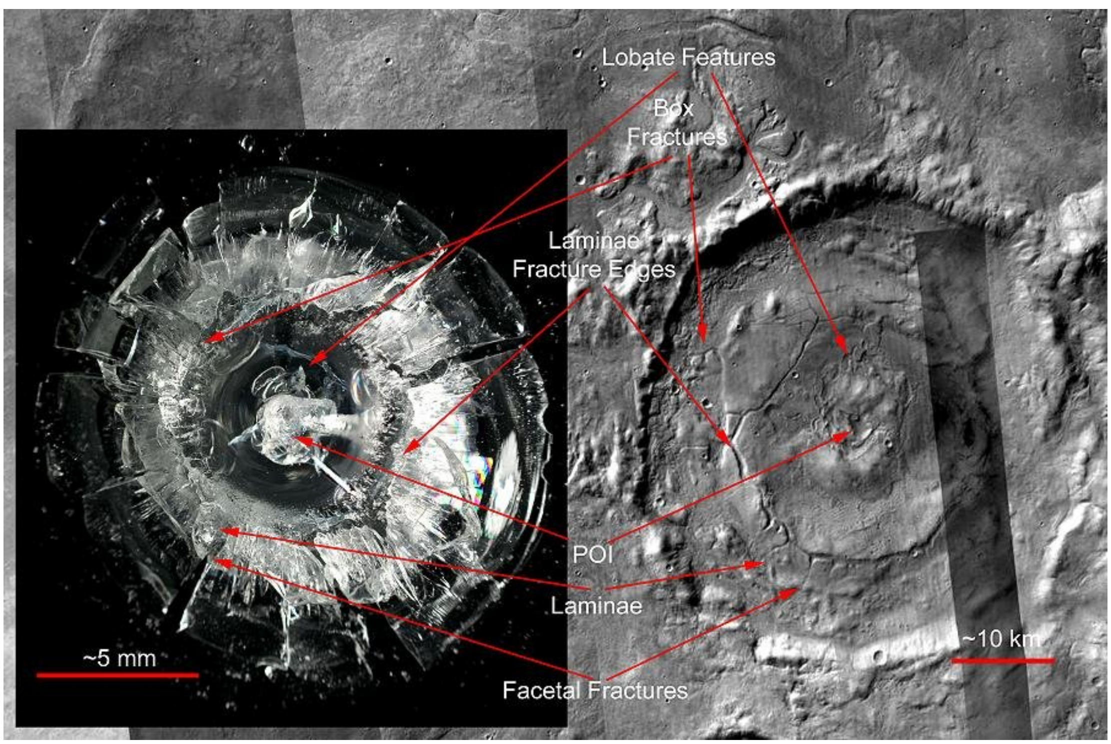

Figure 22 *At right is a floor fracture crater highlighted in a paper by J. Korteniemi et al*[16]*. At left is a fractured HC with similar features that include laminae edges, points of impact, lobate features and facetal fractures. Inner laminae rims could also be the source for multi-ring craters if the central spinner segment is crushed during impact and eroded.*
Mars Coordinates: -36.739679° 81.826526°.

[16] J. Korteniemi, M. Aittola, T. Ohman, J. Raitala, *Floor Fractured Craters On The Terrestrial planets – The Martian Perspective*, Researchgate.com, 2013.

Cydonia "Face" Mound

The Cydonia "Face" mound is an example of a compound, shield-shaped crater. At least two and possibly three contributing impacts created the shape that is now seen after erosion removed the surrounding overburden. The mound has classic HC properties including POI's, shield buttress, hackles, laminae and a surrounding flange. The shield buttress is located on the north, figure 23, and displays at least three layers of laminae. During some impacts energy is diverted outward creating onion-skin-like layers around the dome. Small HC's in our study have exhibited up to three layers. This appears to be a pattern in the "Face" mound where laminae layers combine with Wallner undulations to form the step as seen in figure 24. Along the mound boundary the edge of a lamina flange can be seen along the margin.

