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The significance of the Vredefort Dome for the thermal and structural evolution of the Witwatersrand Basin, South Africa

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With 5 Figures

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Summary

The Vredefort Dome represents an area of significant (~ 10 km) structural uplift within the central parts of the economically important Witwatersrand Basin. Its rocks experienced higher grades of metamorphism than the equivalent stratigraphic horizons exposed around the periphery of the basin. Recent studies of this medium- to high-grade metamorphism, as well as new evidence concerning the origin of the dome, have contributed to a metamorphic model for the Witwatersrand Basin as a whole. This evidence shows that the gold-bearing strata experienced at least two metamorphic events at ca. 2 Ga. The unusually high strain rate and shock deformation features exposed in the rocks of the dome rule out an endogenous origin by tectonic or diapiric processes. Recent work on these features has shown that the dome is best explained as the central uplift of a large, 250–300 km diameter, 2023±4 Ma old meteorite impact structure, the extent of which closely correlates with the present-day limits of the Witwatersrand Basin. Impact-related deformation features in the Vredefort rocks facilitate the separation of metamorphic textures developed during a pre-impact event associated with the 2.05–2.06 Ga Bushveld magmatism, and textures developed during a slightly lower-grade, post-impact, static overprint. The post-impact overprint decreases in intensity outwards from the dome. It is attributed to the massive disturbance of the thermal structure of the crust by impact-induced exhumation, and to shock heating of the rocks as a consequence of the impact event.

Zusammenfassung

Die Bedeutung des Vredefort-Domes für die thermische und strukturelle Entwicklung des Witwatersrand-Beckens, Südafrika

Der Vredefort Dom ist ein Gebiet von signifikantem (ca. 10 km), strukturellem Uplift im Zentralbereich des wirtschaftlich bedeutungsvollen Witwatersrand-Beckens. Die Gesteine des Doms haben höhere Metamorphosebedingungen erfahren als die stratigraphisch äquivalenten Lagen, die im Randbereich des Beckens aufgeschlossen sind. Kürzlich durchgeführte Untersuchungen dieser mittel-bis hochgradigen Metamorphose und neueste Ergebnisse zur Entstehung des Domes haben einen Beitrag zu einem Metamorphose-Modell für das gesamte Witwatersrand-Becken geleistet. Diese neuen Befunde zeigen, daß die Gold-hältigen Gesteinsschichten zumindest zwei metamorphe Ereignisse vor ca. 2 Ga erfahren haben. Die ungewöhnlich hohen Beanspruchungsraten und die Stoßwellendeformationsstrukturen, die in den Gesteinen des Doms belegt sind, sprechen gegen einen endogenen Ursprung durch tektonische oder diapirische Prozesse. Neuere Arbeiten an diesen Phänomenen haben gezeigt, daß der Dom am besten als die zentrale Struktureinheit ('Zentralberg') einer sehr grossen, 250–300 km weiten und 2023±4 Ma alten Meteoriteneinschlagsstruktur verstanden werden kann, deren Ausmaß eng mit den jetzigen Grenzen des Witwatersrand-Beckens übereinstimmt. Die Gegenwart von Impakt-bezogenen Deformationsstrukturen in Vredefort-Gesteinen erlaubt es, die metamorphen Texturen, die während eines hochgradigen, mit dem 2.05–2.06 Ga Bushveld Magmatismus korrelierten, metamorphen Stadiums vor dem Impaktereignis entstanden sind, von den Texturen zu trennen, die ein statisch metamorphes Ereignis von etwas geringerer Stärke, das nach dem Impakt stattfand, produzierte. Die Spuren des post-Impakt Ereignisses nehmen in ihrer Stärke zum Rand des Domes ab. Dieser Effekt wird durch eine massive Störung der thermischen Krusten-Struktur erklärt, die als Resultat einer Kombination von impakt-induzierter Exhumierung, von Schock-Aufheizung der Krustengesteine, und von Erwärmung durch einen gewaltigen, jetzt erodierten Impaktschmelzgesteinskörper gesehen wird.

Introduction

The past decade has witnessed a shift in the paradigm for mineralization in the Witwatersrand basin, the source of 40% of the world's gold, from a sedimentary placer model (e.g., *Minter* et al., 1993) towards modified-placer, or even epigenetic, models (e.g., *Frimmel*, 1994; *Phillips* and *Law*, 1994; *Robb* and *Meyer*, 1995; *Barnicoat* et al., 1996; *Robb* et al., 1997; *Stevens* et al., 1997a).

This shift has been largely driven by, and is itself driving, a renewed focus on the post-depositional thermal and structural evolution of the Witwatersrand Basin. Central to such studies is the Vredefort dome, a ~70 km diametre structure in the central parts of the basin, which marks an area of extreme uplift and relatively higher-grade metamorphism of the Witwatersrand strata (Fig. 1). In this paper, we review the various hypotheses that have been proposed to explain the origin of the Vredefort dome, and the most recent research results that support a close association between the formation of the dome by a large meteorite impact and metamorphic-hydrothermal events that affected the gold mineralization in the basin. The deformation and metamorphism associated with the formation of the dome provide an important time-line within the complex history of the basin and its mineralization.

Regional geology

The Vredefort dome is a broadly circular feature centred on 27° S, 27°30′ E some 120 km SW of Johannesburg (Figs. 1, 2). It comprises a 40 km wide core of

