STRUCTURAL ANALYSIS OF THE M4 DRILL CORE, MOROKWENG IMPACT STRUCTURE (SOUTH AFRICA) – IMPLICATIONS FOR PEAK RING FORMATION PROCESSES. R. L. Gibson, S. S. Wela and M. A. G. Andreoli, School of Geosciences, University of the Witwatersrand, PO WITS, Johannesburg 2050, South Africa (roger.gibson@wits.ac.za).

**Introduction:** The formation of peak rings within large impact craters is one of the most intriguing aspects of cratering mechanics, requiring as it does extreme initial short-term mechanical weakening of the rock volume to facilitate substantial vertical and radial transport, followed by almost immediate recovery of rock strength to sustain structural and topographic elevation differences [1]. Mechanisms proposed for this weakening include impact-induced fracturing and fragmentation, fault weakening by shear heating, shock-induced thermal softening, and acoustic fluidization [1, and references therein]. Interpretation of the recently-recovered IODP/ICDP Expedition 364 M0077A drill core from the peak ring of the Chixculub crater by [1] has suggested that it preserves, *inter alia*, structures related to initial shock-induced cataclasis and ensuing quasi-continuous flow facilitated by acoustic fluidization, as well as more discrete fault structures related to peak ring collapse. Here we describe structural features intersected in a core recovered from near the center of the Morokweng impact structure in northwestern South Africa that share some similarities with those described by [1] but which appear to fit a more restricted strain history.

**Geological Setting:** The 146.1 ± 0.02 Ma [2] Morokweng impact structure (MIS) is largely buried beneath up to 150 m of Cenozoic Kalahari Group sediments and is, thus, mainly constrained from regional geophysical surveys and samples recovered from borehole cores [3]. Although the structure is poorly defined and appears to have been eroded by 1-1.5 km prior to deposition of the Kalahari Group, the most likely original crater diameter estimate appears to be 70-100 km [4]. The M4 hole is located 18 km NNW of the center of an oval cluster of (350 nT) magnetic anomalies interpreted as the extent of the melt sheet [3] (see [2] for map). Four other exploration holes drilled into the cluster intersected impact-melt sheet, with the thickest intersection (800 m) occurring in the M3 hole only 6 km from the M4 hole [2, 4]. The >800 m difference in the elevation of crater floor rocks relative to the M3 hole may relate to its location at the edge of the oval cluster, leading [4] to propose that M4 is sited in the MIS peak ring.

The 368 m M4 core comprises Kalahari Group sand and calcrite to a depth of 96 m and a lower section of crystalline, moderately to weakly foliated, Archean granitoid gneisses and younger metaultramafite and dolerite intrusions that all display variable levels of brecciation and cataclasis and that are cut by mm- to m-scale melt, cataclasite and suevite dikes that overall constitute 12% of the core. Between 140-160 m and 260-300 m depths the core comprises 50% melt and suevite dikes.

**Shock metamorphism and impact-induced hydrothermal effects:** The gneisses contain ubiquitous evidence of shock effects, including multiple decorated PDF sets, reduced birefringence and toasting in quartz and feldspar, feather features, ladder features in plagioclase, exsolution in alkali feldspar and kinked biotite [4]. Based on PDF measurements in quartz, a relatively uniform peak shock pressure of >22 GPa is estimated throughout the core. All lithologies display evidence of hydrothermal alteration that overprints the impact shock features and breccias and which is most comprehensive in the cataclasite, suevite and melt dikes and in areas of intense faulting. The alteration assemblage is dominated by smectites, zeolites, quartz, calcite and hematite ± magnetite, but chlorite, pyrite, garnet and epidote are increasingly found in the deeper parts. These parageneses also occur in mm- to cm-wide dilational veins that cut all other impact-related features.

**Impact-related structural features:** The most ubiquitous macroscopic impact-related feature in the M4 core is a network of shear faults exhibiting predominant shallow to moderate dips that are generally characterized by kaolinite ± hematite alteration. The fault spacing varies from meters to <1 cm and displacements from a few mm to greater than the core width. Almost all displacements are reverse. Fault geometry ranges from planar to anastomosing and curved, with continuity between moderately dipping and steep segments being relatively common. In places, a conjugate pattern defined by paired shallow and moderately dipping fault sets is found. Where cm-scale fault spacing occurs, the gneiss foliation may display a sigmoidal crenulation consistent with reverse shear. Straight fault segments may also be stepped along mm- to cm-scale sigmoidal breccia lenses. Slickenlines are commonly evident where the core has broken along a shear fault surface.