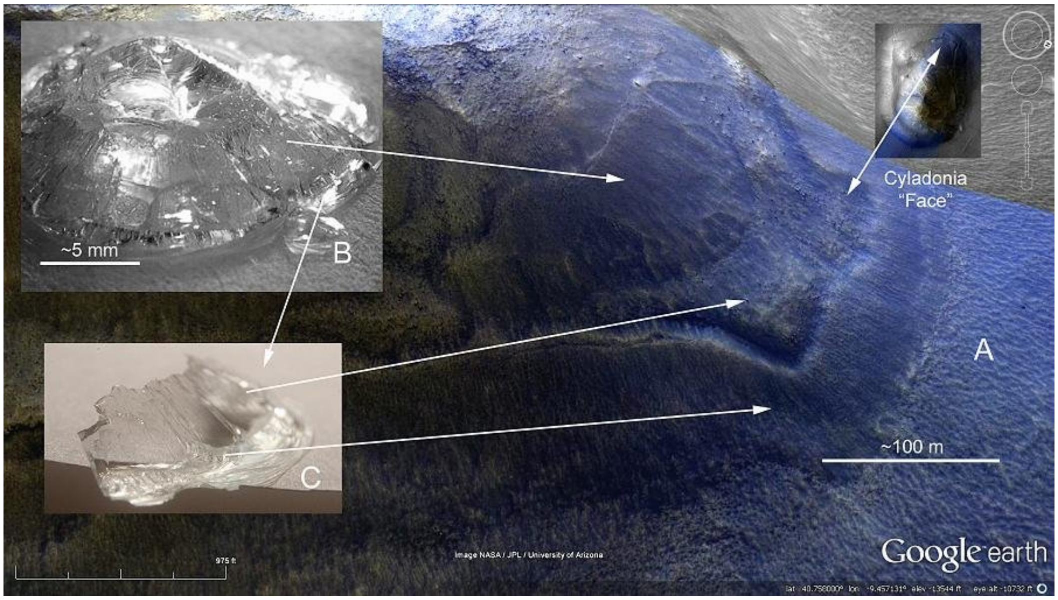

Figure 3 *The Cydonia "Face" mound displays lamina and hackle and flange features. The lamina flange in images B and C contains hackles very similar to those shown on the buttress area in the mound shown in image A.*

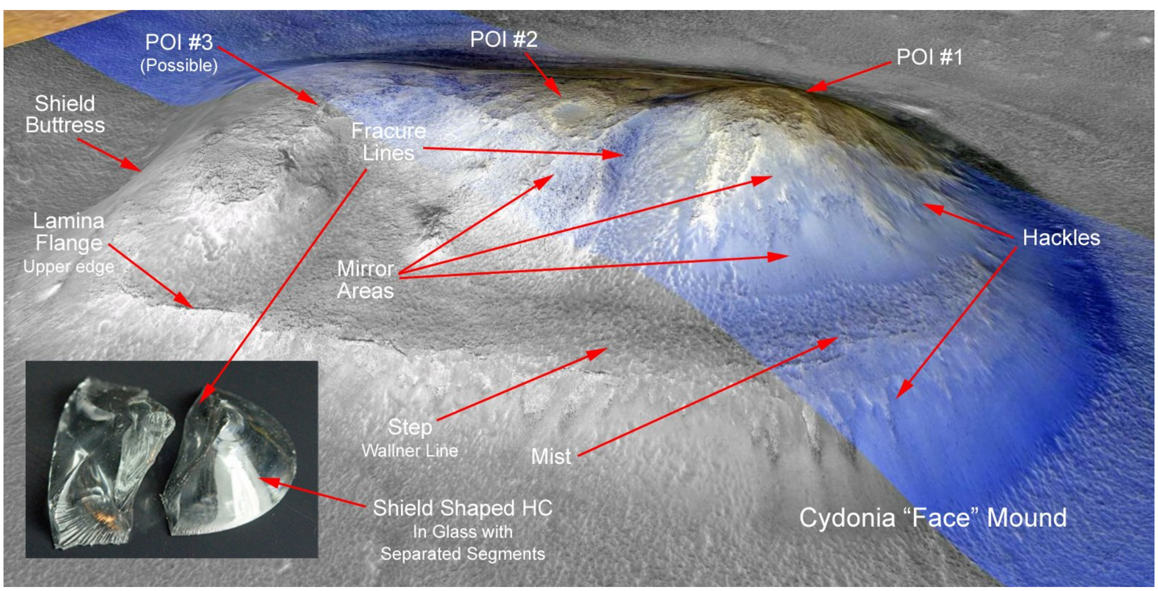

Figure 24 *Cydonia "Face" mound from the southwest. HC features are visible including at least two points of impact. The mound has a line that corresponds to a fracture in the shield-shaped cone in the inset. Cydonia mound appears to be multiple HC's with the overburden and surrounding terrain eroded to the level of the base.*

Volcanism

The hypotheses vary in the formation of dome and fractured craters. Kraft and Christensen suggest tectonic intrusion into the crater to form Gale mound. From our research this is a partial explanation since fractures within dome can provide conduits for volcanic activity. This should also be considered for the formation in fractured craters as mentioned by Korteniemi, et al in their study of samples on the moon and Mars as well as for the outward tilt of strata as described in Rossi, et al.

In some impacts in glass a reach - a cogenic subsurface fracture - is formed below the crater and HF, figure 25. They extend far below levels suggested in most impact crater diagrams and are supported by Ahrens, et al, studies of impacts into rock at Caltech. In planetary impacts these fractures would provide a channel for magmatic intrusion within and around the HC perimeter. Intra-crater basalt dunes in Martian craters are probably the resultant seepage of lava through these fractures, figure 26.

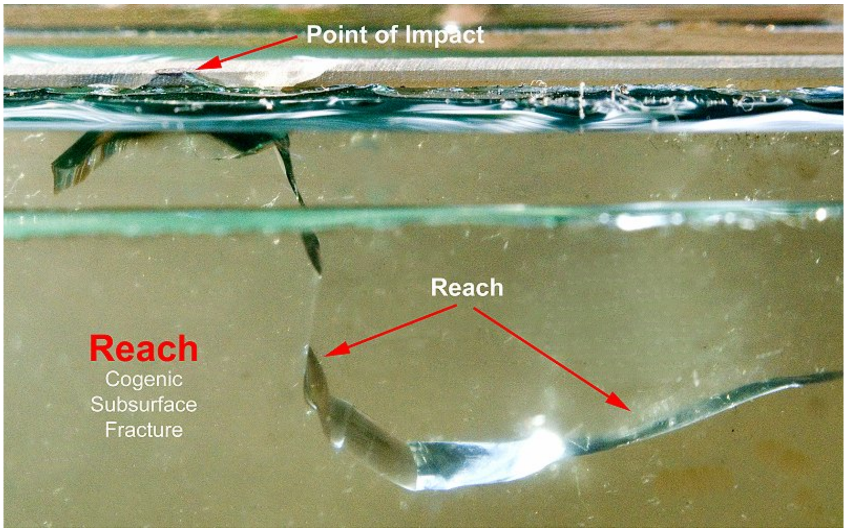

Figure 25 *A reach is a subsurface fracture created at the time of impact. Here it can be seen diving below the crater to depths many times greater than that of the HF. The HC above left is tilted due to a lower angle projectile trajectory from left of frame to right.*

