Structural analysis of the collar of the Vredefort Dome, South Africa—Significance for impact-related deformation and central uplift formation

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Abstract—Landsat TM, aerial photograph image analysis, and field mapping of Witwatersrand supergroup meta-sedimentary strata in the collar of the Vredefort Dome reveals a highly heterogeneous internal structure involving folds, faults, fractures, and melt breccias that are interpreted as the product of shock deformation and central uplift formation during the 2.02 Ga Vredefort impact event. Broadly radially oriented symmetric and asymmetric folds with wavelengths ranging from tens of meters to kilometers and conjugate radial to oblique faults with strike-slip displacements of, typically, tens to hundreds of meters accommodated tangential shortening of the collar of the dome that decreased from \( \sim 17\% \) at a radius from the dome center of 21 km to <5% at a radius of 29 km. Ubiquitous shear fractures containing pseudotachylitic breccia, particularly in the metapelitic units, display local slip senses consistent with either tangential shortening or tangential extension; however, it is uncertain whether they formed at the same time as the larger faults or earlier, during the shock pulse. In addition to shatter cones, quartzite units show two fracture types—a cm-spaced rhomboidal to orthogonal type that may be the product of shock-induced deformation and later joints accomplishing tangential and radial extension. The occurrence of pseudotachylitic breccia within some of these later joints, and the presence of radial and tangential dikes of impact melt rock, confirm the impact timing of these features and are suggestive of late-stage collapse of the central uplift.

INTRODUCTION

Meteorite impacts are catastrophic and extremely complex deformational events marked by both extreme and rapidly changing centro-symmetric strain patterns. On the one hand, the creation of first-order structures, such as central uplifts in complex craters, is currently best reconciled by hydrodynamic models and is consistent with the results of continuum numerical modeling (e.g., Melosh 1989; Melosh and Ivanov 1999). In contrast, however, these central uplifts and the surrounding crater floor rocks contain second-order structures that indicate that localized strain heterogeneity and pre-existing or newly formed structural discontinuities play a major role in the impact-induced structural evolution at scales far smaller than can currently be resolved with the models (e.g., Wilshire et al. 1972; Milton et al. 1996; Kriens et al. 1999). Several studies of the internal structure of shallowly eroded complex craters ranging in diameter from a few kilometers (Upheaval Dome, Kriens et al. 1999; Kenkmann et al. 2005) to several tens of kilometers (Sierra Madera, Wilshire et al. 1972; Gosses Bluff, Milton et al. 1996; Araguainha, Bischoff and Prinz 1994) have provided some constraints on the deformation history accompanying impact and central uplift formation. They suggest that, while lithology exerts some control on the types and geometries of the second-order structures observed, the main controlling factors appear to be the size (duration) of the impact event and the level of subsequent exhumation of the impact structure (Dence 2004).

The Vredefort impact structure in South Africa is one of the three largest impact structures known on Earth (e.g., Grieve and Therriault 2000), having had an estimated original diameter of 250–300 km (Therriault et al. 1997; Henkel and Reimold 1998). It is also the most deeply eroded of the three, with independent estimates suggesting removal of 5–10 km of overburden following its formation (McCarthy et al. 1990; Gibson et al. 1998; Henkel and Reimold 1998). Consequently, the deep levels of the impact structure that are exposed provide an unparalleled opportunity to study the subcrater basement features relating to the impact. This study focuses on the well-exposed Archean supracrustal rocks that occupy an intermediate radial position within the 80 km wide central
uplift of the structure (the Vredefort Dome). It complements previous structural studies of the crystalline basement core of the dome (Lana et al. 2003a) and the surrounding marginal syncline (Simpson 1978; Brink et al. 1997).

**GEOLOGICAL SETTING**

The Vredefort Dome is located some 120 km southwest of Johannesburg, South Africa, in the center of the economically important Witwatersrand Basin (Fig. 1). It consists of an ~40 km wide core of Mesoarchean basement gneisses enclosed by a 20–25 km wide collar of generally vertical to overturned late Archean to Paleoproterozoic supracrustal strata, and is surrounded by an ~50 km wide structural trough known as the Potchefstroom Synclinorium (Figs. 1a and 1c). Evidence of the impact origin of the dome is largely restricted to rocks within a 30–35 km radius of its center and includes shatter cones (Hargraves 1961; Manton 1962, 1965; Albat 1988; Albat and Mayer 1989; Nicolaysen and Reimold 1999), planar microdeformation features in quartz (e.g., Lilly 1978; Fricke et al. 1990; Griev et al. 1990; Leroux et al. 1994) and zircon (Kamo et al. 1996; Gibson et al. 1997), coesite and stishovite (Martini 1978, 1991), microdeformation features, recrystallized diaplectic glass and shock melts in feldspars (Gibson and Reimold 2005), impact melt breccia dikes (Reimold et al. 1990; Koebel et al. 1996), and extremely voluminous pseudotachylitic breccia dikes (Dressler and Reimold 2004; Reimold and Gibson 2005). While these features have been studied in some detail, only limited investigation has been conducted of the larger-scale structures (faults and folds) in the collar of the dome by, among others, Manton (1962, 1965) and Lilly (1978). Additional geophysical work by Antoine et al. (1990) and geological interpretation by Lana et al. (2003a, 2003b) considered the large-scale implications of doming in terms of differential block rotations, but without specifically focusing on any individual structures.

Regional reflection seismic profiles across the dome (e.g., Durrheim 1986; Henkel and Reimold 1998; Therriault et al. 1996) indicate that the contact between the crystalline basement and supracrustal sequence has been uplifted by a minimum of 12 km relative to the deepest part of the rim syncline (Fig. 1c). The impact-related uplift in the central parts of the dome is estimated at a minimum of 20 km (Henkel and Reimold 1998; Lana et al. 2003a, 2003b). Based on an analysis of the Archean fabrics in the basement gneisses, Lana et al. (2003a) concluded that little impact-related rotation occurred in rocks within a radial distance of ~12 km from the center, whereas rocks beyond this distance typically underwent rotations of 90° or more. The transition between these two domains appears to be relatively sharp, occurring over a radial distance of only a few kilometers; consequently, the dome displays an overall plug-like geometry (Lana et al. 2003a).

