it might reduce the need for such weakening mechanisms as acoustic fluidization [16], and might provide a substitute for the "asthenospheric" flow required in these models of basin-forming events.

A few central uplifted structures in complex craters are acentrally located, which has been ascribed to preimpact structural control [17]. Oblique impact, however, can produce asymmetric melt zones, with increased melting in the direction of impact [18]. Thus, asymmetric impact melting followed by uplift may be an alternative mechanism of formation of acentral peaks.

**Impact Lithologies:** There will be second-order differences in the impact lithologies at comparable-sized craters on the terrestrial planets because of the effect of gravity on scaling relations. For example, the levels of recorded shock in uplifted central structures and the ratio between melted and clastic material will be lower in lunar craters than in those on other terrestrial planets, other parameters being equal. These potential differences must be considered when interpreting remote-sensing data [19]. Similarly, the various proportions of impact lithologies and their second-order characteristics will vary with the size of the event. At larger impact events, for instance, there will be less clastic debris available within the transient cavity for incorporation into the melt. Such implications of differential melting and cratering have been used to explain some of the observations at large terrestrial impact melt sheets such as at Sudbury [20]. Similar arguments apply to lunar samples. The lack of clasts is therefore an insufficient single condition to rule out an impact-melt origin for relatively coarse-grained, igneous-textured rocks in the samples from the lunar highlands.

**References:** [1] Cintala M. J. (1992) *JGR, 97*, 947. [2] Grieve R. A. F. and Cintala M. J., this volume. [3] Grieve R. A. F. and Cintala M. J. (1992) *Meteoritics*, submitted. [4] Strom R. G. and Neukum G. (1988) In *Mercury* (F. Vilas et al., eds.), 336, Univ. Ariz., Tucson. [5] Schmidt R. M. and Housen K. L. (1987) *Int. J. Impact Eng., 5*, 543. [6] Croft S. K. (1985) *Proc. LPSC 15th*, 828. [7] Pike R. J. (1980) *Icarus, 43*, 1. [8] Melosh H. J. (1989) *Impact Cratering: A Geologic Process*, Oxford, 245 pp. [9] Cintala M. J. et al. (1977) *Proc. LPSC 8th*, 3409. [10] Garvin J. B. and Schaber G. G. (1992) *LPSC XXIII*, 399. [11] Head J. W. (1977) In *Impact and Explosion Cratering* (D. J. Roddy et al., eds.), 563, Pergamon, New York. [12] McKinnon W. B. (1981) In *Multi-Ring Basins*, 259, Pergamon, New York. [13] Alexopoulos J. S. and McKinnon W. B. (1981) *JGR*, in press. [14] Grieve R. A. F. et al. (1981) In *Multi-Ring Basins*, 37, Pergamon, New York. [15] Melosh H. J. (1982) *JGR, 87*, 371. [16] Melosh H. J. (1979) *JGR, 87*, 7513. [17] Schultz P. H. (1972) *Moon Morphology*, Univ. Texas, Austin, 626 pp. [18] O'Keefe J. D. and Ahrens T. J. (1986) *Science, 234*, 346. [19] Pieters C. M. (1982) *Science, 215*, 59. [20] Grieve R. A. F. et al. (1991) *JGR, 96*, 753.

## STRUCTURAL REVIEW OF THE VREDEFORT DOME.

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The structure of the older-than-3.2-Ga Archean basement and Archean-to-Precambrian sedimentary/volcanic rocks (3.07 to ca. 2.2 Ga) in the center of the Witwatersrand Basin to the southwest of Johannesburg (South Africa) is dominated by the ca. 2.0-Ga megascopic Vredefort "Dome" structure.

The effect of the "Vredefort event" is demonstrably large and is evident within a northerly arc of about 100 km radius around the granitic core of the structure. Northerly asymmetric overturning of the strata is observed within the first 17 km (strata is horizontal in the south), followed by a 40-km-wide rim synclinorium. Fold and fault structures (normal, reverse, and strike-slip) are locally as well as regionally concentrically arranged with respect to the northern and western sides of the structure.