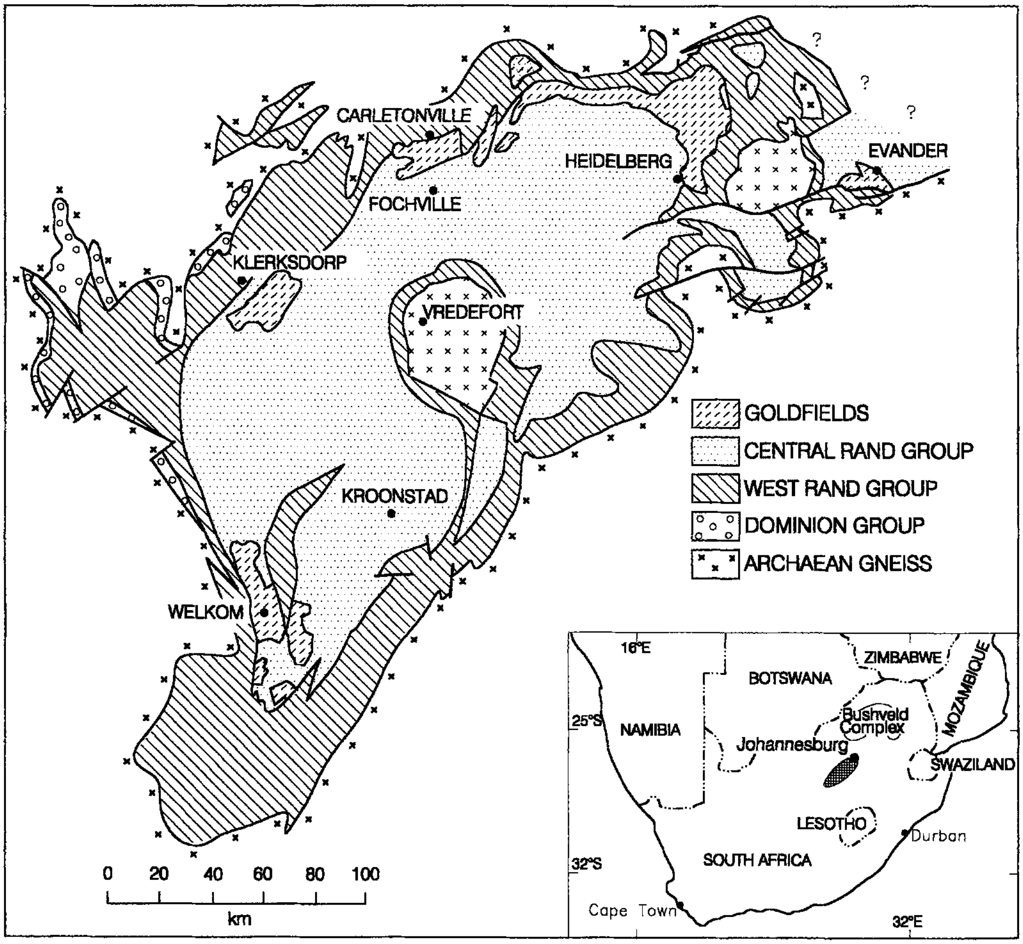

Fig. 1. Map of the Witwatersrand basin, showing the central location of the Vredefort dome. *Henkel* and *Reimold* (1998) proposed that the basin limits correspond roughly to the maximum extent of the Vredefort impact structure and that the present elliptical shape reflects subsequent tectonic deformation of the originally circular structure. Inset shows location of the Witwatersrand basin (hatched) with respect to the Bushveld Complex

>3.1 Ga Archaean basement granitoid gneisses with subsidiary mafic and pelitic gneisses and a surrounding 15–20 km wide collar of steeply dipping to overturned sedimentary and volcanic supracrustal rocks, which contain subsidiary mafic and alkalic granite intrusions. These collar rocks comprise the ca. 3.1 Ga Dominion Group, the 3.0–2.7 Ga Witwatersrand Supergroup (comprising the West Rand and gold-bearing Central Rand Groups), the 2.7 Ga Ventersdorp Supergroup, and the ca. 2.6–2.2 Ga Transvaal Supergroup. The dome is unconformably overlain by Phanerozoic sediments of the Karoo Supergroup in the south.

The Vredefort dome contains several unusual features, which have received considerable attention in the geologic literature (for a full review, see *Reimold* and *Gibson*, 1996):

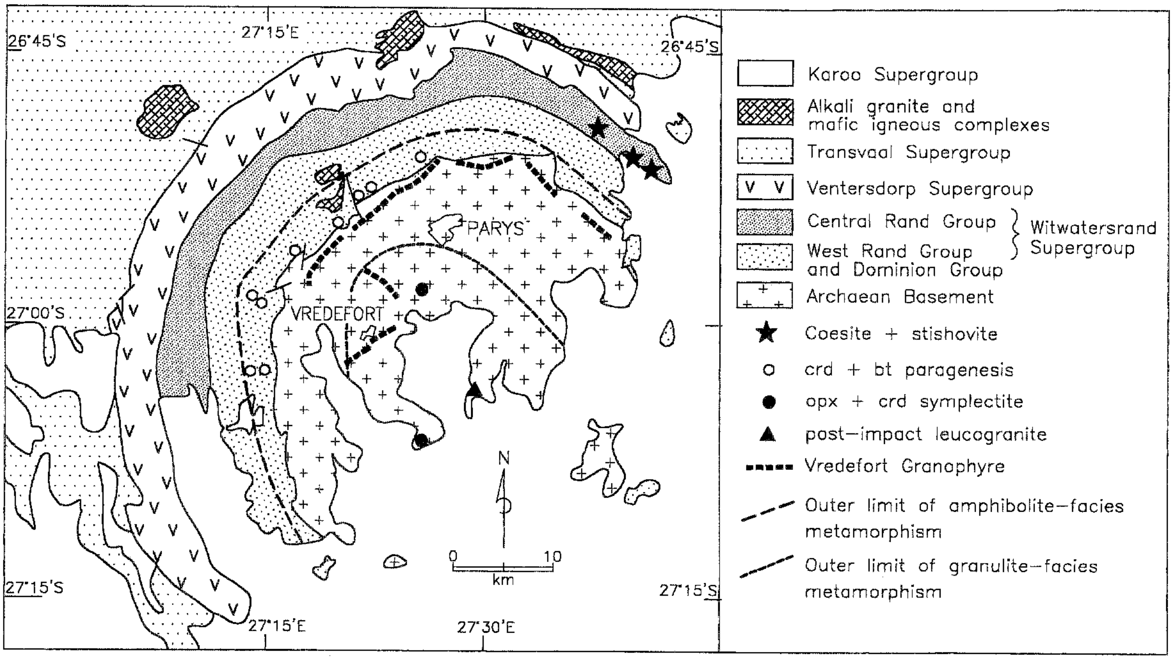

Fig. 2. Geological map of the Vredefort dome showing granophyre and coesite-stishovite localities, annular pre-doming metamorphic isograds, and the distribution of post-doming metamorphic assemblages (*crd* cordierite; *bt* biotite; *opx* orthopyroxene)