The limited outcrop and absence of large-scale layering in the basement gneisses in the core of the dome hampered efforts by Lana et al. (2003a) to establish whether it displays a megabreccia structure similar to that proposed for other large central uplifts (e.g., Ivanov et al. 1996). Assuming that gneissic fabrics were uniformly oriented prior to impact, Lana et al. (2003a) did obtain reasonably consistent results when back-rotating these fabrics in the outer parts of the core around axes parallel to the local strike of the adjacent collar strata. In this way, they identified six sectors around the exposed portions of the dome. However, in the absence of evidence for large radial faults delimiting these sectors in the core of the dome, they suggested that impact-induced differential slip and rotations within the core of the central uplift could have been accommodated along a pervasive pseudotachylitic breccia vein-fracture network instead.

The quality of exposure of the supracrustal strata in the collar is better than that of the gneisses in the core of the dome (Fig. 1) and structural interpretation of the collar is aided by the well-layered nature of the rocks, which provides numerous marker horizons. These supracrustal rocks range in age from 3.07 Ga to ~2.1 Ga (Armstrong et al. 1991) and comprise two volcanic sequences (the 3.07 Ga Dominion group and the 2.71 Ga Ventersdorp supergroup) intercalated with two major sedimentary sequences (the 2.9–2.71 Ga Witwatersrand supergroup and the 2.6–2.1 Ga Transvaal supergroup). In addition to several small alkali granite intrusions, mafic and ultramafic sills associated with the extrusive 2.71 Ga Ventersdorp event (Pybus 1995; Reimold et al. 2000) and the intrusive 2.06 Ga (Walraven et al. 1990) Bushveld magmatic event occur in the collar rocks.

The present study focuses on the well-exposed siliciclastic strata of the Witwatersrand supergroup that form the innermost collar, at a radial distance 20–30 km from the center of the dome (Figs. 1 and 2). In comparison, the outer parts of the collar, underlain by the Ventersdorp supergroup and lower Transvaal supergroup, are poorly exposed (Fig. 2). The Witwatersrand supergroup strata consist of a lower sequence of pelitic, quartzite, and ironstone units (West Rand group, ~4 km thick), and an upper, quartzite-conglomerate-dominated sequence (Central Rand group, ~3 km thick). The sedimentary strata and the Ventersdorp-age sills were metamorphosed before the impact event (Bisschoff 1982; Gibson and Wallmach 1995), with the maximum grade of metamorphism increasing with stratigraphic depth from lower greenschist facies (~350 °C) in the Central Rand group to mid-amphibolite facies (~600 °C) in the lower West Rand group (Gibson and Wallmach 1995). Pressure-temperature constraints and geochronological data suggest that this metamorphism accompanied the 2.06 Ga Bushveld magmatism that also appears to be linked to the formation of the alkali granites (Gibson and Wallmach 1995; Gibson et al. 2000; Moser and Hart 1996).

Following the impact, the rocks experienced renewed
Metamorphism through shock heating and impact-induced uplift. Temperatures attained in the Witwatersrand supergroup strata during this event decreased radially outwards from \( \sim 525 \, ^\circ C \) in the lowermost West Rand group to \( \sim 300 \, ^\circ C \) in the Central Rand group, and the deep levels of burial of the rocks presently exposed at surface facilitated widespread recrystallization and new mineral growth, particularly in pelitic rocks (Gibson et al. 1998).

**REGIONAL STRUCTURAL FRAMEWORK**

Given the large size and great age of the Vredefort impact and the fact that the Witwatersrand rocks were deposited some 700–1000 Myr prior to the impact, it is necessary to consider the possibility that the rocks in the Vredefort Dome also record structures related to pre- and/or post-impact deformation events. In terms of pre-impact tectonics, two
major faulting events affecting the Witwatersrand basin have been identified (e.g., Myers et al. 1990; Roering et al. 1990): NE-SW regional shortening that created a series of large fault-bounded blocks in Central Rand group times (2.89–2.71 Ga) and 2.7 Ga Ventersdorp-age rifting that produced broadly NE- and E-trending listric normal faults in the basin (Tinker et al. 2002), some of which represent reactivated Central Rand group faults.

Evidence exists for at least two major pre-Transvaal supergroup faults in the northern collar of the Vredefort Dome (Figs. 1b and 2). The larger of the two trends NNE-SSW and displays ∼2.5 km offset of Central Rand group and Ventersdorp supergroup rocks and thickening of the latter to the west, whereas the second fault, which lies to the west, trends NW-SE and displays ∼1.2 km of offset (Fig. 1b). If the 90° or more of impact-related rotation found in the collar of the dome is removed (see below), these faults define a conjugate set bounding a central graben structure. Palaeocurrent and clast size data from the Central Rand group rocks in the dome (Holland et al. 1990) do not support these faults being active in Witwatersrand times. The orientation, timing, and magnitude and sense of slip of these faults are, however, consistent with Ventersdorp-age rifting. Although outcrop in the outer collar of the dome is poor, there appears to be little, if any, offset of the Transvaal supergroup strata, suggesting that impact-related reactivation of these faults must have been relatively minor at best. Interpreted seismic profiles from west and south of the dome ( Pretorius et al. 1986; Tinker et al. 2002) similarly suggest that most of the large-scale fault structures in the central Witwatersrand basin are related to the Ventersdorp extension at ∼2.7 Ga and show little post-Transvaal (<2.1 Ga) reactivation.