Microscopically, apart from the intragranular shock features, the gneisses show intergranular fracturing and, locally, jigsaw-like brecciation (particularly of quartz). Internal strain and brittle disaggregation of mineral grains increases on a microscale towards the shear faults. The faults are characterized by mm-wide zones of microcataclasite to ultracataclasite with internal sigmoidal fabric elements indicating shear. The shear fault spacing is most intense between 140-160 m and 260-
300 m depths, grading into highly kaolinitized cataclasite and associated with the widest breccia dikes.

Three types of clast-bearing dikes are found: (1) narrow (mm-scale), subvertical, planar to branching, black to red dikes characterized by iron oxide (predominantly hematite) but locally with angular quartz and feldspar fragments; (2) red to orange melt breccias ranging in width from 1-2 mm to ~3 m; and (3) red, grey and green suevite, from 1-2 cm up to 6 m wide. Bulk-rock major, trace and rare-earth element geochemistry confirms that the melt dikes formed from the granitoid and doleritic wallrocks, with the most voluminous and least viscous melts being derived from the mafic lithologies. Petrographic analysis reveals incomplete mixing of melts in larger dikes, including disrupted fluidal melt clasts; additionally the dolerite-derived melts incorporate granite-derived cataclasite masses that are themselves plastically deformed. Melt dikes are intruded into cataclasite and the boundaries between the melt and cataclasite commonly display folds consistent with flow instabilities between two low-viscosity media. Petrographic analysis confirms that the suevite matrix is cataclastic in origin and that the melt clasts were derived by brecciation of thin quenched melt dikes. Rare wispy melt particles in the suevite suggest an intimate timing relationship between melting and cataclasite formation. Overall, these relationships support contemporaneous cataclasite, melting and melt and cataclasite mobilization into dikes.

Although establishing lithological contact relationships in high-grade granitoid gneisses in a drill core is difficult, the three dike types are typically located along lithological contacts that transect the gneiss foliation, thus supporting their link to faulting. On a smaller scale, the dike margins not only exploit the reverse shear faults but thinner melt dikes may be displaced by the shear faults. In contrast, thicker melt dikes are not truncated but their internal flow lamination may be deflected with a reverse shear sense adjacent to shear faults in the wallrock. Pinch-and-swell of the internal layering of steeply-dipping dikes occurs via steep to moderately dipping asymmetric ductile shear bands.

Whilst evidence exists locally of subvertical offsets of melt from larger melt dikes, the thin vertical hematite-bearing dikes are not interpreted as highly oxidized melt dikes as their highly angular clasts suggest a more explosive, in situ, brecciation. These dikes are always displaced by shear faults.

**Discussion and Conclusions:** The range of structural features observed in the M4 core shows strong similarities to features documented by [1] in the M0077A Chicxulub core, supporting the peak ring setting for M4. [1] proposed that the M0077A core features document a major part of the cratering history, from initial shock-related fragmentation and acoustic fluidization following the impact, followed by the progressive regaining of shear and cohesive strength leading to increasing partitioning of strain. This model proposes (ultra)cataclasite formation in response to acoustic fluidization and that subsequent peak ring collapse produced an imbricate thrust zone into which impact melt trapped beneath the peak ring intruded before crystallizing and being weakly deformed by ductile shear bands related to final gravitational spreading of the peak ring.

Whilst the Morokweng M4 core contains evidence of significant strain heterogeneity, the overall orientation and vergence of structures and their timing relationships can be reconciled within a somewhat simpler model than that proposed for the M0077A core. Specifically, the reverse shear fault network throughout the core can be linked to two fault zones, at 140-160 m and 260-300 m depths. The higher strains in each of these fault zones led to intensification of shear faulting, possibly exploiting the gneiss-(meta)dolerite contacts. Complex fault breccias, comprising dm- and larger lithic clasts in a matrix of cataclasite and friction melt (pseudotachylite), formed. Within each fault zone ongoing slip over tens of seconds facilitated intrusion and mingling of the melt and cataclasite, and even brecciation of quenched melt dikes in the incoherent cataclasite. The prolonged and significant slip provided a mechanism for intrusion of melt, cataclasite and suevite into dilatant sites associated with block rotations in the fault zones, or into the adjacent wallrock. Extrapolating the reverse slip sense seen in the shear faults to the larger faults can also explain the vertical extension of dikes manifested in internal pinch-and-swell and extensional shear band features. Although no directional data are available for the M4 core, consideration of models for peak ring formation would suggest that this strain pattern would be compatible with outward collapse of the peak ring over time spans of tens of seconds. The only inconsistent feature is the narrow subvertical breccia dikes; however, these appear to predate the thrust faulting and, thus, might represent an explosive dilational feature produced by acoustic fluidization.

In conclusion, structural evidence preserved in the M4 core is compatible with a major low-angle thrust fault that generated voluminous cataclasite, pseudotachylite and mixed suevite breccias as a result of its unique long-lived slip history during collapse of the Morokweng peak ring.