1. pseudotachylitic breccia dykes, ranging from small veinlets to bodies 1 km long and 50 m wide (e.g., *Reimold* and *Colliston*, 1994);
2. shatter cones and striated joint surfaces (e.g., *Dietz*, 1961; *Hargraves*, 1961; *Manton*, 1965; *Nicolaysen* and *Reimold*, 1999);
3. coesite and stishovite in rocks in the NE collar of the dome (Fig. 2) (*Martini*, 1978; 1991; *White*, 1993);
4. planar microdeformation features in quartz (e.g., *Fricke* et al., 1990; *Leroux* et al., 1994) and zircon (*Kamo* et al., 1996; *Gibson* et al., 1997a); and
5. dykes of a clast-laden granophyric rock with an unusual, yet remarkably homogeneous, composition across the dome (the Vredefort Granophyre, Fig. 2) (*French* et al., 1989; *Reimold* et al., 1990; *Köberl* et al., 1996).

Structurally, the dome is extremely complex. *Stepto* (1990) and *Colliston* (1990) identified several folding and shearing events, predating the Dominion Group, in the Archaean basement rocks. *Gibson* (1993) identified a further two cleavage-forming events in the Witwatersrand Supergroup that occurred prior to doming. Recent mapping has also identified several km-scale fold structures of indeterminate age in the Witwatersrand Supergroup (*R. van der Merwe*, pers. comm., 1998). In addition, the supracrustal succession is disrupted by a complex pattern of faults, possibly related to the formation of the dome, but probably involving older and/or younger movements as well (e.g., *Coward* et al., 1995; *Friese* et al., 1995; *Brink* et al., 1997). *Antoine* et al. (1990) described the outcrop pattern in the dome as polygonal, rather than circular, due to these faults. The dome is surrounded by a rim synclinorium, the development of which *McCarthy* et al.

(1990) regarded as an important factor contributing to the preservation of the gold-bearing Witwatersrand strata along the basin margin. A series of tangentially-arranged folds in the upper Transvaal Supergroup strata within the core of this synclinorium were linked by *Simpson* (1978) to the formation of the dome. *McCarthy* et al. (1986) and *Gibson* et al. (1999) described centrifugally-directed structures (thrust faults, shear zones, folds and cleavages) beyond the limits of the Witwatersrand basin, up to 150 km from the dome, which they also attributed to the doming event. In the goldfields, abundant pseudotachylitic breccia occurrences have been correlated with out-of-basin thrusting directed away from the dome (e.g., *Killick*, 1993; *Fletcher* and *Reimold*, 1989). A geochronological study of such breccias by *Trieloff* et al. (1994) has confirmed the genetic link between this deformation and the formation of the dome (see below) and indicates that deformation structures associated with the doming event provide an important time-line throughout the basin.

The disturbance of the 2.6–2.2 Ga Transvaal Supergroup strata in the dome and rim synclinorium indicates that the dome is younger than ~2.2 Ga. A ca. 2.0 Ga age for the doming event was originally suggested from radiometric studies of the Granophyre dykes [2016 ± 24 Ma, K-Ar isochron from biotite and 2002 ± 52 Ma U-Pb zircon age (*Walraven* et al., 1990), 2006 ± 9 Ma, biotite ^{40}Ar-^{39}Ar (*Allsopp* et al., 1991)]. These results are in close agreement with recently obtained ages from pseudotachylitic breccias of 2006 ± 17 Ma (^{40}Ar-^{39}Ar stepheating, *Trieloff* et al., 1994), 2018 ± 7 Ma (weighted mean, ^{40}Ar-^{39}Ar laser probe, *Spray* et al., 1995) and 2023±4 Ma (U-Pb zircon, *Kamo* et al., 1996) and an undeformed leucogranite in the centre of the dome (Fig. 2) (2017±5 Ma; SHRIMP U-Pb single-grain zircon; *Gibson* et al., 1997a).

The rocks exposed in the dome display variable grades of metamorphism, increasing from greenschist facies in the outer parts of the collar to granulite facies in the central core (*Bisschoff*, 1982; *Schreyer*, 1983; *Gibson* and *Stevens*, 1998) (Fig. 2). The Vredefort dome, thus, represents a thermal "high" within the otherwise greenschist-facies grade Witwatersrand Basin (*Phillips* and *Law*, 1994; *Stevens* et al., 1997a). Various hypotheses have been advanced to reconcile the extreme uplift associated with the formation of the dome with the unusual deformation features and the development of high metamorphic grades in its rocks. These can be grouped into endogenous and exogenous hypotheses.

Endogenous models for the Vredefort Dome

Several endogenous models have been proposed to account for the formation of the Vredefort dome. Central to these models has been the view that the dome is a structural and metamorphic hub, and that its central location within the Witwatersrand Basin is too fortuitous to be explained by an exogenous origin. *Brock* and *Pretorius* (1964) and *Ramberg* (1967) proposed a diapiric origin for the dome, the former suggesting that it was one of several domes formed in the immediate vicinity of the Witwatersrand Basin. However, they did not attempt to explain why unusual deformation phenomena are found only in the Vredefort Dome or why the grade of metamorphism in the Witwatersrand Supergroup is higher in the dome than in other parts of the basin. *Du Toit* (1954) and, more recently, *Colliston* (1990) and *Coward* et al. (1995) suggested that the dome is the product of complex fault-related deformation. *Colliston* (1990) proposed a fault-bend fold model involving N- to NW-directed thrusting on a SE-dipping shear zone rooted at the Moho discontinuity. He proposed a pre-thrusting episode of metamorphism in the Witwatersrand Supergroup accompanying the intrusion of the alkali granite bodies observed in the collar of the dome (Fig. 2), and a late- to post-doming episode, including partial melting, related to uplift-induced decompression. *Coward* et al. (1995) suggested that the dome represents a push-up structure on a compressional bend in a large NNW-trending left-lateral strike-slip zone.