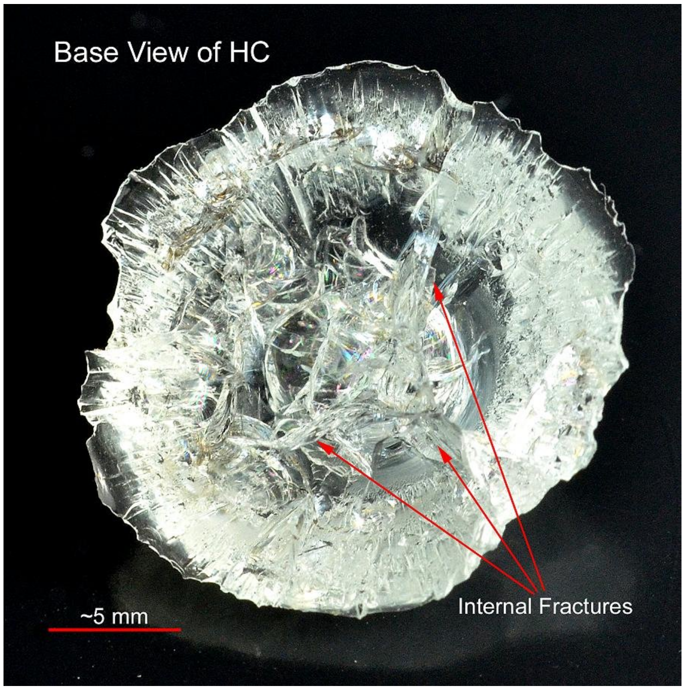

Figure 264 *A sample of an HC with multiple intra-dome fractures, none of which penetrate the upper surface of the cone. In planetoid impacts similar fractures may provide conduits for magma to form sills, dikes and laccoliths.*

Within an HC mound fracturing is often present without obvious surface breeching. Bolide impacts in planetoids can be compared to impacts of small projectiles into living tissue. If a small steel ball is fired at one's hand from an air gun three things can result. If it is of low velocity a light red mark may appear or it may leave no mark at all. If of medium velocity a subcutaneous hematoma, a blood blister, may appear creating a small lump or mound. If the projectile is fired at a high velocity the skin is penetrated and blood seeps from the open wound.

The same scenario should be considered in bolide impacts. Low velocity creates a mark on the surface, medium velocity creates sub-surface fracturing with an associated doming of the target site and high velocity could penetrate in the manner described above to provide a conduit for magma to escape and create basaltic seepage or a volcano. Dark dunes and areas of intrusion can be found in many craters including Orson Welles which is featured in figure 20. The dark canyon areas shown in the lower right of the oblique inset are samples of these features as is the upper center of the fractured crater in figure 21. Dye forced into glass HF samples display the ability for magma intrusion into and around Hertzian cones. Seepage to the surface of the companion crater provides access for basaltic dunes, figure 27.

Conclusion on paper

Hertzian fractures are common in nature. With projectile impact the fracture created the mold and cone as it separates the two segments. Gale Crater mound, Mount Sharp, has all five main features of a complex Hertzian cone with the addition of many from the neoteric glossary. The conclusion must be addressed that Mount Sharp is a sample of a mega HC.

Fragmented craters in glass can be created with projectiles in glass at varying velocities. Therefore, they too must be studied and considered for the possibility of Hertzian formation.

Below are several examples of HC's in glass with diagrams to show creational processes. – JB

Sample of images and diagrams

Figure 27 *Above is a sample of a Hertzian cone in situ with overburden intact. Dye was forced into the HF around the cones to simulate volcanic intrusion. The POI can be seen in the center of the shield cone with a winged crack along the base directly below.*

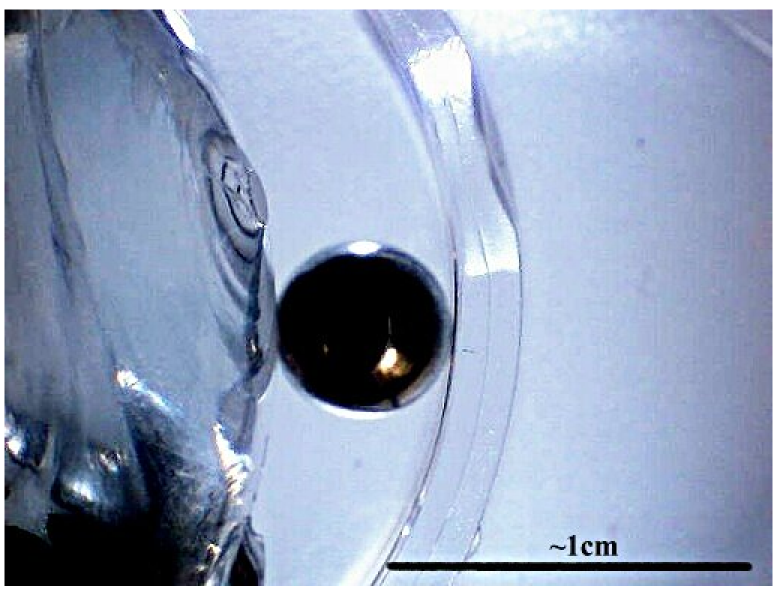

Figure 28 *A 5mm steel ball and the dome of an HC it created. Note the POI on the dome compared to the size of the ball.*

