FIELD STUDIES IN THE CENTRAL UPLIFT OF THE VREDEFORT IMPACT STRUCTURE.

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Summary: This study presents results of a structural investigation of the inner parts of the central uplift of the Vredefort impact structure. The dome posseses a polygonal geometry, with the polygon segments separated by zones of asymmetric homoclinal folding and radial oblique-slip faulting related to tangential compression. Multiple joint sets developed in all rock types display predominantly normal-slip displacements related to late-stage central uplift collapse.

Introduction: A structural investigation of the inner parts of the central uplift of one of the largest and the oldest [1] impact structures on earth – the Vredefort dome – has been carried out. Between 7 and 10 km of erosion has led to the exposure of the root zone of this structure. The Vredefort dome consists of an ~ 40 km wide core of Archean gneiss basement surrounded by a collar of supracrustal rocks of the 2.71-2.98 Ga Witwatersrand Supergroup, followed outward by the Ventersdorp and Transvaal supergroup strata of 2.7-2.15 Ga age. These rocks have been uplifted by at least 15 km relative to the deepest part of the surrounding rim syncline [2]. Recent structural mapping in the Archean gneissic basement by Lana et al. [3] has shown differential rotation of the rocks related to doming. However, a detailed structural investigation in the core is hampered by poor outcrop. In contrast to the core, the rocks of the collar are generally well exposed.

This study: Evaluation of Landsat images and aerial photographs has shown that the structure has a polygonal shape. The collar strata can be divided into different segments with internally consistent orientations of structural features, such as bedding, faults and folds. Polygon segments are arranged at angles of ~30-40^{o} to each other. Individual segments are separated by narrow zones of homoclinal flexure or folding, and associated radial faults. Large-scale faults cut through and displace the Transvaal, Ventersdorp and Witwatersrand supergroup strata in a radial, as well as in a transverse, pattern. However, these faults are usually restricted to one or more subgroups and rarely traverse the entire collar. The exceptions are two north-south trending faults in the northern part of the collar (West Rand and Bank faults), that have been interpreted as pre-Vredefort faults, based on evaluation of stratigraphic thickness of Ventersdorp strata across at least one of these faults. Pre-Vredefort impact faulting in the region has been described by Robb et al. [4] and Myers et al. [5] as north-south and east-west trending deformation features developed during the development of the Witwatersrand basin. As some of these early faults cut across the later Ventersdorp and Transvaal strata, they must have been reactivated in post-Witwatersrand, and most likely in post-Transvaal – likely Vredefort – times. A radial set of large-scale faults displays mostly sinistral displacements of a few hundreds of meters. However, fault exposure is poor and kinematic indicators are missing, consequently the displacements have been estimated from Landsat images and aerial photos only. A second set of transverse faults shows both dextral and sinsitral offsets.

On an outcrop-scale the fracture pattern is more complex. At least four different joint sets have been identified. Two joint sets show radial orientation, but different dip angles. One set, which is also the most dominant one in the collar of the dome, is subvertical, whereas the other set dips with angles of up to 45^{o} and is only locally present. Displacements on these small-scale fractures are on a centimeter scale; however, consistent patterns of movements and overprinting characters of one set over the others are completely absent. A bedding-parallel set of joints is present throughout the collar, but is listric in places, dipping towards the center of the dome. Striations are observed on joint surfaces of this set, indicating a movement of the hangingwall towards the crater center. The bedding-parallel joints are commonly filled with submillimeter-wide veins of pseudotachylitic breccia. A shallowly outward-dipping set of joints has a spacing that is wider compared to the other joints sets and is only rarely pervasive. Striations are also observed on surfaces of this joint set, with a normal sense of slip, i.e. outward-directed movement of the hangingwall. Due to the limited extent of these exposures, the slip magnitude is not absolutely clear, but it appears to be generally on a millimeter to centimeter scale. No interference of these striated surfaces with the striations on bedding-parallel joint surfaces could be observed, making it impossible to establish a time relationship between these two movements (see also [6]). This could, of course, imply, that these two joint types are coeval. The density of all joint sets increases towards the traces of large-scale faults. In general, the intensity of faulting, folding, jointing and pseudotachylitic breccia development decreases radially outwards.

Pseudotachylitic breccias occur throughout the collar. They are clearly most abundant in the vicinity of, and within, large-scale structural features, such as faults and folds. Breccia development is especially prominent in the hinge zones of some large-scale (wavelength hundreds of meters) folds. The most typical appearance of pseudotachylitic breccias in the collar is, however, along bedding planes, where it fills the bedding-parallel fractures and commonly forms submillimeter- to millimeter-wide veinlets. These are cut, but rarely displaced, by radial subvertical faults. These bedding-parallel occurrences of breccia commonly have offshoots, often into radial joints; however, orientations oblique to the bedding have also been observed. The offshoots show many different geometries. Pseudotachylitic breccias can also occur oblique and perpendicular to the bedding. They may be subvertical, as indicated on surface, however, some of them turn sharply into different, even subhorizontal attitudes. It is believed that these sudden changes in orientation could have been influenced by the presence of pre-existing inhomogeneities, such as fractures or cross-bedding.

Shatter cones are present throughout the collar. The local distribution of shatter cones appears to be dependent on rock type – they are preferentially developed in fine-grained argillaceous rocks or even fine-grained volcanics [e.g. 6,7]. Complete shatter cones are rare. Shatter cones have been found by us up to 65 km from the dome center. Previous studies suggested that the main orientation of shatter cone apices is towards the crater center, after rotating the strata back to their pre-impact position [e.g. 8]. However, many other orientations were also observed. The findings by Sagy et al. [9], that so-called striation angles on shatter cone surfaces increase with the distance from the crater center, cannot be confirmed by us. The diversity of shatter cone orientations and the form of shatter cone surfaces are consistent with the model of Baratoux and Melosh [10], which attributes them to heterogeneities in the target rock during decompression.

Discussion: This work has established a time relationship between specific structural features, such as large-scale and small-scale faults and has linked them to different stages of crater development. The early cratering stage is represented by shock deformation features, such as shatter cones and (some) pseudotachylitic breccias (see also [1]). Our findings of the importance of bedding-parallel pseudotachylitic breccia development and massive breccia found in the hinge zones of large-scale folds with offshoots of small veins, thinning out towards the core of the fold, suggest that melt was generated during shock compression but did not quench prior to the onset of the crater modification phase and, consequently, migrated into younger dilational sites.

The formation of the Vredefort central uplift involved partitioning of strain into radial zones of high strain, as evidenced by high-strain features, such as faults and folds, concentrated along the margins of polygon segments. In contrast, the interiors of segments usually show consistent structural features and lack major faults and folds. The consistent sinistral asymmetry of these large-scale fault and homoclinal zones and of dips between the northwestern and southeastern sectors of the dome suggest a northwesterly dipping supracrustal sequence prior to the impact (Lana et al., [3]). Brittle and ductile deformation features, such as large-scale radial and transverse faults and folds, indicate compression and tangential shortening during the initial formation of the central uplift (early modification stage). Most of the small-scale joints (radial, outward dipping and oblique sets) show a complex pattern of either dextral and sinistral displacements by not more than a few millimeters up to 1 centimeter, and with joints of all sets cutting each other. They appear to be related to radial extension, which most likely occurred during the collapse of the central uplift.

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