

Proterozoic sequence begins with pillow lavas and is terminated by the sedimentary sequence with shallow water fossils (from <10 m depth; Vavrdová, oral communication), indicating the successive filling of the hole. The total thickness of this formation is not known, though geophysical models indicate several kilometers. The restriction of breccias to the base of this formation provides age constraints that would indicate the age of the impact is 1.8–1.2 m.y.

The circular structure is defined by the topography, water courses, and geological contacts in the Tertiary through Upper Proterozoic sequences. It is visible also on the fault geometries in the brittle and in the ductile stages from later orogenies as featured by the half circular Permian and Cretaceous sedimentary basins. The rigid conservation of the circular form is tentatively explained by the later cooling of the upper mantle rocks under the structure after the impact, enabling them to behave rigidly. Several shearing phenomena encountered in crystalline rocks of the Moldanubian can be attributed to the excavation stage.

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THE VREDEFORT DOME—REVIEW OF GEOLOGY AND DEFORMATION PHENOMENA AND STATUS REPORT ON CURRENT KNOWLEDGE AND REMAINING PROBLEMATICS (FIVE YEARS AFTER THE CRYPTOEXPLOSION WORKSHOP). W. U. Reimold, Econ. Geological Res. Unit at the Department of Geology, University of the Witwatersrand, P.O. Wits 2050, Johannesburg, R.S.A.

The Vredefort Structure located in the center of the Witwatersrand basin in South Africa and the Sudbury structure in Canada are widely considered the two oldest and largest impact structures still evident on Earth. Both structures are very similar in a number of geological aspects (e.g., association with major economic ore deposits, similar ages of ca. 2 Ga, abundant pseudotachylite as well as shatter cone occurrences, overturned collar), as summarized by [1]. However, whereas the geological community generally accepts an impact origin for the Sudbury structure, a number of researchers are still reluctant to accept this for the Vredefort Dome.

Five years ago an international workshop focusing on the Vredefort structure [2] scrutinized the evidence and attempted to resolve the differences between impact supporters and protagonists of internal genetic processes. Clearly, this goal was not achieved, but at least a number of important areas of further research were defined. Research in the Vredefort structure gained new momentum in 1991, partially in anticipation of the Sudbury '92 Conference, and because several mining houses realized how important full understanding of the structure and evolution of the Vredefort Dome is with regard to exploration and mining activities in the surrounding Witwatersrand basin.

Besides the long-established impact and gas explosion hypotheses, several other genetic processes have been discussed in recent years: rapid updoming, thrusting, combinations of several tectonic processes, and an impact event at 2 Ga ago followed by tectonic modification. Reviews of the geology and geophysics of the Vredefort structure were repeatedly presented in recent years (e.g., [3,4] and several papers in [2]). Therefore the aim of this review is to present new data, to highlight the most obvious shortcomings in the current database, and to summarize the major arguments in the genetic controversy.

Since 1987 important new results were provided by Hart et al. [3, and refs. therein] dealing with the geochemistry of the granitic core and aspects of dynamic metamorphism. Reimold [4] evaluated the geochemical database for Vredefort pseudotachylite, and new chronological data were contributed by [5] and [6]. Continued structural work had been demanded by the participants of the 1987 workshop. Colliston and Reimold [7] presented the results of a first detailed structural study in the southern part of the Dome and in areas of the northwestern sector. Minnitt et al. [8] mapped the Archean greenstone terrane in the southeastern quadrant and completed structural analysis of the granite-gneiss exposures in the southern part. Both studies resulted in similar findings, suggesting that deformation in the basement is mainly of Archean age and related to a stress field, in which the principal stresses operated in a near-horizontal plane (cf. Colliston and Reimold, this volume). Later macroscopic deformation is mainly restricted to local subvertical shear zones scattered throughout the granitic core. In the central part of the core deformation is very limited. New ^{40}Ar - ^{39}Ar stepheating results [9] for mineral separates from host rocks to two pseudotachylite samples that were dated by [6] at ca. 1.4 Ga further supported the conclusion that these breccias were formed at post-2-Ga times.