Schreyer (1983) favoured an (unspecified) internal origin for the dome, arguing that the high strain rate deformation occurred penecontemporaneously with the granulite-facies metamorphism in the core of the dome. However, he remained puzzled by the unusually high post-doming metamorphic pressure of ~ 0.5 GPa from the core rocks obtained by *Schreyer* and *Abraham* (1978), as this necessitated that the Vredefort rocks were exhumed by some 18 km *after* the formation of the dome. Other proponents of internal processes (e.g., *Antoine* et al., 1990; *Nicolaysen* and *Ferguson*, 1990; *Nicolaysen* and *Antoine*, 1997; *Nicolaysen*, 1998) based their model on the spatial coincidence of the dome with what they interpreted as a centre of pre-doming magmatism defined by the alkali granites and mafic intrusions in the supracrustal succession, and with regional geophysical structures such as the alleged, NW trending, Vredefort axis, as well as the medium-to high-grade metamorphism that predated the shock deformation features. *Nicolaysen* and *Ferguson* (1990) explained the shock deformation features as the result of catastrophic degassing of volatile-rich mantle magmas, concluding that the dome reflects mantle processes.

Recent results and an exogenous origin for the Vredefort dome

Although a meteorite impact origin for the Vredefort Dome was originally proposed by *Boon* and *Albritton* (1936) and received widespread support among the international scientific community in the ensuing decades, local geologists were concerned about several inconsistencies with regard to the so-called "impact-diagnostic" deformation features identified in the dome (see review in *Reimold* and *Gibson*, 1996). The issue was further complicated by evidence from the Archaean basement core rocks that suggested a close temporal relationship between the formation of the dome and the high-grade metamorphism (e.g., *Bisschoff*, 1982; *Schreyer*, 1983; *Stepto*, 1990).

Impact-diagnostic features

The most important criteria for the recognition of a meteorite impact structure – besides circular morphological and geophysical anomalies and the occurrence of shatter cones or massive melt breccias – are micropetrographic indicators that the rocks experienced shock deformation. These indicators are mineral deformation effects which, on the basis of natural and experimental observations, are known to be produced in upper crustal rocks only by the extreme high strain rate, high-pressure (>5 GPa), and high-temperature processes associated with hypervelocity impact events. Such mineral deformation effects include planar deformation features (PDFs), diaplectic glass, shock mosaicism, partial and complete isotropization of minerals, high-pressure mineral polymorphs, and partial melting of rocks in the shock pressure regime between about 10 and >50 GPa (e.g., *Stöffler* and *Langenhorst*, 1994; *Grieve* et al., 1996; *Huffman* and *Reimold*, 1996).

The first unequivocal mineralogical evidence that the rocks in the Vredefort dome experienced shock deformation was obtained by *Martini* (1978, 1991) who identified coesite and – rare – stishovite associated with pseudotachylitic breccias in quartzites of the Central Rand Group at several localities in the NE collar of the dome (Fig. 2). Experimental shock data indicate minimum pressures of 2 GPa for coesite formation and 7.5 GPa for stishovite (*Akaogi* and *Navrotsky*, 1984). The rather restricted distribution of the coesite and stishovite samples in the dome was attributed by *Martini* (1991) to post-shock thermal effects over much of the dome (see below).

Quartz crystals from the granitoid gneisses in the outer core and the quartzites of the Witwatersrand Supergroup commonly contain one or more sets of planar trails of fluid inclusions (Fig. 3a), or planar zones defined by fine-grained quartz