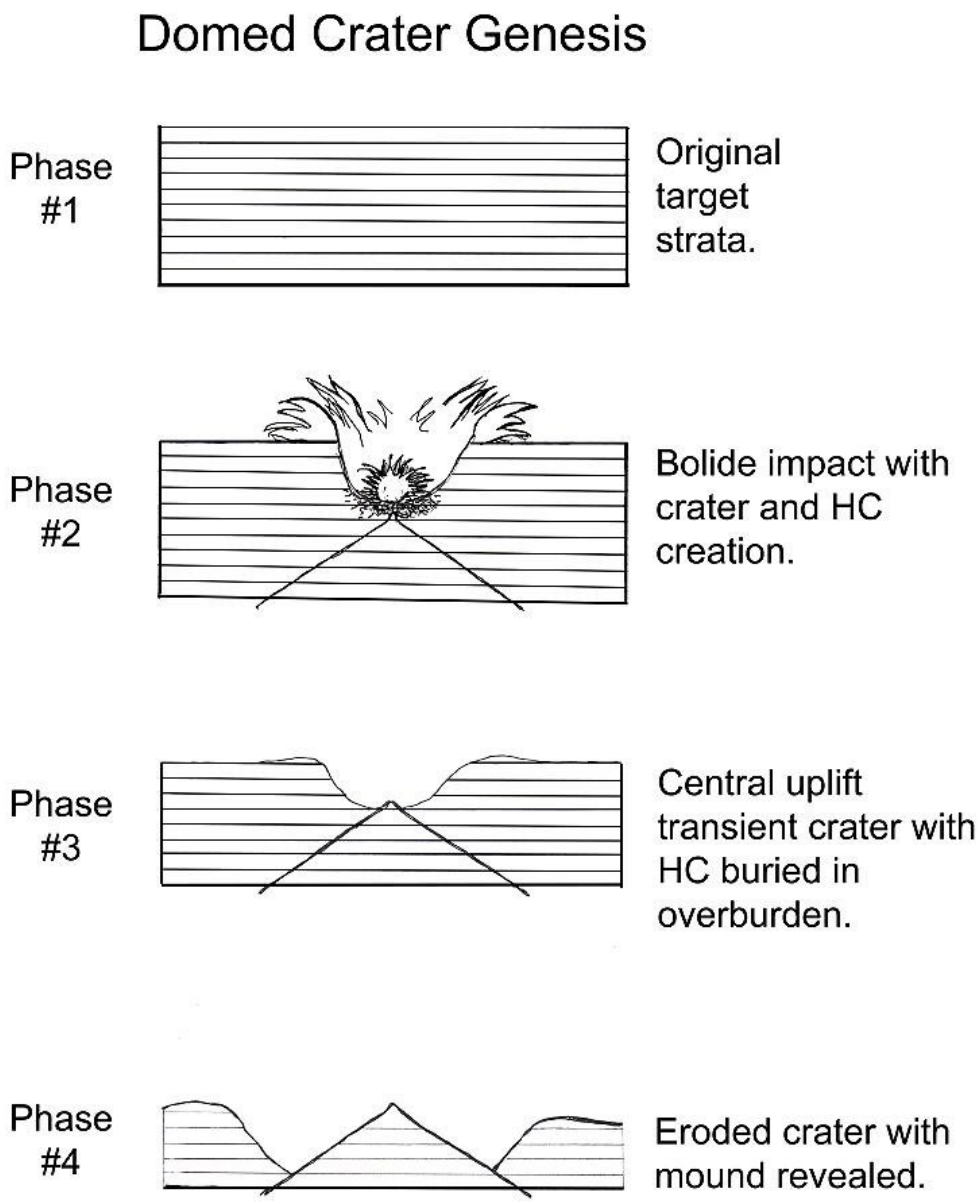

Figure 29 *The four phases of a domed crater. View is exaggerated.*

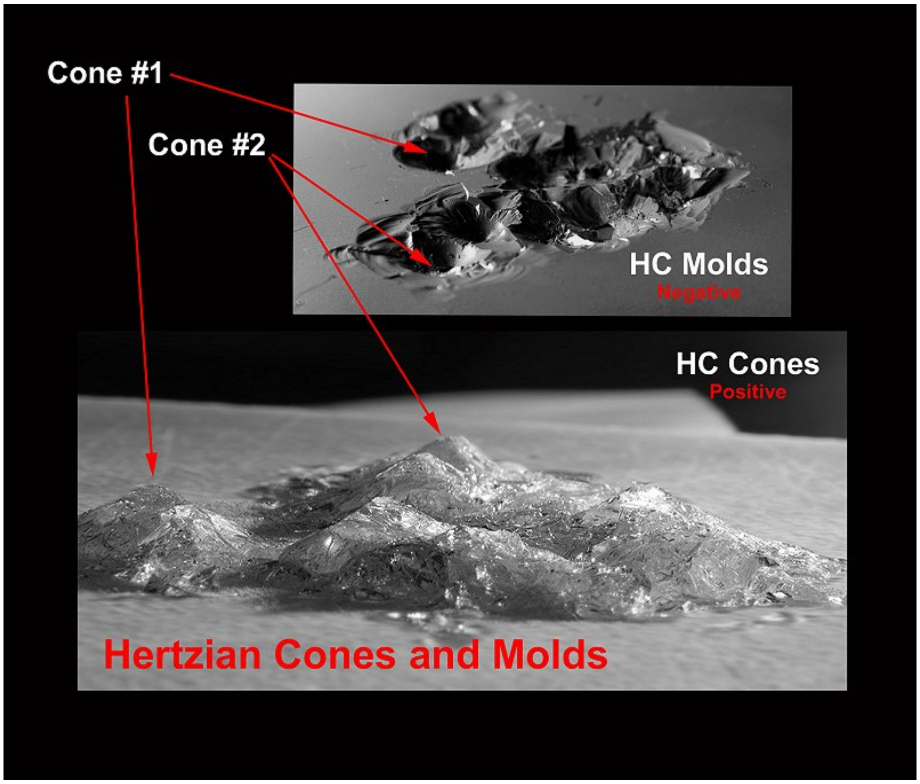

Figure 30 *How to make a mini-mountain range.* *In the image above the two physical segments of Hertzian fractures can be seen. The upper image is an example of the negative section of an HF containing the overburden and Hertzian mold (shown upside down.) The lower image shows the cone section. In this example the mounds are made up of comminuted cones. Cones in lab experiments tend to crush from the base to the crater. Individual cones and their respective molds are highlighted by arrows.*

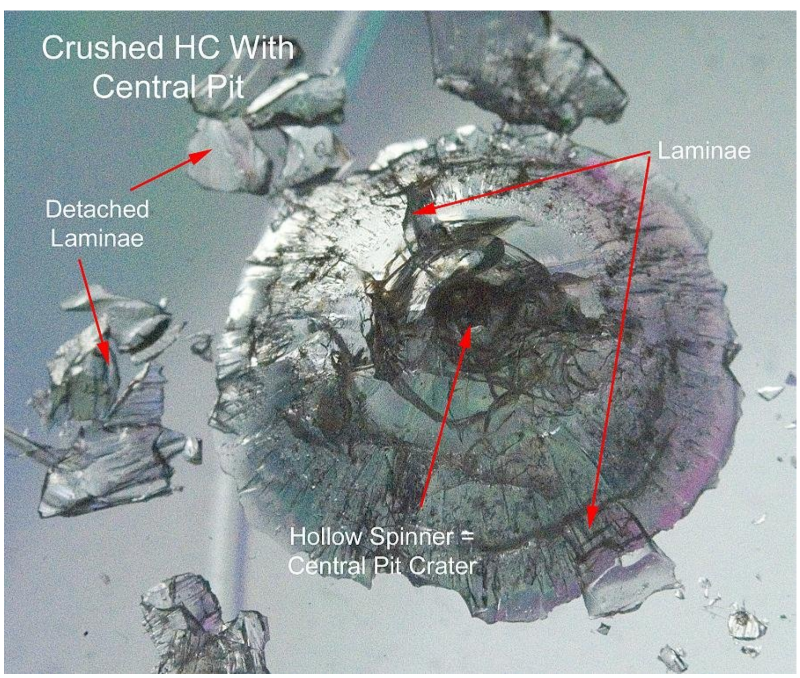