Gravity and magnetic geophysical data and limited borehole information from the southeastern sector of the dome suggests a complicated structure beneath the Karoo supergroup cover rocks (e.g., Pretorius et al. 1986; Antoine et al. 1990; Corner et al. 1990; Martini 1992). The dominant feature in this sector appears to be a NW-trending horst that displaces the core-collar contact radially outwards by ∼5 km along at least two inferred faults (Corner et al. 1990) (Fig. 1b). The pre-impact timing of this feature is indicated by the apparent lack of offset of impact-related post-shock annealing textures in borehole core samples from the area (Martini 1992). Given the results of Tinker et al.’s (2002) regional study, this is most likely a Ventersdorp age (2.7 Ga) structure, as are the large subsurface faults inferred in the northern collar of the dome (Fig. 1c).

In addition to these large faults, Albat (1988) proposed 20–30° of pre-impact scissor rotation along a radial fault in the western collar of the dome to explain anomalous shatter cone-bedding relationships. In general, however, the supracrustal sequence exposed in the northern and western sectors of the dome shows strong continuity of strata with minimal thickness variations along strike (Holland et al. 1990). This points to conformable relationships of stratigraphic units and thus relatively minor tectonic disturbance prior to the impact event.

In addition to the inferred large faults in the southeastern sector of the dome, the few small outcrops of Witwatersrand supergroup strata in this area display moderately steep radial outward dips, in contrast to the predominantly steep overturned inward dips in the remainder of the collar (Figs. 1b and 3). Various explanations, including post-impact regional tilting toward the northwest (McCarthy et al. 1990), or NW-directed post-impact thrusting (Friese et al. 1995) have been proposed. Lana et al. (2003a) noted that the pre-impact metamorphic isograd in the collar rocks cuts upward through the collar stratigraphy toward the northwest (Fig. 1b). By assuming that this isograd formed horizontally, they suggested that the discordance and the slight NW-SE elongation of the basement-supracrustal contact indicated a pre-metamorphic (and thus pre-impact) northwestward tilt of the strata. However, while a tilt of only a few degrees can explain the discordant isograd, the tilt required to reconcile the dip variation in the collar strata would have had to have been of the order of 30–60°, which would be implausible on a regional scale. The most likely explanation is that the anomalous dips in the poorly exposed southeastern sector reflect pre- or syn-impact fault-block rotations, the former associated with the significant zone of Ventersdorp faulting lying southeast of the dome (Pretorius et al. 1986) (Fig. 1a) and the latter related to formation of the central uplift (Fig. 8). As shown in the next section, bedding orientation varies considerably in localized areas throughout the collar of the dome.
Given the metamorphism of the Witwatersrand supergroup strata to lower greenschist- to mid-amphibolite-facies grades shortly before the impact (Gibson and Wallmach 1995), older fault zone rocks are likely to have been partially or completely annealed. Some evidence exists for at least two episodes of small-scale crenulation folding and foliation development in the metapelitic units in the collar during this metamorphism (Gibson 1993; Gibson and Reimold 2001), and similar features have been described associated with bedding-parallel thrusting in the Witwatersrand goldfields (Phillips and Law 1994). However, no map-scale structures appear to be related to this deformation. The emplacement of the alkali granite plutons may account for some of the structural complexity of the Witwatersrand supergroup strata in their vicinity, with bedding striking radial to the dome in places (Fig. 2).

Reconstruction of the Vredefort craterform based on geophysical data led Henkel and Reimold (1998) to propose that post-impact SE-directed thrusting, possibly related to the poorly constrained Mesoproterozoic Kheis orogeny, may have shortened the northwestern part of the impact structure by ∼65 km. They also proposed uplift by several kilometers of the southeastern third of the structure along a major, NNE-trending lineament or flexure now lying beneath the Karoo basin, or as a result of NW-directed, 1.1 Ga, Namaqua-Natal thrusting (see also Friese et al. 1995). However, they noted that these events did not substantially affect the gross structure of the Vredefort Dome itself.

**RESULTS**

The present study involves interpretation of the large-scale structure of the northern and western parts of the collar of the Vredefort Dome using 1:250,000 Landsat TM (Fig. 2), 1:25,000 stereoscopic aerial photographs, and 1:10,000 orthophotos, together with both regional and detailed local structural mapping. Most data were collected from quartzite units of the West Rand and Central Rand groups because of their generally excellent exposure (Fig. 2). The principal results are presented below.
Gross Collar Morphology

The results of our analysis of bedding orientations in the Witwatersrand supergroup strata around the dome (Fig. 3) confirm the mostly overturned nature of the strata in the northeastern, northern, and western parts of the collar and moderate, right-way-up dips in the southeastern sector; however, dips in the northern and northeastern quadrants are also locally right-way-up. Within the limitations of the dataset, which shows significant spread in bedding orientations within comparatively small areas (Figs. 3b–3g), the data do not appear to support Lana et al.’s (2003a) contention that the angle of overturning is discernibly lower in the southwestern and northeastern quadrants than in the northwestern quadrant because of a pre-impact shallow northwestward dip of the supracrustal strata. This implies that the average 120° of overturning of the collar rocks (Fig. 3) is a true reflection of the amount of impact-induced rotation.

Based on interpretation of regional gravity and magnetic datasets, Antoine et al. (1990) suggested that the dome has a polygonal, rather than circular, shape. They divided the exposed section of the dome into six segments, arranged at angles of 40° to 45° to each other, with possibly two more segments to the south hidden beneath the Karoo Supergroup cover rocks (Fig. 3a). In order to test this polygon model, we subdivided our dataset to correspond to Antoine et al.’s (1990) segments (Fig. 3a). The resultant stereonets (Figs. 3b–3g) show considerable variation in bedding orientations stemming from both symmetric and asymmetric folding of the bedding on a ten to hundred m-scale (km-scale fold data such as shown in Figs. 4 and 5 were excluded from the datasets) and fault-related block rotations (Fig. 8). The results indicate angles of 30° to 45° between the individual maxima of poles to bedding only in the northeastern and western sectors (Figs. 3b, 3c, 3e, and 3f); however, considerable overlap exists even for these sectors, indicating that bedding rotation in response to doming was distributed on a smaller scale than that envisaged by Antoine et al. (1990). A further argument against the polygonal model is that our study failed to identify any large radial faults extending across the entire collar of the dome in the positions proposed by Antoine et al. (1990) (compare Figs. 2 and 3a).