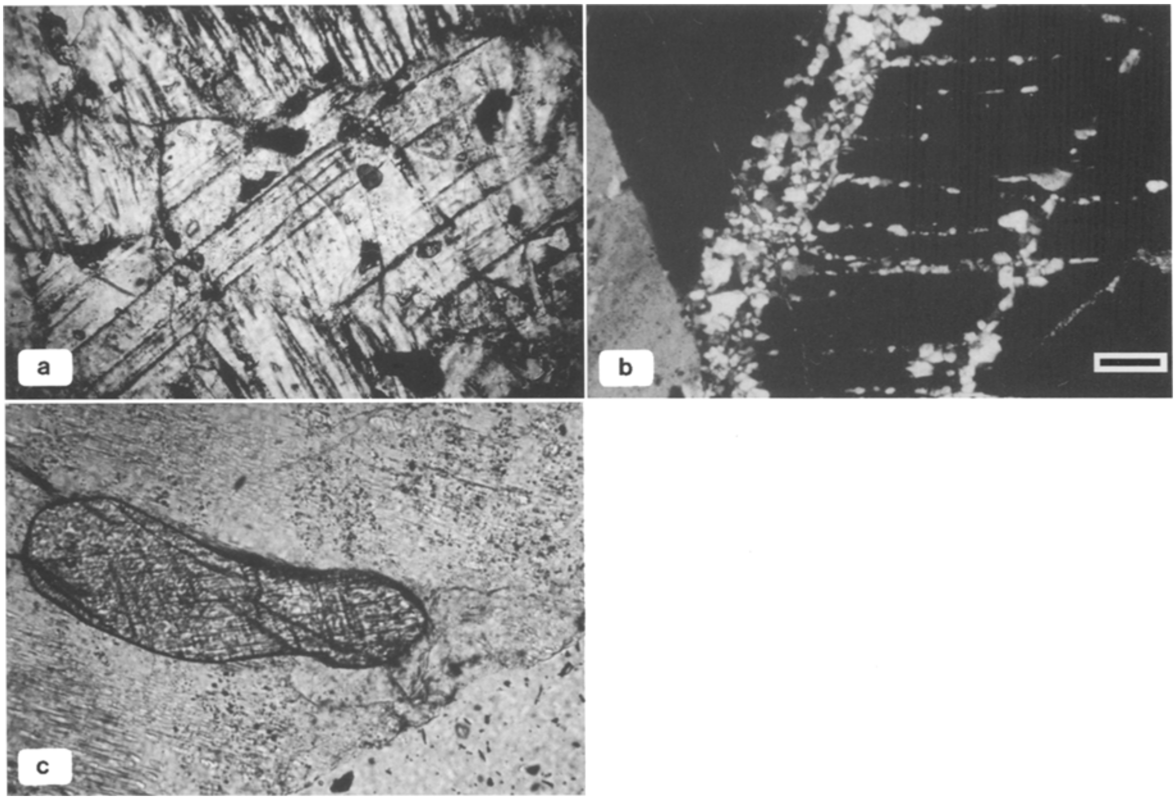

Fig. 3. **a** Planar microdeformation features in quartz of West Rand Group quartzite. The planes are commonly defined by trails of fluid inclusions. Parallel polars. Width of view 800 µm. **b** Mosaic recrystallization of PDFs in quartz from metapelitic granulite from the core of the dome. Crossed polars, scale bar 100 µm. **c** Planar microdeformation features in zircon in metapelitic granulite from the core of the dome, SE of Vredefort. Parallel polars. Width of view 300 µm

mosaics (Fig. 3b). *Grieve* et al. (1990) noted the similarity of the crystallographic orientations of these planes with those of PDFs found in shocked quartz crystals. While many workers were prepared to accept that the inclusion trails and recrystallized zones in the Vredefort quartz represent original PDFs that underwent annealing during a subsequent metamorphic overprint, others expressed concern about the lack of evidence of any other impact-diagnostic features such as diaplectic glass and shock mosaicism, or shock effects in other common minerals such as feldspar (e.g., *Reimold*, 1990). A second anomalous aspect of these planar features relates to the fact that experimental studies show that the crystallographic orientations of the PDFs in quartz vary as a function of the shock pressure (e.g., *Stöffler* and *Langenhorst*, 1994). As shock pressure will be highest in the centre of an impact structure, the crystallographic orientations of quartz PDFs should vary systematically along radial traverses across the dome; however, no such variation has been observed in the Vredefort Dome (e.g., *Hart* et al., 1991). Both these anomalies may be the product of selective annealing of certain shock features following the impact event (e.g., *Grieve* et al., 1990); however, this remains difficult to prove.

Conclusive proof that the planar fluid inclusion trails in the Vredefort quartz were, indeed, originally PDFs was finally obtained from transmission electron microscopy (TEM) by *Leroux* et al. (1994) who were able to ascertain that the planar features in the basal crystallographic orientation in Vredefort quartz are Brazil twins. Apart from developing as a growth feature in natural rocks, Brazil twins have only ever been described elsewhere as the result of shock deformation in rocks from confirmed impact structures and from the impact-related Cretaceous-Tertiary Boundary Layer (ibid).

Recently, *Kamo* et al. (1996) and *Gibson* et al. (1997a) identified multiple sets of planar microdeformation features in zircon crystals in rocks from the core of the dome (Fig. 3c). *Kamo* et al. (1996) also identified a "strawberry texture" (aggregates of tiny, euhedral zircon crystals grown within a primary crystal, obviously as the result of a high-temperature event) in some zircon grains from Vredefort rocks. These distinctive features have only ever been identified elsewhere in samples derived from confirmed impact structures (e.g., Sudbury, Manicouagan, Chicxulub) and from the K-T Boundary (references in *Kamo* et al., 1996). While not much work has been carried out as to the nature and formation conditions of these deformation textures in zircon, a recent study by *Leroux* et al. (1999) strongly suggests that shock pressures of at least 20 GPa are required to produce such planar features. TEM analysis by these authors showed that planar microcleavage as well as glassy planar deformation features in zircon form first in the shock pressure interval between 20 and 40 GPa.

Although shatter cones were identified in the collar rocks of the dome by *Dietz* (1961), considerable debate remains about whether these features are true cones or whether most or all of them represent intersecting sets of striated joint surfaces (*Nicolaysen* and *Reimold*, 1999). *Gash* (1971) proposed that shatter cones, *sensu stricto*, form by the interaction of an incident shock wave with a tensile wave reflecting from a source such as a large grain, pore space or fracture. From shock wave experiments (*Roddy* and *Davis*, 1977), it is estimated that they form at shock pressures of between 4 and 30–45 GPa. Several studies in the Vredefort dome have attempted to reconstruct the impact geometry using cone "axes" (e.g., *Albat*, 1988), as has been done for smaller, simple impact structures; however, *Nicolaysen* and *Reimold* (1999) continue to urge caution about this approach.

The dykes of Vredefort Granophyre in the basement core of the dome (Fig. 2), long suspected of being intrusions of impact melt into the floor of the impact crater due to their unusual composition and the abundance of clasts derived from the Witwatersrand Supergroup, have been investigated geochemically in an attempt to isolate a meteoritic component. Modelling of the Granophyre chemistry suggests that it could have been derived largely from melting of the supracrustal succession in the dome, however, initial studies of siderophile element concentrations failed to detect an Ir enrichment consistent with a contribution from a meteoritic source (*French* et al., 1989; *Reimold* et al., 1990). Possible reasons for this include the presence of Ir-rich shales in the West Rand Group, and the fact that detection limits for conventional chemical methods are too high to permit such discrimination if the meteoritic component is extremely small (*French* et al., 1989). Recently, however, *Köberl* et al. (1996) employed the much more sensitive Re–Os isotopic tracer method (e.g., *Köberl* and *Shirey*, 1993) and found that the Os content of the Granophyre is considerably higher than that of the rocks from which the bulk of the Granophyre is likely to have been derived. From the very low, near-meteoritic, ^{187}Re/^{188}Os and ^{187}Os/^{188}Os ratios, *Köberl* et al. (1996) determined that the Granophyre melt contained a very small ($\sim 0.2\%$) meteoritic component. By implication, the Vredefort dome must have formed as the result of the impact of a large meteoritic projectile.

Although not a shock deformation feature as such, the pseudotachylitic breccias in the dome indicate that the dome formed by a highly unusual process because of their excessively large volumes. Similar breccias with dimensions of tens of metres or kilometres have only been recorded elsewhere from the 200 km diametre Sudbury impact structure (e.g., *Spray* and *Thompson*, 1995). In contrast, tectonic pseudotachylitic breccias usually display dimensions of centimetres to a few tens of centimetres (see review in *Gibson* et al., 1997b).