Figure 31 *Pit craters may be related to this HC physical feature.* *When high velocity impacts strike glass the HC is crushed in varying amounts. In some samples the spinner section around the crater is comminuted whereby removing the overburden allows the small fragments to escape creating a central pit.*

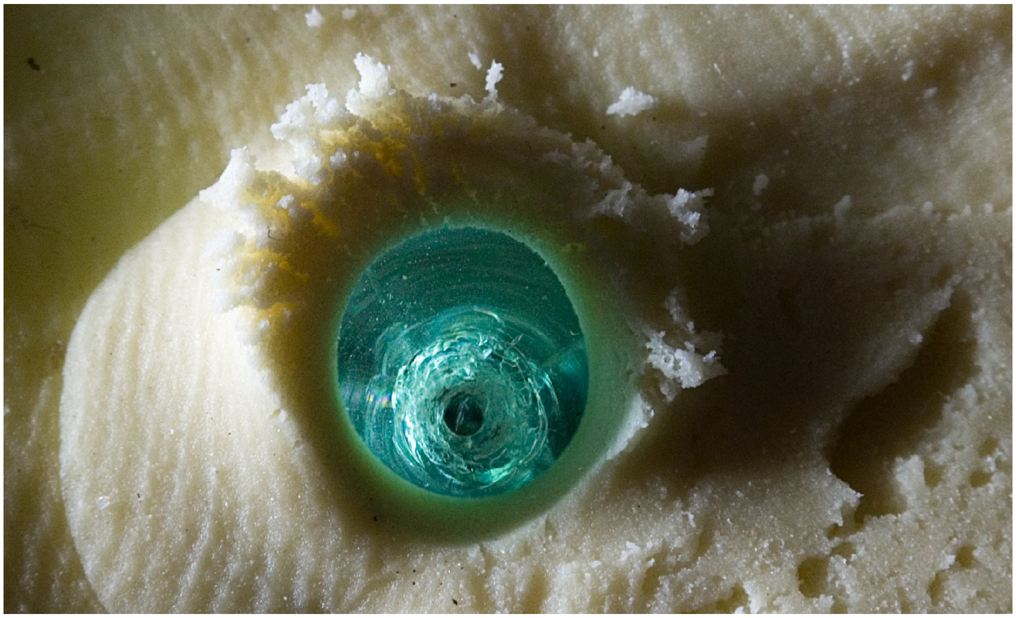

Figure 32 *A view of the results of the impact by a 5 mm steel ball on glass coated with clay. The upper section of the HC can be seen below the crater with the overburden in place. The clay crater has turned rim features, but is smaller proportionally than bolide impacts in rock.due to the lack of explosive forces. The size of the crater is ~7mm.*