A first-order calculation of the amount of tangential shortening associated with the formation of the central uplift was made by comparing the cumulative strike length of three marker horizons in the Witwatersrand supergroup on the 1:50,000 geological map of the Vredefort Dome (Bisschoff 2000) with the calculated circumference based on radial distance from the center of the dome (Table 1). In the Hospital Hill Subgroup quartzite horizons of the West Rand group (Figs. 2, 4, and 6), the measured shortening by faulting and folding is approximately 17%, whereas the amount of shortening in the upper Government Subgroup and the upper units of the Central Rand group (Turffontein subgroup) is less than 5% (Table 1). Given the structural complexity of the collar, the impersistent outcrop in places, the variation in radial distance of individual marker units from the center (Fig. 2), and the existence of Ventersdorp-age extensional faults, these values should be regarded as only crude approximations. For instance, a 1 km variation in radial distance changes the calculated shortening by approximately 5%.

Folds

Based on the regional-scale mapping and image analysis, ductile strain in the collar rocks is heterogeneous. For convenience, three structural subdomains have been identified, although, as argued below, they form a continuum: 1) relatively straight segments up to several km long with or without internal m- to km-scale gentle to open symmetric undulations; 2) open to tight km-scale symmetric folds oriented radially to the dome; and 3) asymmetric km-scale open homoclinal folds with axial planes trending oblique to the dome.

Much of the local variation in bedding orientation recorded in individual sectors around the dome (Fig. 3) relates to the outcrop-scale gentle folding of bedding, although fault-related block rotations also play a role locally. Smaller-scale folds (meters to tens of meters) appear to be restricted to the strongly layered West Rand group. Large, km-scale, broadly symmetric, gentle to open folds occur in both the West Rand and Central Rand group strata, but are more common in the former. At an even larger scale, the collar rocks show a cuspate-lobate pattern indicating heterogeneous strain around the dome. The cusps point both towards and away from the center of the dome (Fig. 2) and are invariably faulted.

The most intense km-scale folding occurs in the West Rand group in the northeastern sector of the collar where five synformal anticlines are developed in the Hospital Hill Subgroup over a strike length of ~13 km (Fig. 4). Symmetric folds in the northern and northeastern sectors of the dome are generally more open than those in the northwestern sector, with interlimb angles typically between 20° and 30°. All the folds show synformal anticline geometries, with subvertical axial planes and steeply inward-plunging hinges, both of which trend radial to the dome. Bedding in the northwestern segment displays a general southeasterly overturned dip (Figs. 3c and 4). The three central folds (B to D in Fig. 4) are largely symmetric with radially-striking axial planes and are characterized by limbs of roughly equal length that strike oblique to the general NE-SW bedding trend. In two of these folds, the layering on the southwestern limb is partially or completely right-way-up (folds B and C, Figs. 4c, 4d, and 5), whereas the more open fold (D, Fig. 4e) displays overturned layering on both limbs. Fold D is less disrupted by faults than folds B and C, which have been displaced radially outward by conjugate faults by 0.5–2 km (Figs. 4a and 5). Folds B and D have steep to vertical radially-trending axial planes and
moderate to steeply radially inward-plunging hinges, whereas fold C has a gently southwest-dipping axial plane and tangential gently southwest-plunging hinges, (Fig. 4d). Given the general radial trend of the other symmetric folds around the dome, we suggest that post-folding fault-block rotation may explain this particular anomaly. On a smaller scale, the fold limbs display m- to dm-scale secondary folds and both the limbs and hinges are disrupted by curviplanar faults that are typically poorly exposed.

Quartzite units in the hinges of the more intense symmetric folds (e.g., fold B, Figs. 4 and 5) are highly fractured and progressive rotation of bedding around the hinge is typically not seen (Fig. 5b). Instead, these hinge zones contain irregular networks of pseudotachylitic breccia up to 20–30 m wide (see also Dressler and Reimold 2004). In contrast, pseudotachylitic breccias in the quartzites in the fold limbs or in the straight segments of the collar are considerably less voluminous and are generally bedding-parallel with only minor discordant offshoots (see below). Outcrop of the metapelitic units in the fold hinges is generally poor; however, they do not appear to show similar voluminous network breccias.

Folds A and E in the northwestern sector of the dome are asymmetric and both display sinistral vergence (Fig. 4). They are homoclinal, with short southwestern limbs striking between 45° and 90° to the regional trend of bedding. While bedding remains overturned on the short limb of fold E (Fig. 4f), bedding in fold A has a steep right-way-up orientation (Fig. 4b). Fold A is associated with a smaller, open, asymmetric, dextral-verging fold some 500 m to the northeast that suggests that it is, in fact, part of a larger asymmetric box fold. The short limb of fold E is displaced along a radial fault with a sinistral slip sense (Fig. 7b), whereas fold A lies within a few km of a major oblique fault with a sinistral slip sense (compare Figs. 2, 4, and 6). The hinge of fold E plunges steeply south-southeast and the foldaxial plane dips steeply to the southeast (Fig. 4f). In contrast, fold A displays a moderately south-southwest plunging fold hinge and a moderately southwest-dipping fold axial plane (Fig. 4b). A noteworthy aspect of the asymmetric folds is that, despite exposure of more than 200° of arc-length around the dome, the major asymmetric folds all show a sinistral vergence.

Faults

The quartzites of the Witwatersrand supergroup provide excellent markers with which to investigate faulting in the collar of the Vredefort Dome (Figs. 6 and 7). Although the faults themselves seldom crop out, the exposures afforded by
the significant topographic relief in the collar and analysis of fractures in the vicinity of the fault traces suggest that most faults are vertical. The orientation of the faults varies from radial to oblique with respect to the circumference of the dome (Fig. 7) and the largest faults can be traced for more than 5 km along strike. Among the larger faults, oblique trends dominate in the western sector, whereas the northwestern, northern, and northeastern sectors display a preponderance of radial fault orientations (see also Lilly 1978) (Fig. 6). Curvature of the faults is common, particularly in the western sector where the faults are longest. Based on Nel’s (1927) map, Lilly (1978) suggested that most of the curved faults are concave toward the core of the dome; in contrast, we detected no preferential pattern. Faults in the Transvaal supergroup rocks in the outer collar show similar oblique-radial strikes and apparent offsets to the inner collar faults (Simpson 1978; Bisschoff 2000), confirming that these structures are younger than the ∼2.7 Ga Ventersdorp age faults.