In summary, several studies in the past few years have confirmed that the rocks in the Vredefort dome experienced shock and other highly unusual deformation at 2023 Ma ago and, therefore, that the dome is the product of an impact event. Endogenous models cannot explain, in particular, how the shock pressures necessary to effect the observed deformation could be generated by mantle or crustal processes, or how such large volumes of pseudotachylitic breccia could be produced by normal tectonic processes. Arguments, by *Nicolaysen* and *Ferguson* (1990), *Nicolaysen* and *Antoine* (1997) and *Nicolaysen* (1998) that the dome is a locus of mafic magmatism cannot be substantiated as the mafic intrusions to which they refer are related to the much older 2.7 Ga Ventersdorp Supergroup (*Pybus*, 1995).

Timing and origin of the medium- to high-grade metamorphism

Studies by Phillips and co-workers in the Witwatersrand goldfields (e.g., *Phillips* and *Law*, 1994) established that the Witwatersrand Supergroup around the margins of the basin experienced a relatively uniform, lower greenschist-facies, meta-

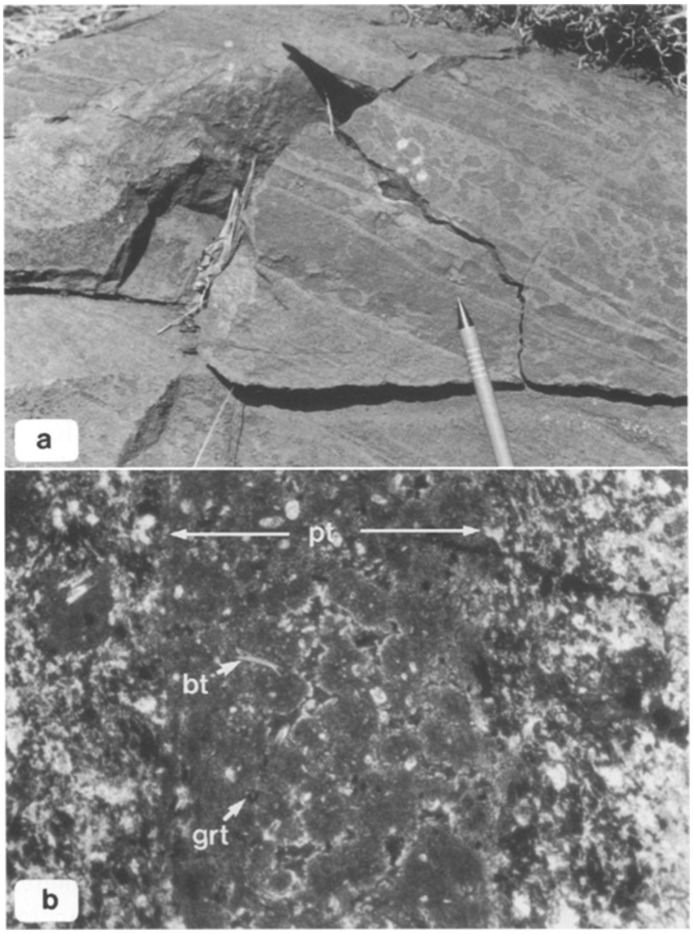

Fig. 4. **a** Andalusite-cordierite-biotite-staurolite metapelite from the West Rand Group showing an irregular cross-cutting fracture containing pseudotachylitic breccia (to right of pencil). Pencil indicates twinned andalusite; dark ovals are cordierite. **b** Photomicrograph of pseudotachylitic breccia vein (pt) from West Rand Group metapelite showing recrystallization to cordierite-biotite paragenesis (cordierite crystals are ovals $\sim 100\,\mu m$ in diameter, with dark, biotite-rich, cores and thin, inclusion-free, rims). Breccia contains quartz, garnet (grt) and biotite (bt) clasts. Parallel polars. Width of view 1 mm

morphic event ($T \sim 350 \pm 50\,°C$; $P \sim 0.2$–0.3 GPa), implying the existence of a ca. 40 °C/km regional geothermal gradient at some point in the post-depositional evolution of the basin. However, the relationship between this metamorphism and the amphibolite-facies metamorphism in the Witwatersrand Supergroup in the Vredefort dome remained obscure. Workers such as *Bisschoff* (1982) and *Schreyer* (1983) suggested that the Vredefort metamorphism may have been related to localised intrusions in the vicinity of the dome, one manifestation of which were the alkali granites (Fig. 2). This metamorphism occurred prior to doming as the metamorphic parageneses are affected by the high strain rate deformation features such as the pseudotachylitic breccias (Fig. 4a) and PDFs. In the core of the dome, however, evidence suggested that the high strain rate features were accompanied or followed by an additional high-grade metamorphic event (e.g., *Schreyer* and *Abraham*, 1978; *Schreyer*, 1983; *Fricke* et al., 1990; *Grieve* et al., 1990; *Hart* et al., 1991; *Martini*, 1992) (Figs. 3b, 4b). This evidence of high-grade metamorphism both pre- and post-dating the doming-related deformation effects was used by proponents of an endogenous origin for the dome to support a model of the Vredefort dome as a thermal centre. In the context of recent results favouring an impact origin for the dome, however, such a model is problematic.