Currently several structural projects in the collar are in progress, with preliminary reports indicating that several deformation events since deposition of the Witwatersrand Supergroup (ca. 2.75–3.05 Ga ago) could be recognized. Consequently, one aspect of utmost importance for future research must be to establish a complete chronological framework for the geological evolution in this region. The igneous rocks that intruded core and collar of the Dome at various times since Ventersdorp volcanism (ca. 2.7 Ga ago) are currently being studied as possible candidates for radiometric dating. ^{40}Ar - ^{39}Ar stepheating and laser Ar dating of the various generations of pseudotachylite identified in both the structure and the Witwatersrand basin should be continued as well. A detailed metamorphic project, comparing the rocks of different metamorphic grades in the northwest/west (high) and northeast (low) sectors respectively with the metamorphic record for the whole Witwatersrand basin, has just been initiated. It is also still uncertain at what times the major metamorphic events took place and whether the enhanced metamorphism in the northwest/west is the result of contact metamorphism in the vicinity of alkali granitic intrusions or of regional metamorphism. The nature of the pseudotachylite-rich and charnockite-bearing transition zone between Outer Granite gneiss and Inlandsee Leucogranofels is still controversial: Does it represent a pre-Vredefort intracrustal lithological boundary, a thrust plane, or a decollement zone possibly linked to major pre-Vredefort gravity slides in the northern Witwatersrand basin? What is the significance of the charnockite occurrences that to date have not been studied in detail? New quarry exposures in and near this zone are being studied and could reveal the three-dimensional geometry of pseudotachylite breccia zones. Finally, (sub)planar micro-deformations in Vredefort quartz have now become the object of TEM investigations.

At this point in time, the main arguments in favor and against an impact origin for the Vredefort structure can be summarized as follows.

Pro Impact: (1) The structure is regarded as being circular and (2) surrounded by ring faults. (3) The dome itself is considered to be the central uplift of a gigantic impact structure with (4) a "crust-on-edge" configuration of the structure, involving both overturned collar and basement. (5) The presence of shatter cones. (6) Pseudotachylite is regarded as an equivalent of impact breccia and (7) the

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granophyre as melt rock. (8) Shock metamorphism occurs in the form of shock-characteristic planar microdeformation features (PDFs) in quartz.

Contra Impact: (1) The structure is asymmetrical and polygonal. (2) The southern equivalent to the collar in other sectors shows subhorizontal stratigraphy. (3) The "crust-on-edge" model is only valid for the northern part of the dome. (4) There is only limited structural evidence for 2-Ga deformation. (5) Deformation intensity does not increase toward the center, and deformation in the central area is generally poorly developed. (6) Deformation is magnified along northeast-southwest-trending lineaments. (7) Several phases of deformation have been identified. (8) Vredefort deformation phenomena are also observed in the northern Witwatersrand basin. (9) Temporal relationships between MSJS/shatter cones and pseudotachylite are complex and multiple. (10) Microdeformation is restricted to controversial "features" in quartz and kinkbanding of mica and occasionally hornblende. No other characteristic shock effects have been described from other minerals. (11) Temporal relationships between the various deformation and structural/magmatic events are complex and as yet not sufficiently resolved.

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 THE PSEUDOTACHYLITES FROM THE VREDEFORT STRUCTURE AND THE WITWATERSRANDBASIN. W. U. Reimold¹ and W. P. Colliston², ¹Econ. Geol. Res. Unit, Department of Geology, University of the Witwatersrand, P.O. Wits 2050, Johannesburg, R.S.A., ²Department of Geology, University of the Orange Free State, P.O. Box 339, Bloemfontein 9300, R.S.A.

Pseudotachylite (pt) from both the Sudbury structure in Ontario and the Vredefort Dome in South Africa have been widely cited as the result of shock(impact)-induced brecciation. In the scientific [e.g., 1] and popular [2] literature pt has been described as "shock melt" or even as "impact melt rock" [2, p. 22]. In contrast, others have for years requested that a clarification of the definitions for "pseudotachylite" and "impact melt rock" be pursued [e.g., 3]. We have suggested that, until that time when well-defined criteria for genetically different melt rock types (e.g., generated by impact or tectonic processes) will have been established, the term "pseudotachylite" should only be used as a descriptive one and that, wherever genetic implications are discussed, other terms, such as impact melt (rock) or friction melt, should be applied. It is obvious that these suggestions are not only of value for the discussion of terrestrial melt rocks of controversial origin, but also apply to the characterization of melt veins in extraterrestrial materials [1,4].