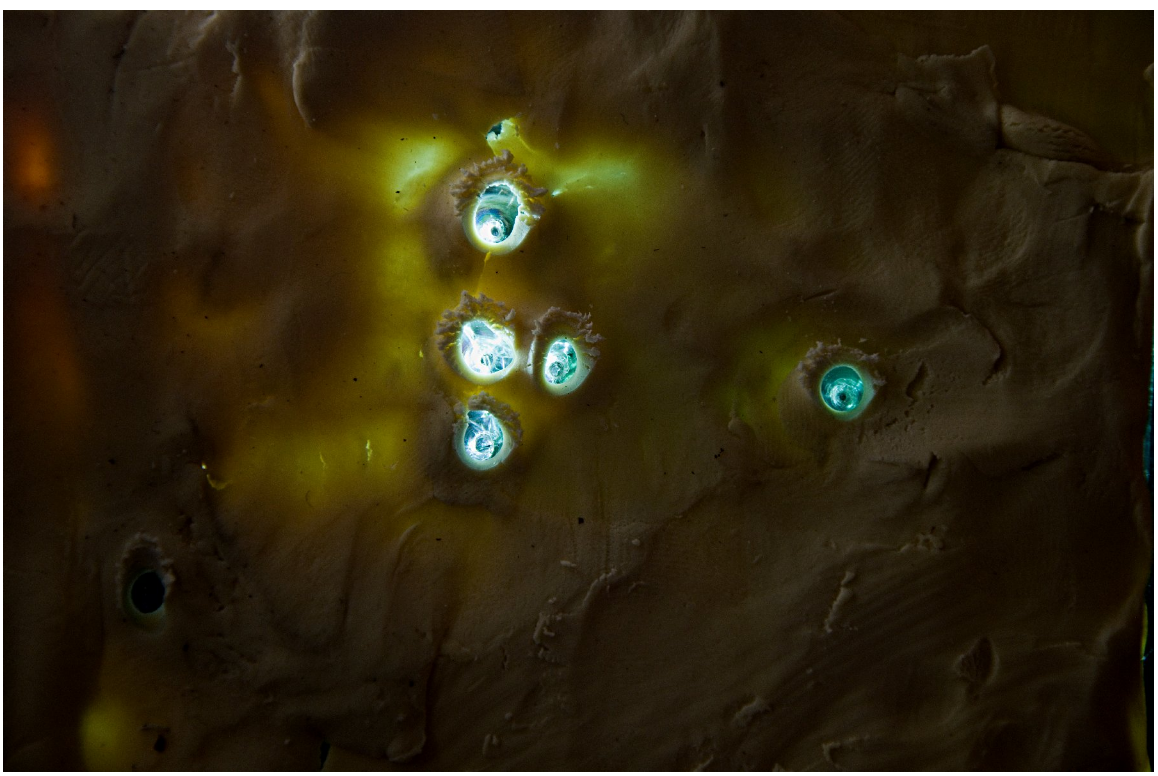

Figure 33 *Multiple hits of 5 mm steel balls in glass coated with clay. The crater shown in figure 32 is at right.*