In an investigation of the mid-amphibolite-facies metamorphism in the West Rand Group rocks in the inner collar of the dome (Fig. 2), *Gibson* and *Wallmach* (1995) demonstrated that the rocks evolved along an anticlockwise P-T path (increasing P with increasing T), consistent with syn-metamorphic thickening of the overlying crust during metamorphism. Based on P-T estimates, they concluded that the peak geothermal gradient during this event reached ~40–50 °C/km. An anticlockwise P-T path for the metamorphism is not consistent with a diapiric model, which should involve decompression during heating, as hot diapiric material moves closer to the surface. This, together with the extreme crustal geotherm and P estimates of ~0.4–0.45 GPa for the metamorphism, led *Gibson* and *Wallmach* (1995) to propose that the metamorphism was related to the 2.05–2.06 Ga Bushveld magmatic event. *Gibson* and *Stevens* (1998) proposed, further, that this metamorphism occurred coeval with the peak metamorphism in the goldfields, and that the higher grade of the metamorphism in the dome compared with the goldfields reflects originally deeper levels of burial of the rocks towards the centre of the basin (ca. 14–16 km vs. < 10 km in the goldfields). *Stevens* et al. (1997b) suggested that the granulite facies metamorphism in the core of the dome (Fig. 2) was also related to this event. The current broadly annular distribution of the isograds around the dome, with grade increasing towards its centre, thus, reflects greater amounts of exhumation towards the centre of the dome of originally subhorizontal regional isograds, rather than a localised heat source centred on the dome as suggested by *Bisschoff* (1982) and *Schreyer* (1983).

Gibson and *Wallmach* (1995) and *Gibson* et al. (1997b) were able to link the formation of the pseudotachylitic breccias to the formation of the dome, as the breccias separate the peak-T paragenesis in the Witwatersrand Supergroup from a younger, lower-T, lower-P (~500 °C, 0.3 GPa; *Gibson* et al., 1998) paragenesis (Fig. 4b). Based on the geobarometric estimates obtained from these parageneses, *Gibson* et al. (1998) calculated that the West Rand Group rocks in the inner collar were exhumed by ~3–5 km during the doming event. In the core rocks, doming involved at least 7 km of exhumation. The high post-doming temperatures of these rocks, ranging from ~400 °C in the mid-collar to >700 °C in the core of the dome (*Gibson* et al., 1998), explain the anomalous, and heterogeneous, annealing of the PDFs across the dome observed by many workers (e.g., *Grieve* et al., 1990; *Martini*, 1992) (Figs. 3a,b).

In summary, the recent work by our group has identified two distinct metamorphic events in the Vredefort rocks, with the older, pre-doming, metamorphism being unrelated to the doming event itself, although it occurred sufficiently close to the latter that most radiometric dating studies have been unable to satisfactorily separate the two. The post-impact metamorphism decreases in intensity radially outwards. *Gibson* et al. (1998) interpreted this as evidence that the latter metamorphism occurred as a direct consequence of the doming event. Based on thermometric calculations, *Gibson* et al. (1998) attributed the post-doming metamorphism to the combined effects of shock heating, caused by the release of elastic strain energy from shock-compressed mineral lattices during the impact event, and differential uplift, induced by cratering and rebound of the crater basement, which produced the dome. They suggested that, at the present levels of exposure, heating effects from the impact melt body are likely to have been negligible.

What was the original size of the Vredefort impact structure?

In the past, proponents of an impact origin for the Vredefort Dome have quoted varied size estimates ranging from 70–80 km (the current diameter of the dome) to 140 km (the current diameter of the dome and surrounding Potchefstroom Synclinorium) for the Vredefort impact structure. *Therriault* et al. (1997) examined the spatial distribution of Vredefort rock and mineral deformation features (shatter cones, pseudotachylitic breccias, and PDFs in quartz) and compared these scaling observations with scaling equations derived for other confirmed impact structures. This empirical study resulted in estimates for the original transient cavity of between 110 and 140 km and for the diameter of the final (modified) impact structure between 225 and >300 km. Very similar results of between 250–280 km were obtained by *Henkel* and *Reimold* (1998) for the final diameter, based on integrated geophysical (particularly gravity) modelling across the Witwatersrand Basin and geometric reconstruction of the original impact structure largely based on available gravity and reflection seismic data. This means that the Witwatersrand

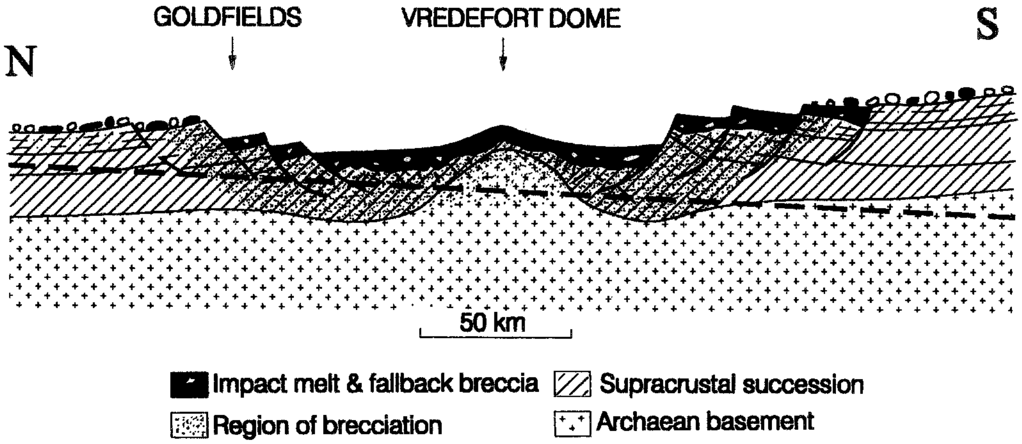

Fig. 5. Schematic cross-section through the Vredefort impact structure at 2023 Ma showing approximate positions of goldfields relative to the impact centre (Vredefort dome). The present level of erosion is indicated by the heavy dashed line – the deeper levels of erosion to the south reflect regional tilting of the crust subsequent to the impact event (*McCarthy* et al., 1990). Further modification of the structure, producing the elliptical outline of the Witwatersrand Basin shown in Fig. 1, occurred during the Kheis and Kibaran events (*Friese* et al., 1995)

Basin itself is the deeply-eroded remnant of the Vredefort impact structure (Figs. 2, 5). At these values, the Vredefort impact structure is the largest known terrestrial impact structure, slightly larger than the Sudbury and Chicxulub structures. With an age of 2023 Ma, Vredefort is also the oldest known terrestrial impact structure.

The NE-SW elongation of the Witwatersrand Basin (Fig. 1) is attributed by *Friese* et al. (1995) and *Henkel* and *Reimold* (1998) to deformation of the originally circular impact structure due to plate tectonic accretion events along the margins of the Kaapvaal craton at ~ 1.8 Ga (Kheis event) and 1.3–1.0 Ga (Kibaran event).