The majority of planetologists currently support the impact hypothesis for the origin of the Vredefort Dome. However, those workers that have actively pursued research in the structure still feel uncomfortable about the severe limitations of the Vredefort database and the widely held belief that a few particular observations should hold the key to the understanding of the origin of the Dome. When the whole database is considered, there is a lot of (mainly

structural or pt-related) evidence that is not readily explained by the impact hypothesis. Unfortunately, in recent years these workers have been ridiculed in a quite unscientific way, e.g., as "academic dinosaurs" or "reactionary diehards."

In this paper important observations on Vredefort and Witwatersrand pseudotachylite are summarized (for more detail, cf. [5]).

Distribution and Styles of Development: Major pt occurrences on the Dome are concentrated along the transition zone between Outer Granite gneiss and Inlandsee Leucogranofels, as well as along a northeast-southwest-trending zone just south of the Inlandsee. Brecciation in the central core region is extremely limited. Within the collar strata, pt mainly occurs in the form of <30-cm-wide veins along bedding faults, but up to several-meter-wide zones comprised of intercalated networks of narrow veinlets and more massive melt breccia have recently been observed in mafic intrusives in the collar. Throughout the Dome and the northern part of the Witwatersrand basin pt is also found as thin melt films on slickenside and shatter cone (MSJS) surfaces. In the granitic core one finds either massive development (network breccia) or up to 50-cm-wide veins. Network breccias are occasionally seen to be delimited at one side by a thick, straight vein that possibly represents the initial generation vein. Several new quarry exposures indicate subhorizontal internal structures within major breccia developments, but individual large-scale breccia zones appear to have overall vertical attitude. Thin veins generally resemble tectonic pt occurrences. Displacement is usually variable in dm to m intervals and ranges normally from <1 mm to >50 cm (but <1 m). Sense of movement is found to be equally variable along a given vein (but only rarely can three-dimensional geometries be studied). Frequently orthogonal pairs of veins—at 90° angles—are observed. Most veins trend parallel to the main orientations (northwest-southeast and northeast-southwest) defined by the pervasive Archean fabric. Other veins are generally injection veins off master veins or network breccia.

Pt in the Witwatersrand basin has been described from the north and northwest portions—the remainder is barren. Most pt here is bound to important bedding faults (dipping generally at low angles to the south) and to a few north-south-trending normal faults. Drilling has revealed several up to 40-m-wide breccia zones with up to 60% melt development. Steeper pt veins are thought to represent injection veins. As in the Vredefort case, several generations of fault rocks (including pt) have been recognized. Ages for Vredefort pt range from 2.2 to 1.1 Ga. Further support for some of the lower ages has recently been presented by [6,7]; for one occurrence of Witwatersrand pt, ages of 2.0 Ga have been established (Trieloff et al., this volume). This could possibly mean that formation of at least some of the Witwatersrand pt could be linked with either Bushveld or Vredefort activity.

Mineralogical data are still scarce and no quantitative micropetrographic results are available yet. The limited data at hand have, however, shown that at least some of the Vredefort pt was formed by cataclasis prior to melting. Chemical results for Vredefort pt [8] show that most of the analyzed pt was formed locally and that lateral mixing, probably not exceeding distances of a few meters, is restricted to network breccias. Comparative analysis of host rock and pt pairs illustrated that the same melting processes apply to Vredefort pt and to tectonic occurrences. A discussion of Vredefort pt would be incomplete if Martini's [9] findings of HP SiO₂ polymorphs in narrow veinlets from the outer collar were to be ignored (discussion of this aspect is in press elsewhere). Also of importance is the debate about the nature of mineral deformation associated with host rock contact zones and clasts within pt: e.g., do