Fig. 5. Structural data from fold B in Fig. 4 and its vicinity showing the relationship between bedding, faults, and joints. The scatter of bedding data on the western limb of the fold (b and f) is a consequence of dm-scale folding and the change from right-way-up dips near the hinge of the fold to overturned dips in the south. a) A sketch map of Hospital Hill quartzite from which data was obtained. b) An annotated aerial photograph of fold, showing faults and absence of clear hinge curvature. Diagrams (c) to (f) are lower hemisphere equal area Schmidt net projections of the poles to bedding and joints (contour plots) in the continuations to the (c) SW and (d) NE of the fold, (e) northern limb of fold and (f) western limb of fold (great circles refer to average bedding orientations, Roman numerals to joint sets described in text).
Together with the pseudotachylitic breccias in the hinges of long, but cataclastic fault breccias have not been found. Vein networks up to several meters wide and tens of meters quartzites. They regularly contain pseudotachylitic breccia for their development. Conjugate faults (e.g., Fig. 5) suggest a consistent strain field the close spatial association between symmetric folds and of both the asymmetric folds and the majority of the faults and ductile deformation; however, the similar sinistral asymmetry West Rand group (Figs. 4–6), suggesting that they postdate group seldom displaying slip magnitudes of more than 100 m. Such faults are displacement occur along the core-collar contact in the southwestern sector of the dome (Lilly 1978). Such faults are difficult to locate in the more deeply weathered metapelitic and ironstone units of the Witwatersrand supergroup; however, sharp variations in dip angles of up to 40° between stratigraphically-adjacent sedimentary units suggest that such faults must exist.

### Joints and Shear Fractures

Previous studies of fracture phenomena in the Vredefort Dome have focused primarily on shatter cones (Hargraves 1961; Manton 1962, 1965; Albat 1988; Albat and Mayer 1989) and the so-called multiply striated joint sets (MSJS) that Nicolaysen and Reimold (1999) linked to the shatter cones. The results of our study of shatter cones are the subject of another paper and will not be discussed further here, except to note that they assist in constraining the formation age of other fractures (Fig. 9a).

Given the general ease with which joints appear to form in upper crustal environments, the most obvious problem is whether particular joint sets can be related with any certainty to the impact event. Apart from the distinctive shatter cones and MSJS, some fractures can be attributed to the impact-related deformation as a consequence of their association with impact-related melts. The most obvious of these are the nine dikes of impact-melt rock (Vredefort Granophyre) that occur in single or en-echelon radial and tangential fractures of up to several km length in the inner collar and outer core of the dome (Therriault et al. 1996) (Fig. 1b). These dikes, which have widths ranging from 10 to 60 m, appear to be unaffected by either the large-scale folds or the radial and oblique faults in the West Rand group (Bisschoff 2000), consistent with their emplacement having occurred after tangential shortening. This suggests that the latter stages of the evolution of the dome, prior to final crystallization of the impact melt, were characterized by simultaneous tangential and radial extension. A similar conclusion of radially directed dilation can also be drawn from the dm-thick bedding-parallel pseudotachylitic breccia veins that extend for tens to hundreds of meters in the West Rand group quartzites, for example, along the northern limb of fold E in Fig. 4. Like the voluminous pseudotachylitic network breccias that occur preferentially within quartzites in the large fault zones and in the hinges of the large-scale folds, the fillings of these veins appear to have migrated from their sites of generation (see Discussion section).

In the metapelitic rocks of the West Rand group,
however, a more complex geometric relationship exists between fractures and pseudotachylitic breccia veins. The rocks are pervaded by a network of hairline, irregular to curviplanar shear fractures that display mm- to cm-scale offset of both bedding and pre-impact metamorphic porphyroblasts (Gibson et al. 1997) (Fig. 9b). Gibson (1996) and Gibson et al. (1997) described this phenomenon as a “spaced fracture cleavage” because of the intense, cm- to dm-scale spacing of the fractures. The fractures commonly contain mm-thick veinlets and pods of pseudotachylitic breccia that have chemical compositions consistent with largely in situ derivation, and the veins and fractures are overgrown by the post-impact metamorphic paragenesis found in the host rock, which commonly obscures the fractures in hand specimen (Gibson et al. 1997). Locally, larger breccia networks are present. Precise slip directions along the shear fractures are difficult to determine, and offsets of bedding locally suggest either horizontal tangential extension or shortening. The latter may indicate formation of these fractures in conjunction with the large-scale folds and faults, while the former might be compatible with either the shock compression stage or the final collapse of the central uplift (see Discussion section). Morphologically similar breccia-filled fractures in the core of the dome (Gibson and Reimold 2005) and the Central Rand group quartzites in the northeastern collar (Martini 1991) have been identified as shock features because of the localization of shock metamorphic effects along their margins.