Implications for metamorphism in the Witwatersrand goldfields

Recent studies in the Vredefort Dome have greatly clarified the relationship between the thermal evolution of the dome and its development by meteorite impact (*Gibson* and *Wallmach*, 1995; *Gibson* and *Stevens*, 1998; *Gibson* et al., 1998). The correlation of pseudotachylitic breccias with the doming event, based on geochronological (e.g., *Spray* et al., 1995; *Kamo* et al., 1996) and P-T path studies (e.g., *Gibson* and *Wallmach*, 1995; *Stevens* et al., 1997b), provides a useful time-line which can be extended into the Witwatersrand goldfields where such breccias are common. Several studies have established that the pseudotachylitic breccias in the goldfields postdated the ca. 350 °C lower greenschist-facies metamorphic event in the reef packages, but that they are themselves overprinted by a slightly lower-grade event (*Trieloff* et al., 1994; *Frimmel* and *Gartz*, 1999). We suggest that this latter event, which was marked by chlorite±sericite growth in the reefs at T ~ 300 °C, and which has been dated as being penecontemporaneous with the breccia-forming event (*Trieloff* et al., 1994; *Frimmel* and *Gartz*, 1997), was part of a massive hydrothermal system that developed in the floor of the Vredefort impact crater following the impact event. The thermal energy for this metamorphic-hydrothermal system is ascribed to the combined effects of shock heating and differential uplift of the crater basement to form the Vredefort dome, thereby forming a post-impact thermal " high" in the centre of the Witwatersrand basin (Figs. 2, 5). Closer to the surface, additional heat would have been provided by crystallization of the impact melt body within the crater (Fig. 5). The post-impact metamorphism is, thus, an integral part of the Vredefort event. The brecciation which accompanied the impact and post-impact tectonic readjustment likely facilitated the channeling of fluids associated with this event into specific structural environments. *Gartz* and *Frimmel* (1999) have argued that the extensive alteration of the Ventersdorp Contact Reef was related to channeling of these fluids along the contact with the less-permeable Ventersdorp lavas. Widespread evidence that gold crystallized, or at least recrystallized, as part of the post-pseudotachylite paragenesis (e.g., *Robb* et al., 1997; *Frimmel* et al., 1999) indicates that the mineralization itself was affected by the Vredefort event. Although the general significance of this event has only recently been established petrographically, evidence for its existence has been known for several years from geochronological studies within the basin which have rendered ca. 2 Ga ages (e.g., *Layer* et al., 1988). These earlier studies generally attributed these results to low-T effects related to the Bushveld Event, however, the recent Vredefort studies now allow a distinction to be made between pre-Vredefort metamorphism related to the Bushveld event, and metamorphism linked to the impact event.

Pressure estimates from the post-impact metamorphic parageneses in the dome indicate that the current levels of exposure were originally buried at a depth of between 8 and 11 km following the impact event (*Gibson* et al., 1998). This result corroborates earlier P estimates made from fluid inclusion barometry (*Fricke* et al., 1990) and from a regional tectonic synthesis of the amount of post-Vredefort erosion in the region (*McCarthy* et al., 1990). The impact structure has, thus, experienced considerable erosion since its formation. At a probable original diameter of 250–300 km, this erosion remnant encompasses – in fact, represents – the whole of the structurally preserved Witwatersrand basin (Fig. 1). The Vredefort dome must be considered the central uplift feature and the surrounding basin the impact ring basin (*Henkel* and *Reimold*, 1998). *Stevens* et al. (1997b) and *Henkel* and *Reimold* (1998) have further shown that only upper and middle crustal lithologies are exposed in the Vredefort dome, in contrast to the proposal by *Hart* et al. (1990) that lower crustal, and perhaps even upper mantle, rocks could have been sampled in the centre of the dome (see also *Merkle* and *Wallmach*, 1997, for discussion of this point).

This interpretation of the Witwatersrand basin does not mean that the basin should be regarded as a primary impact basin – to the contrary, there can be no doubt that the Archaean part of the evolution of this basin entails formation of a sedimentary basin. However, abundant evidence exists that Witwatersrand strata occur beneath younger cover rocks over a much wider area on the Kaapvaal craton (*M. J. Viljoen*, personal communication, 1998). The impact event at 2023 Ma occurred into the partially-eroded remnants of this larger sedimentary basin and resulted in Witwatersrand sedimentary strata being downwarped and impact ejecta-covered in the region around the dome (Fig. 5) – effects that led to the preservation from erosion of this spectacular mineral resource.

Conclusions

Several recent studies have provided extensive and unambiguous evidence that the rocks in the Vredefort dome experienced shock deformation and related massive structural disturbance consistent with a large meteorite impact event at 2023±4 Ma. The dome itself is now interpreted as the central, uplifted, portion of an originally 250–300 km wide impact structure, the extent of which corresponds broadly to the known limits of the Witwatersrand Basin. High strain rate deformation features related to the formation of the dome, such as pseudotachylitic breccias, occur throughout the basin and provide an important time line for correlation of post-depositional thermal and tectonic events. The Witwatersrand Supergroup in the dome experienced mid-amphibolite facies peak metamorphism prior to the impact event. This is correlated with the lower greenschist facies peak metamorphism in the goldfields and attributed to the 2.05–2.06 Ga Bushveld magmatic event, the higher grades in the vicinity of the dome reflecting deeper levels of burial of these rocks than in the goldfields. A second metamorphic event followed the formation of the dome, decreasing in intensity radially outwards from the dome from granulite facies in its core to lower greenchist facies in the goldfields. It is attributed to the impact shock event and the consequent uplift of the dome. Continued Vredefort studies still have the potential to make further important contributions to the understanding of the post-depositional evolution of the Witwatersrand Basin and its mineralization. In particular, the styles of deformation associated with the formation of the dome and the nature of the thermal-hydrothermal overprint caused by the impact event in the wider basin and its gold resources remain to be more fully elucidated.

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