The unusual category of brittle deformation, the so-called "shock deformation," observed in the collar strata has attracted worldwide attention over the past two decades. These deformation phenomena include the presence of coesite and stishovite, mylonites and pseudotachylites, cataclasis at a microscopic scale, and the ubiquitous development of multiply striated joint surfaces (which include "shatter cones," orthogonal, curviplanar, and conjugate fractures).

The macroscopic to microscopic deformation features have led to the formulation of various hypotheses to account for the origin of the Vredefort structure: (1) tectonic hypotheses: deep crustal shear model [1], doming and N-directed thrust fault model [2], fold interference model [3], and diapir model [4]; (2) the exogenous bolide impact hypothesis [e.g., 5,6]; and (3) the endogenous cryptoexplosion model [7].

Ongoing structural studies on the dome [8] have aided in narrowing the field of possible hypotheses. The subvertical faults and shears associated with diapirs or an endogenic cryptoexplosion could not be identified in either the basement or the collar rocks. The subvertical conjugate northwest- and northeast-trending shear zones that occur in the migmatitic basement predate the extrusion of the ca. 3.07-Ga-old Dominion Group volcanics. Toward the southern extremity of the structure, subhorizontal gneissic fabrics, which are deformed by the subvertical shears, become more prominent. The majority of the macrostructural deformation (faulting, folding) in the collar is related to the Vredefort event, and the remainder to reactivation of pre-Vredefort structures. Pseudotachylite occurrence is not exclusive to the Vredefort structure and is found throughout the northern and northwestern Witwatersrand Basin. Several pseudotachylite generations were produced over a wide interval from 2.2 to 1.1 Ga (pre- to post-Vredefort event) [9]. This suggests the regional occurrence of episodic brittle deformation events with associated high-strain intensities.

It has been identified that the multiply striated joint surfaces postdate the overturning and related faulting in the structure, as well as a phase of postoverturning pseudotachylite development. These observations do not conform to the generalizations proposed by other workers who assume a horizontal stratigraphy prior to shatter cone development by an impact-generated shock wave [e.g., 10,11]. It also places doubt on the validity of using shatter cones as a diagnostic criterion for impact structures. Although the presence of coesite and stishovite cannot yet be fully explained, it is suggested that these high-pressure polymorphs and multiply striated joint surfaces may also be produced in a tectonic regime by Mohr-Coulomb fracture within varying local stress fields.

According to regional gravity and aeromagnetic data the domal structure is interpreted to be located at the intersection of a northwest-trending anticlinal arch (which uplifts lower crust) and a north/northwest-axis of crustal downwarp (corresponding to the long axis of the Witwatersrand Basin) [12]. Reflection seismic data along a line roughly parallel to the northwest-anticlinal arch confirms regional structural data and interpretations of the structure [13,1]: The deep structure in the basement reveals only subhorizontal reflectors, which undergo a change in dip (overturned with the collar rocks) in the northwest. Structural information suggests that the structure is open to the southeast. From this it may be inferred that contractional forces acted from south to north.

In conclusion, the structural studies coupled with the geophysical results suggest that the Vredefort structure was produced by subhorizontal forces. No macro- or megascopic structural deformation that could be related to a 2-Ga central catastrophic event could be identified.

**References:** [1] Colliston W. P. (1990) *Tectonophysics, 171,* 115–118. [2] Du Toit A. L. (1954) *The Geology of South Africa,* Oliver and Boyd, Edinburgh, 611 pp. [3] Brock B. B. and Pretorius D. A. (1964) *Geol. Soc. S. Afr. Spec. Publ. 1,* 549–599. [4] Ramberg H. (1967) *Gravity, Deformation and the Earth's Crust,* Academic, London, 214 pp. [5] Dietz R. S. (1961) *J. Geol., 69,* 499–516. [6] Hargraves R. B. (1961) *Trans. Geol. Soc. S. Afr., 64,* 147–154. [7] Nicolaysen L. O. (1972) *GSA Mem., 132,* 605–620. [8] Colliston W. P. and Reimold W. U. (1990) *Econ. Geol. Res. Unit Inf. Circ. 229,* 31 pp. [9] Reimold W. U. et al. (1990) *Tectonophysics, 171,* 139–152. [10] Manton W. I. (1965) *N.Y. Acad. Sci. Ann., 123,* 1017–1049. [11] Albat H. M. (1988) *S. Afr. J. Geol., 91,* 106–113. [12] Corner B. et al. (1990) *Tectonophysics, 171,* 9961. [13] Colliston W. P. and Reimold W. U. (1989) *Abstr. First Tech. Meet. S. Afr. Geophys. Assoc.,* 13–14, BPI Geophysics.