Thin psammitic layers within the pelitic rocks locally show an orthogonal to rhomboidal fracture pattern on bedding surfaces involving up to three sets of closely spaced (typically mm- to cm-scale spacing and tens of centimeters long) fractures, similar to the pattern seen in thinly bedded quartzite units (Fig. 9c). In both scale and geometry, these fractures resemble the “shatter cleavage” described by Milton et al. (1996) in the thinly bedded units in the Gosses Bluff structure (Australia) that they linked to the shatter cone phenomenon. Their lack of discernible dilation distinguishes them from the larger-scale, more irregular joints, which clearly cut them and which have a dilational origin (Fig. 9c). These joints form the most striking large-scale fracture phenomenon in these rocks (Fig. 10). Joint spacing and length is generally directly proportional to layer thickness, with the largest joints in the quartzites being hundreds of meters long and tens of meters apart (Fig. 10a). Although Lilly (1978) suggested that the joints are parallel to the faults in the collar, his analysis was
Based purely on strike data. We agree that fracture intensity increases in the quartzites in the fault zones and that therefore at least some of the fractures are fault-related. However, a full 3-D analysis of numerous sites around the dome indicates that the principal geometric control on these joints is bedding orientation, with the main sets typically being oriented either perpendicular or parallel to bedding (Figs. 5 and 10). Fractures parallel to bedding have been removed from all stereoplots in Figs. 5 and 10, as they are represented by the bedding orientation.

Apart from the bedding-parallel fractures, the most prominent set of joints in outcrop is typically subvertical and perpendicular to bedding (labeled I in Figs. 5, 9a, and 10). This set displays a general radial orientation with respect to the dome. The exceptions are sections where the bedding has been folded or rotated by faulting and, thus, is no longer tangential to the dome (Figs. 5e and f). This set bisects the acute angle between two inclined shear fracture/joint sets (II and III in Figs. 5e, 5f, 9a, and 10), although the two sets commonly show slightly different dips (e.g., Figs. 5 and 10) and may be unequally developed. Locally, these fractures display mm- to cm-scale normal dip-slip displacement, consistent with tangential extension and vertical shortening (Fig. 9d). A fifth set (IV in Figs. 5 and 10) strikes parallel to bedding and displays a shallow outward radial dip. Joints of this set are typically short and may be irregular. The metapelitic rocks show a similar joint pattern to the quartzites (Figs. 10b and 10c). The lack of prominence of set IV in the metapelitic units might reflect the general lack of vertical relief in the metapelitic outcrops. The amphibolite-grade metapelitic units in the West Rand group show considerably less jointing than the intercalated quartzites, whereas the low-grade (or greenschist-facies metamorphic) metapelitic rocks further from the center of the dome are typically more intensely jointed than the adjacent quartzites (Fig. 9a).

Pseudotachylitic breccias are found both within the joints and shear fractures (Figs. 9b and 9e). In the former case, the breccias appear to occupy purely dilational structures, an interpretation supported by the local development of veins in en-echelon tension gash geometries (Dressler and Reimold 2004; Reimold and Gibson 2005). The absence of clear-cut generation planes for most of the breccias in the dome has been noted by other authors (e.g., Reimold and Colliston 1994; Dressler and Reimold 2004). In general, thinner veins of pseudotachylitic breccia are more likely to be displaced by small amounts along cross-cutting fractures (Fig. 9d). Thicker veins show less evidence of displacement by fractures. While some of these joints must be related to post-impact tectonic events, this evidence suggests that the joint pattern is largely the product of the final stages of central uplift formation. The overall volume of pseudotachylitic breccia and the size of individual occurrences decrease radially outwards through the Witwatersrand supergroup rocks, but veins up to 1–2 cm thick are still found locally in the Ventersdorp supergroup rocks.

**DISCUSSION**

**Implications for Central Uplift and Cratering Mechanics**

Structural analysis of the Witwatersrand supergroup rocks in the collar of the Vredefort Dome indicates that, rather than exhibiting a comparatively simple geometry involving rigid polygonal segments separated by radial faults as suggested by Antoine et al. (1990), the collar displays a highly heterogeneous internal structure involving both ductile and brittle strain. The 2.06 Ga metamorphic and alkali granite intrusive events provide a convenient time marker with which to distinguish pre-impact brittle structures from those generated during the impact event. The association of the folds, faults, and fractures in the collar with voluminous
pseudotachylitic breccias—that are themselves overprinted by the impact-related thermal event (Gibson et al. 1997)—supports their impact origins.

The bulk of the large-scale structures (folds, radial, and oblique faults) display geometries and kinematic indicators that are consistent with formation during tangential shortening of the collar strata. The amounts of shortening calculated in this study agree with those deduced by Manton (1965) using Nel’s (1927) original map of the dome (he estimated 7% shortening in the West Rand group and no shortening in the Central Rand group). They confirm the radial outward decrease in the amount of shortening that was also postulated by Simpson (1978), who noted no discernible shortening in the Transvaal supergroup rocks in the outer collar. The values obtained—17% in the lower West Rand group and <5% in the Central Rand group—fall well within the range of plastic strains predicted by numerical modeling of large central uplifts (Collins et al. 2004).

The similarity in the strain field responsible for the formation of the folds and faults and their spatial coincidence, together with the similar sense-of-shear of faults and asymmetric folds, suggests that formation of the ductile and brittle features overlapped in time, although ongoing fault-related block rotations may explain the somewhat varied orientation of the folds (Fig. 4) and the generally lesser amounts of overturning of the southwestern limbs of these folds. While fold formation indicates ductile strain, the development of brecciated hinge zones that are commonly pervaded by pseudotachylitic breccias points to brittle deformation as well, which is consistent with the high strain rates typical of impact processes. Ductile behavior in these rocks may have been enhanced by the elevated post-shock temperatures, estimated at >500 °C in the inner parts of the collar but decreasing to ∼300 °C in the Central Rand group rocks (Gibson et al. 1998). This temperature variation—the product of differential shock-induced heating and the pre-impact geotherm (Gibson et al. 1998; Gibson and Reimold 2005)—may have played a role in the radial outward decrease in the relative importance between folding and faulting seen in the collar. However, this pattern may equally be the result of the radial outward decrease in the amount of shortening across the collar, or the change from a mechanically heterogeneous sequence of quartzite and metapelitic units in the West Rand group, which should have favored folding, to the more homogeneous and more competent quartzite-dominated succession in the Central Rand group, which might have favored faulting.