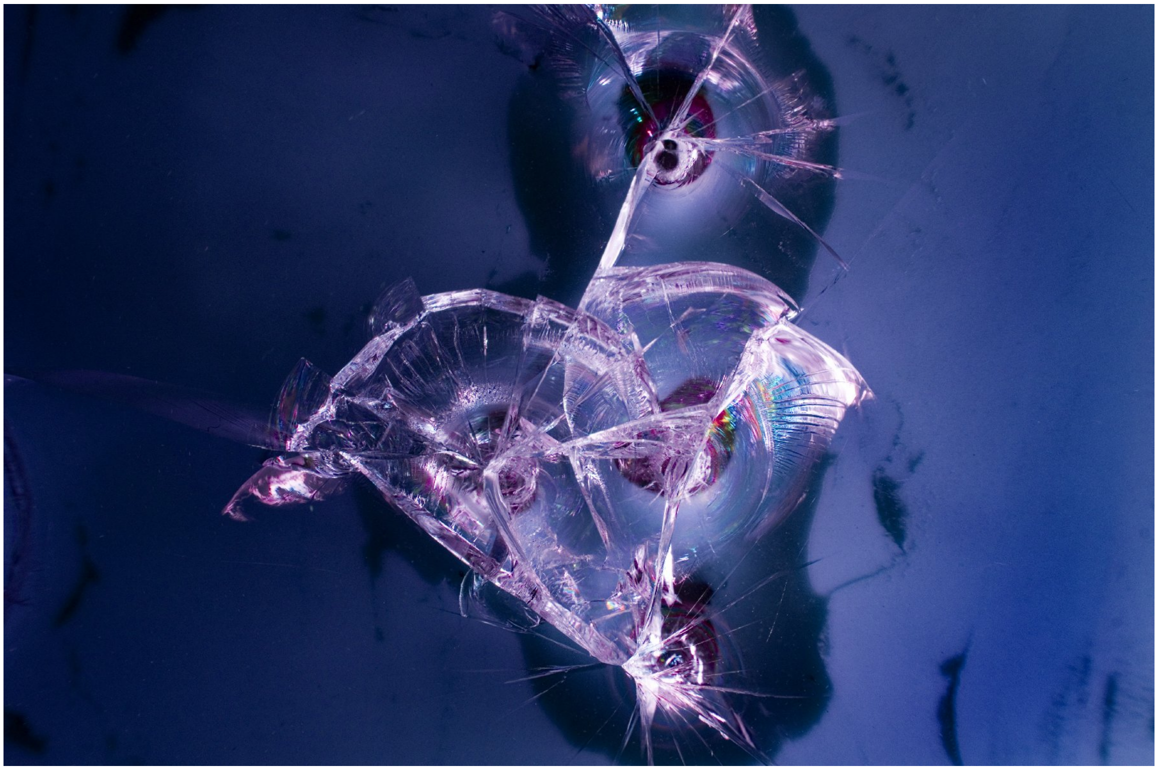

Figure 34 *A base view of the same main cluster of impacts in glass with a clay coating shown in figure 33. Note the size of the cone base to crater ratio. The circular shadow area in the background indicated clay being pulled away from the glass and is more proportional to crater/HC features in rock.*

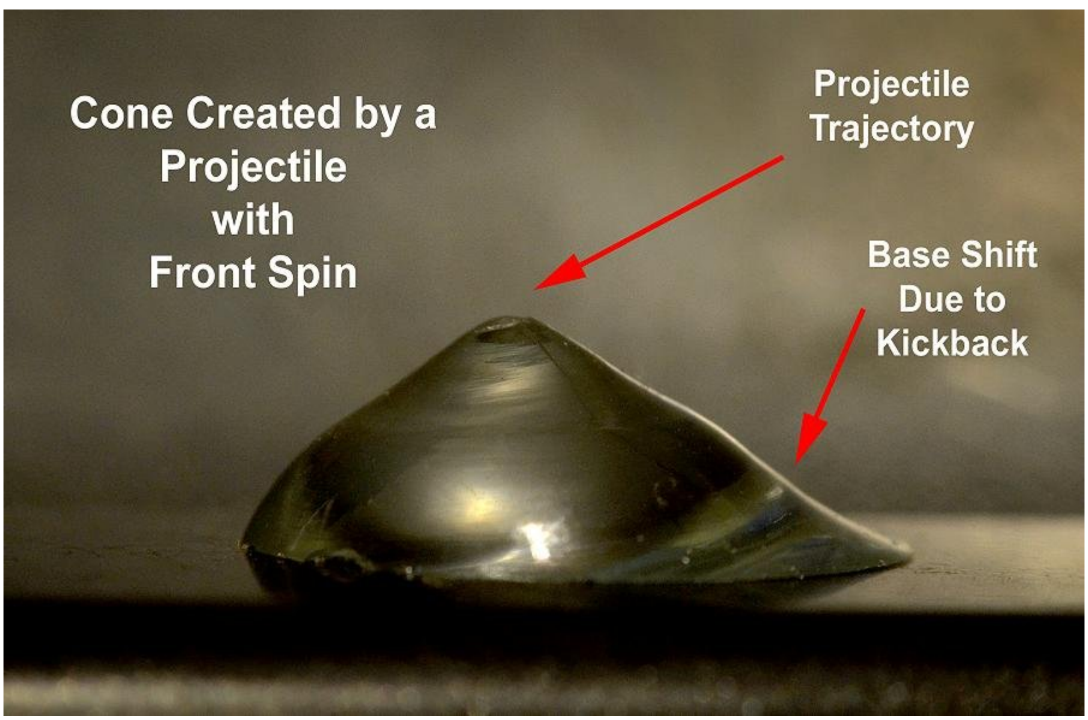

Figure 35 *A simple HC with tilt caused by a projectile with forward spin. Gale crater is tilted in the opposite direction due to low a low angle of impact. Projectile spin can change the direction of the HC tilt by transferring inertia in varying directions.*

