NEW EVIDENCE RELATED TO THE FORMATION OF SHATTER CONES; WITH SPECIAL EMPHASIS ON STRUCTURAL OBSERVATIONS IN THE COLLAR OF THE VREDEFORT DOME, SOUTH AFRICA.

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Summary: Shatter cones have been studied for decades without fully resolving their formation. New field observations on shatter cones from the Vredefort Dome give new insight into the formation of this impact deformation phenomenon. The orientations of shatter cone apeces, as observed in the field, are not uniform with regard to the center of the structure, and show a variety of prominent directions: most apex orientations are normal to the strike of the bedding (and parallel to the dip direction of the bedding plane), as well as parallel to the strike (and normal to the dip direction of the bedding plane). No relationship exists between angles of striations, i.e., "protruding bundles of striations" on shatter cone surfaces as defined by Sagy et al. [1], and the distance of sample location from the crater center.

Introduction: The Vredefort dome, the eroded central uplift of the 2.02 Ga, ca. 300 km wide Vredefort impact structure, is a prominent, ~80 km wide, structural and geophysical feature about 120 km SW of Johannesburg. The dome consists of an ~45 km wide core of Archean basement gneisses surrounded by a collar of subvertical/partially overturned Late Archean to Paleoproterozoic supracrustalsstrata. The impact origin of the Vredefort structure is now widely accepted because of extensive bona fide evidence for impact [cf. review by 2]. Shatter cones are abundant throughout the collar strata [3] and also occur in places in the basement granitoids. Despite much field and some laboratory work, the genesis of shatter cones is still not resolved. Early workers emphasized that shatter cones were formed due to the interaction of a shock wave with heterogeneities in target rock, causing scattering, refraction, and reflection of the wave. It w widely accepted that orientations of shatter cone apeces point away from the center of an impact structure, and after rotation of upturned strata, inward towards the explosion center. Nicolayson and Reimold [4] debated this argument and showed that the variety of apex orientations measured at given sites in the collar of the Vredefort Dome is more complex. They also described a distinct relationship between individual shatter cones and so-called multipli- striated joint sets (MSJS), which occur as planar to curviplanar fractures pervasively throughout the Vredefort collar and are also observed in the South range of the Sudbury Structure. These authors concluded that it was not possible to fit all recorded striation orientations from a single site to a single "master" cone. Recently, Sagy et al. [1] suggested a relationship between so-called "striation angles" and distance of the sample from the center of the crater. They defined striations as forming distinctive ridges on the surface of shatter cone segments. The striation angle was defined by the flanks of these ridges. Recent numerical modeling [5] suggests that shock wave reflection caused by "soft" deformations could result in varied orientations of shatter cones.

This study: Samples were collected from and *in-situ* striation orientation measurements performed at a number of sites throughout the northern collar of the Vredefort Dome, extending to about 60 km from the center of the core. These sites occur in different lithological units, all of them belonging to the Witwatersrand, Ventersdorp and Transvaal supergroups. Surfaces of shatter cones from other impact sites, including Canada and Germany, were also studied. Shatter cones are distributed irregularly throughout the Vredefort collar, with their relative density depending on outcrop accessibility and lithology. Shatter cones have been identified as far north as 65 km from the center of the dome, extending the shatter cone limit given by Therriault et al. [6] by a further 20 km. Generally, only parts of shatter cones are exposed, and complete cones are very rare. The segments are different in size (a few cm to dm) and orientation. Although commonly well developed in fine-grained rocks [4], shatter cones can also be present in massive quartzites. Some of the best exposures of shatter cones are found in the medium-grained Johannesburg and Turffontein quartzites, Upper Witwatersrand Supergroup, in the northern and northwestern part of the collar, and in the Booysens Shale formation exposed along a road-cut in the northwestern sector.

Regarding the orientation of shatter cones, earlier workers suggested a preferred orientation of the apeces downward and outward from the crater center. Taking into account that the strata of the collar have been up- to overturned, rotation of the bedding back to their presumed pre-impact position would result in an orientation of the shatter cone apeces to upward/ inward directions. Recent observations by Nicolayson and Reimold [4], confirmed by the present study, however, indicated a more diverse orientation pattern of shatter cones. Two main cone orientations are observed. The most common one is indeed normal to the strike of the bedding (and within the bedding surface) and would be compatible with the rotation theory. However, the second trend is parallel to the strike of the bedding. Apeces related to both these trends may point both up- and downward. In places, a third orientation is observed, with apex directions at 30 to almost 60° to the strike of the bedding (trending in different directions, e.g., 300, 30, 130, and 230 degrees for bedding trending at 90/93E). Again, cone apeces of set 3 may also face either upward and /or downward.