The predominantly radial to radial-oblique arrangement of structures in the Vredefort Dome and the dominance of subhorizontal displacements in their formation contrast with the tangential to oblique-tangential arrangement of centripetally directed thrusts found in the central uplifts of smaller craters such as Gosses Bluff (Milton et al. 1996), Upheaval Dome (Kriens et al. 1996; Kenkmann et al. 2005),

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Fig. 8. a) Variable dip orientation of West Rand group quartzites disrupted by radial faults in the northwestern part of the collar. The quartzite package is 70 m wide. b) Lower hemisphere equal area Schmidt net projection of the poles to bedding in the different fault blocks B, C, and F. Average bedding orientations are shown as great circles. Data indicate more than 90° of rotation about a subhorizontal, broadly tangential axis.
Fig. 9. Fracture and joint phenomena in the Witwatersrand supergroup rocks in the collar of the Vredefort Dome. 

a) Shatter cones (center, left) in metapelitic unit cut by four sets of joints, Central Rand group in the northwestern collar. The vertical (II in text) and horizontal (IV) sets are most intense, with set II trending NNE across the image (right side) and set III only poorly developed (bottom, center). 

b) Pseudotachylitic breccia-bearing shear fractures showing mm- and cm-scale slip in Hospital Hill subgroup metapelite from the northern limb of fold A (Fig. 4). A weak conjugate pattern is suggested. Although only one set of fractures displays discernible slip, this is consistent with tangential extension (dextral slip sense). However, one fracture (center, left) shows opposing slip. Such complexity is typical of these fractures (length of pen 10 cm). 

c) Intense orthogonal fracture pattern in Hospital Hill quartzite in the northern collar (east of fold E, Fig. 4). The orthogonal fractures are cut by younger, irregular, conjugate joints (NE and NW orientations in the photo), which are also responsible for the way in which the slab has broken. 

d) View of vertical bedding surface showing conjugate shear fractures (sets II and III, see text) cutting thin pseudotachylitic breccia vein (horizontal, east-west), western limb of fold E (Fig. 3) (length of pen 10 cm). 

e) Shallowly outward-dipping pseudotachylitic breccia (pt 2) filling type IV joint cuts a bedding-parallel vein (pt 1), Hospital Hill subgroup, northeastern collar.
Haughton (Bischoff and Oskierski 1988), and Sierra Madera (Wilshire et al. 1972). While this might reflect differing levels of erosion of the central uplifts, with the zone of convergence of the transient crater wall slumps still preserved in the smaller central uplifts, it is more likely that the center of the Vredefort crater was never marked by such a structure. This is because the inward propagation of the faults from the collapsing walls is not sufficiently fast to reach the center of a very large crater before the floor starts to rebound (Dence 2004). Such structural complexity probably exists, instead, in the peak rings of such craters with the added complexity of a strong component of centrifugal thrusting driven by outward collapse of the central uplift, opposing the centripetal motion of the walls. On this basis, it does not appear plausible that the steeply radially-plunging folds in the collar of the Vredefort Dome represent rotated radial transpression ridges, as postulated in Kenkmann and von Dalwigk’s (2000) generic model.

Collapse of the Vredefort central uplift is also indicated by the granophyre dikes and joints in the collar rocks that developed in a strain field involving simultaneous radial and tangential extension. Impact-melt dike intrusion is unlikely to have been possible until vertical uplift had ceased, a fact borne out by the lack of any evidence of displacement of the dikes by the folds and faults. In all likelihood, it indicates that the central uplift collapsed to the point that it formed a topographic low, allowing at least some of the impact-melt to accumulate and be retained above it.

Further evidence for outward collapse of the central uplift to form a peak ring may be provided by the increasing amounts of rotation measured from the center of the dome outwards. Based on structural mapping of the crystalline basement core of the dome, Lana et al. (2003a) concluded that a central region approximately 25 km wide experienced minimal impact-related rotation, and that this is surrounded by an annulus comprising the outer core of the dome, where ∼90° of rotation is needed to explain the present orientation of the gneissic pre-impact structures. In contrast, the inner collar...
rocks studied here show an average of ~120° of overturning (Fig. 3). We can find no support for Lana et al.'s (2003a) suggestion that this reflects only 90° of impact-related rotation superimposed onto a moderately steeply dipping rock sequence. Instead, we propose that this increase reflects the outward collapse of the outer parts of the central uplift in the final stages of crater modification.

The origin of the uniform sinistral sense-of-shear on faults and of folds in the collar of the dome is unknown. Pronounced asymmetry in the central uplifts of smaller complex impact structures such as Gosses Bluff and Upheaval Dome has been interpreted as the result of asymmetric mass displacement of rocks close to the surface caused by oblique impact (Milton et al. 1996; Kenkmann et al. 2005), but the levels exposed in the Vredefort Dome are far deeper than those studied in these smaller craters, making such an option less likely. It is possible that a slight asymmetry in the target rocks—for instance, pre-impact tilting of the supracrustal succession, but by a much smaller amount than proposed by Lana et al. (2003a)—might induce asymmetry in the impact-related structures. Unfortunately, nearly half of the Vredefort Dome is buried beneath younger cover rocks, which hampers investigation of this problem.

Numerical modeling suggests that a central uplift the size of the Vredefort Dome is likely to have formed within a matter of 2–3 min (e.g., Henkel and Reimold 1998; Melosh and Ivanov 1999). During most of this time, the rocks in the central uplift appear to occupy radial positions further from the center of the impact structure than their starting positions (e.g., Collins et al. 2004); it is only in the latter stages of uplift that tangential shortening gains in importance. It thus seems likely that the radial folds and radial and oblique faults developed towards the end of central uplift formation.