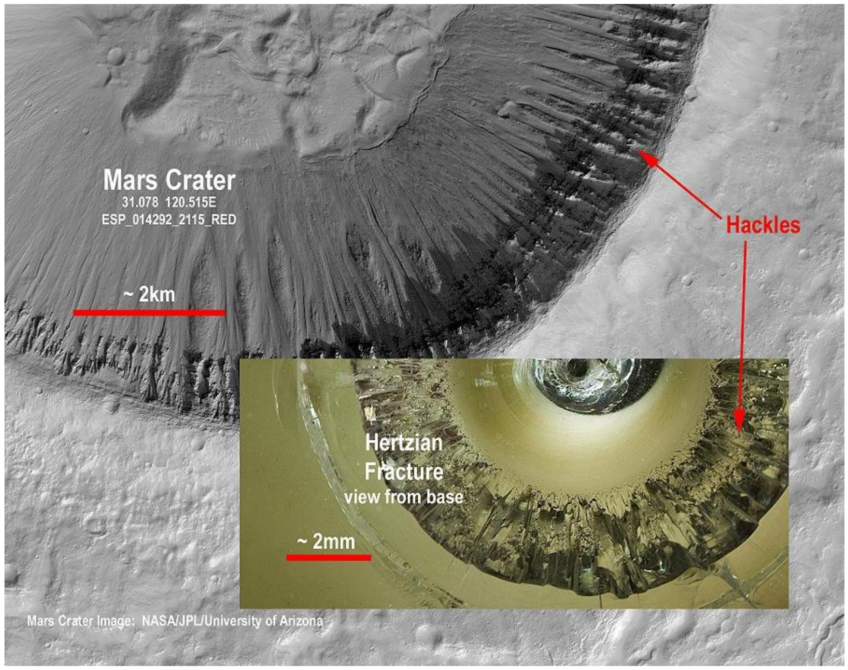

Figure 5 *Here is a comparison of a Mars crater viewed from above and a Hertzian cone in glass from its base. A Hertzian fracture is an enlarged, inverted twin of the crater. Both are created at the same time and display similar features. The crater is limited in size by the overburden depth and penetration of the bolide. The HF in glass is regulated by the thickness of the sample. However, in rock the HC's action/reaction penetration can be many times the size of the crater and is regulated by the hardness of the target material and the exerting force of the projectile or its resultant explosive force.*

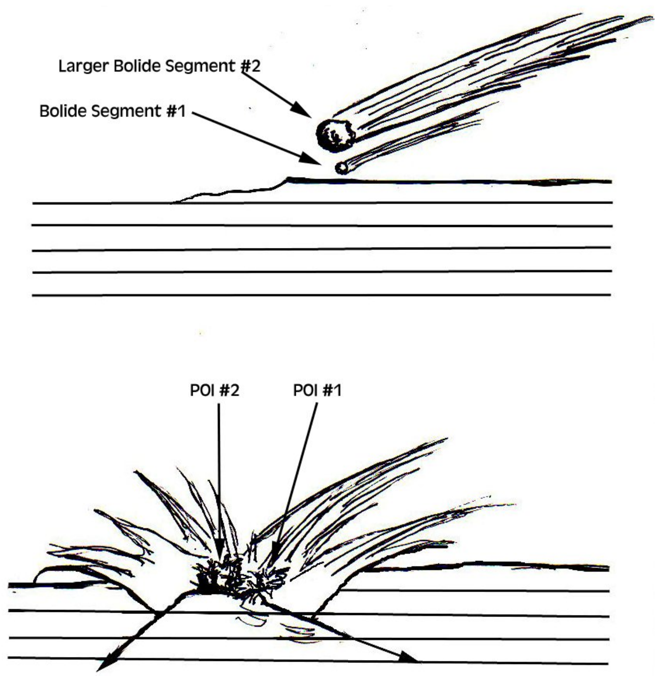

Figure 37 *Gale Crater was created by a fragmented bolide striking in a near simultaneous impact. The smaller segment created the southernmost peak, POI #1 shortly before the second impact struck POI #2 created the main upper mound of Mt. Sharp.*

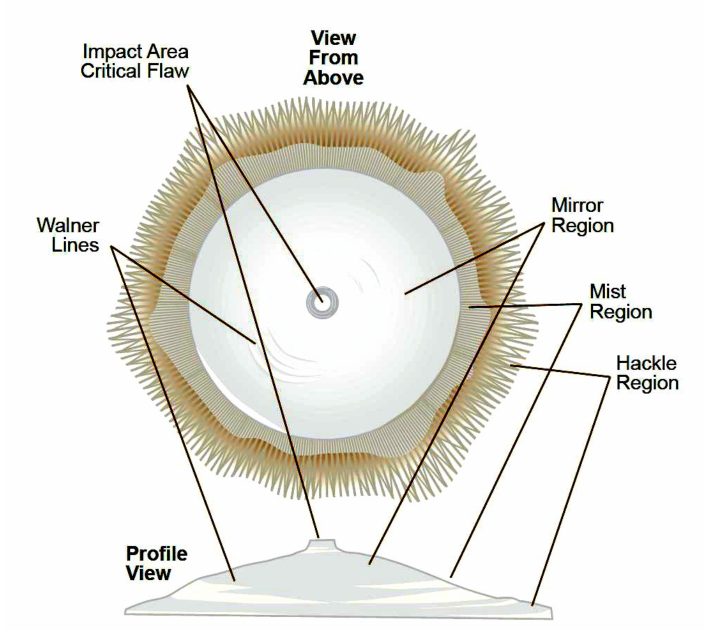

Figure 6 *The five main Hertzian features, point of impact, mirror, mist, hackle and Wallner lines*

Figure 39 *Mount Sharp (Aeolis Mons) from Curiosity Rover in Gale Crater. The shape is that of a classic Hertzian cone. Compare Mount Sharp's profile to the HC in figure 12. The pedestal area on Mount Sharp is POI #2 as shown in figure 8.*
NASA/JPL/University of Arizona/CalTech image.

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We appreciate the participation and help from Kathleen H. McCormick and David P. Ruddy for their service as lab assistants and to Daniel A. Ruddy for his generous loan of equipment. Also we thank Vicki Harrison Patrick for her editorial input. Images of Mars are from Google Earth, NASA, JPL, Arizona State University, Caltech.

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