The geometry of striations on the surface of shatter cones has also been investigated. Striations have commonly been described as directional and branching radially off the apex. This is the most dominent striation pattern in the Vredefort Dome. In some places, however, subparallel to parallel striations are observed, which has already been emphasized by [3] and [4]. Locally, cone segments show an almost flat surface, with subparallel to parallel striations.

The concept of Sagy et al. [1] was investigated and numerous angles of striation ridges measured on cones from Vredefort and elsewhere. Striation bundles/ridges are epitomized in the horsetailing patterns known from many impact structures and, at Vredefort, best observed at Schoemansdrif bridge. The so-called striation angles vary frombundle to bundle and from cone to cone, and not from site to site. Our findings indicate ranges of angles even on the surface of a single cone segment. Usually the variation is from ~20 to 45°, but angles from 15 to 47° on a single sample have been recorded. The variation of average angle width does not change consistently along a radial traverse through the collar of the Vredefort Dome – in stark contrast to the conclusions of [1].

Discussion: The orientation of shatter cones is more diverse than described in previous studies. We confirm that the most prominent direction of cone apeces in the collar strata is normal to the strike of the bedding (pointing upward and outward). After restoring the pre-impact position of the bedding, these shatter cones would point towards the center of the impact structure. However, there are also other orientations, parallel to the strike of the bedding and oblique to it, which have been disregarded in the past. These two orientations are not restricted to certain parts of the collar; they occur together at some sites, whereas at others only one of them may occur – however, always together with the main tend.

Two different patterns of striations have been observed. Most prominent is the radial appearance of striations on typically conical shatter cone surfaces. The striations branch off the apex and show a strong directionality. Locally, however, and for still unexplained reasons (i.e., no field control for this can be offered), where almost flat shatter cone surfaces have been observed, the striations seem to be subparallel to parallel to each other, making it difficult to determine the orientation of a cone apex. In addition, [3,4] described radial trends of striations as well as subparallel trends from joint-related occurrences. Angles formed by each bundle of striations on ridges on shatter cone surfaces show also strong diversity. The width of these angles varies from site to site throughout the collar and even ranges from tight angles to open ones on the same shatter cone segment.

Conclusion: The model of back-rotation of strata to their pre-impact position does not satisfy the variety of apex orientation data recorded. Shatter cones parallel to bedding would not change their orientation towards the center of the crater by simple back-rotation into likely pre-impact orientations. Complex pre-impact structure can not be invoked either, as again simple back-rotation should still show a consistent behavior for measurements from a given site (up to a few m in extent). Complex post-impact faulting/folding deformation on a macro-scale can also be excluded, for the same reason.. If one subscribes to the premise that the cone apex should always point towards the direction of the energy source, these observations imply a scattering or reflection of the shock wave, while propagating through the target rock. This may have been caused by inhomogeneities in the rock (such as textural or structural [joints, bedding planes] heterogeneities) or change in lithology [e.g., grain size, degree of recrystallization] and mineral content. This concept has recently been supported by numerical modelling of shatter cones by Baratoux and Melosh [5]. Angles defining striation bundles on shatter cone segments show absolutely no evidence of a relationship between the width of such angles and the distance of the sample location from the crater center, as was postulated by [1]. A main problem regarding the nature of shatter cones remains the clearly demonstrated [4] relationship between the MSJS fracturing phenomenon and cone geometry.

References [1] Sagy, A. et al. (2002), Nature 418, 310-313; [2] Gibson, R.L. & Reimold, W.U., CoG, Pretoria, Memoir 92, 111pp.; [3] Manton, W.I. (1965), New York Acad. Sci. Ann. 123, 1017-1049 ; [4] Nicolaysen and Reimold, W.U. (1999), JGR 104, 4911-4030; [5] Baratoux, D. & Melosh, H.J., (2003) 34th LPSC Houston, CD-ROM #1013; [6] Therriault et al. (1997a), MAPS 32, 71-77.