Within a larger context, the presence of faults in the collar but apparent lack of them in the core of the dome may reflect a combination of increased post-shock temperatures toward the center of the dome (Gibson et al. 1998; Gibson and Reimold 2005), different rock types (heterogeneously layered collar rocks versus massive crystalline core), and lesser amounts of rotation in the core (plug-like geometry) (Lana et al. 2003a). One option is that slip could have been distributed more evenly through the rocks in the core of the dome because of the increased intensity of pseudotachylitic breccia development toward the center of the dome (Reimold and Colliston 1994; Gibson and Reimold 2005), thereby obviating the need for widely spaced large-magnitude faults (Lana et al. 2003a). Melosh (2005) rejected this possibility on the grounds that the melts would have quenched almost immediately after forming, because of the large temperature difference with the host rocks. However, superheated shock melts such as those described by Gibson and Reimold (2005) may have remained liquid long enough, given the extreme host-rock temperatures found in the center of the dome (Gibson et al. 1998; Gibson 2002). Dence (2004) noted a similar lack of macroscopic fragmentation (i.e., faults) in the central parts of the Charlevoix and Manicouagan central uplifts where shock pressures exceeded 25 GPa, from which he suggested that the amount of brittle deformation in central uplifts may scale inversely with shock pressure.

Pseudotachylitic Breccias

Evidence in support of a syn-impact timing for pseudotachylitic breccia development in the Vredefort Dome is overwhelming (e.g., Dressler and Reimold 2004; Reimold and Gibson 2005), allowing the breccias to be used to constrain the impact origin of other structures. However, the exact mechanism(s) by which the breccias formed remain problematic. Three mechanisms have been proposed (see review in Reimold and Gibson 2005): a) localized shock melting caused by extreme fluctuations in shock pressure, b) friction melting along slip surfaces triggered during the modification stage of cratering, or c) a combination of shock and friction melting during the shock stage. Evidence exists for localized enhancement of shock deformation against fractures hosting narrow melt breccia veins in both the core (Gibson and Reimold 2005) and collar (Martini 1991) of the dome, but these fractures also invariably show small amounts of displacement. Given their small volumes, it is likely that these melt breccias crystallized or quenched virtually instantaneously, and thus constrain the fractures as syn-shock. However, the same argument cannot be made for the structures hosting more voluminous breccias, as these may have been able to retain a molten matrix for several minutes, if not hours (Ogilvie, personal communication 2004). In contrast to the narrow veinlets, which typically show a close correspondence between the chemical composition of their matrix and that of their wallrocks, the larger breccias show abundant evidence of mixing of melt from a variety of sources, as well as exotic clasts (Reimold and Colliston 1994), indicating sufficient time for melts and clasts to move distances of at least meters to tens of meters. In the context of the cratering process, it is thus plausible that the pseudotachylitic breccias could all have formed simultaneously during the shock stage by either shock melting + friction melting, but that crystallization straddled the subsequent stages of central uplift formation and collapse, depending on the degree of superheating of the melts, the host rock temperature, and the volume of melt present. Equally, however, some or even most of the breccias could have formed during the modification phase in response to high-strain-rate slip events. It is beyond the scope of this study to explore this issue further, except that it is worth noting that thinner breccias in the collar of the dome are more likely to have been displaced by fractures than thicker breccias (compare Figs. 9d and 9e) and that a melt capable of surviving for even a few minutes within such a complex structural environment may now reside in a very different structural context from the one in which it originated.
Chronology of Impact-Related Deformation

The oldest mesoscopic impact-related structures seen in the collar rocks of the Vredefort Dome are the shatter cones that, together with at least some of the pseudotachylitic breccia (Martini 1991; Gibson and Reimold 2005), formed during the shock pulse. The orthogonal to rhomboidal fracture cleavage observed in the quartzite units may form part of a structural continuum with the shatter cones and MSJS.

The next structures to form were the folds. Recent modeling by Collins et al. (2004) suggests that rocks in the central uplift follow a trajectory in which they are initially displaced downward and radially outward under shock compression, followed by vertical uplift, only toward the end of which do they move closer to the center of the impact structure than the position from which they started. This suggests that the folds most likely developed close to the end of central uplift formation, although their present overturned geometries may reflect subsequent outward collapse of the central uplift. Continuing tangential shortening was accommodated by asymmetric to conjugate strike-slip faulting. Pre-existing faults do not appear to have been particularly reactivated. It is possible that some pseudotachylitic breccias could have formed at this stage through frictional melting along the faults; however, it is also possible that sufficiently voluminous melts created during the shock pulse (by shock and/or friction melting) could have survived long enough to be driven into extensional sites opening within the younger structures, where they either quenched or crystallized. Given that the central uplift probably formed within only 2–3 min (e.g., Melosh and Ivanov 1999), strain-rates for the tangential shortening were probably of the order of at least $10^{-4}$ to $10^0$ s$^{-1}$.

Possibly overlapping the latter stages of the contractional phase, the collar rocks underwent some tangential faulting and block rotation around horizontal tangential axes. The subvertical tangential faults with collar-side-down displacement in the western part of the collar (Lilly 1978) and radially inward-dipping faults in the outer collar with center-side-down displacement described by Simpson (1978) may belong to this phase.

The granophyre dikes and ubiquitous joints indicate radial and tangential extension, which is consistent with late-stage collapse of the central uplift (stress-release). It is possible that earlier-formed strike-slip faults may have undergone reactivation or become dilated during this phase, allowing the last vestiges of impact-related melts to infiltrate them.

CONCLUSIONS

In contrast to the massive crystalline core and poorly exposed outer parts of the Vredefort Dome, the well-layered siliciclastic rocks of the Witwatersrand supergroup in the inner collar of the dome preserve a variety of fold, fault, fracture, and melt breccia features related to the 2.02 Ga impact event. The bulk of the fold and fault structures relate to tangential shortening of the strata, which reached $\sim 17\%$ in strata closer to the center of the dome, decreasing to $<5\%$ further out. These figures are compatible with the predictions of total plastic strain during central uplift formation in large complex craters obtained by recent computer modeling (Collins et al. 2004). Tangential shortening was followed by radial and tangential extension related to the collapse of the central uplift that produced ubiquitous jointing and rarer faults, and provided the opportunity for downward intrusion of dikes from the impact melt sheet. The origin and timing of crystallization of pseudotachylitic breccias within the Vredefort impact event remains problematic and is the subject of ongoing research.

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REFERENCES