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# INTRUSIVE ORIGIN OF THE SUDBURY IGNEOUS COMPLEX: STRUCTURAL AND SEDIMENTOLOGICAL EVIDENCE.

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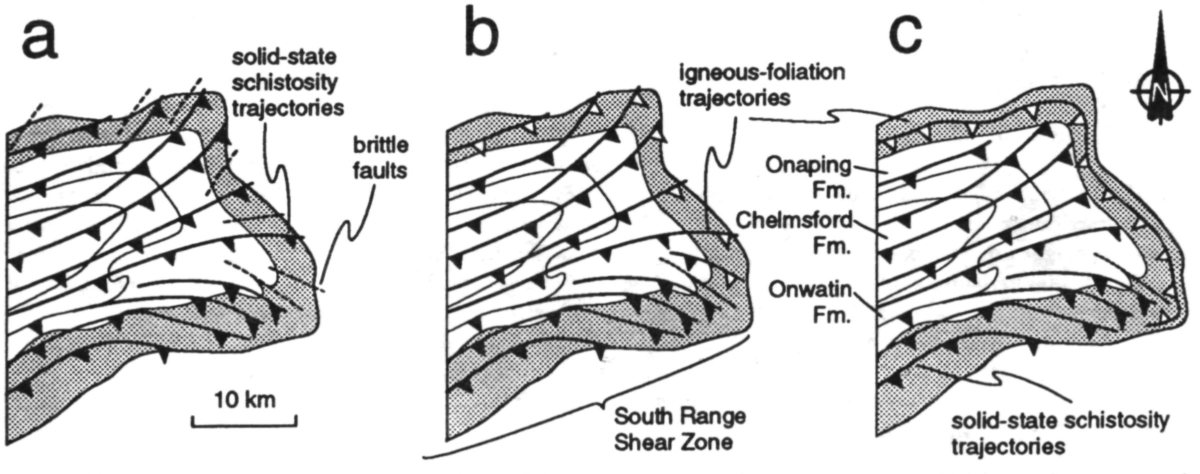
In recent years, many geoscientists have come to believe that the Sudbury event was exogenic rather than endogenic [1–3]. Critical to a recent exogenic hypothesis is the impact melt origin of the Sudbury Igneous Complex (SIC) [3]. Such origin implies that the SIC was emplaced before deposition of the Whitewater Group, in contrast to origins in which the SIC postdates the lithification of the Onaping Formation. Structural and sedimentological evidence is summarized herein that supports an intrusion of the SIC after lithification of all Whitewater Group strata, and conflicts with the hypothesis advanced by Grieve et al. [3].

The SIC has the map pattern of an oval ring, and dips inward at the present erosion level. The bilobate eastern part of the SIC resembles fold interference patterns figured by Stauffer and Lisle et al. [4,5], yet the granophyre, gabbro, and norite have undergone no solid-state deformation at most localities. This rules out the foliation pattern in Fig. 1a, which is consistent with the impact-melt hypothesis [3]. If the SIC acquired its foldlike shape during or immediately after emplacement, metamorphic-foliation trajectories in the Onaping Formation would continue as igneous-foliation trajectories into the granophyre, gabbro, and norite (Fig. 1b) [6,7]. This is true in the northeast lobe of the SIC, and rules out the possibility of post-fold sheet injection (Fig. 1c) [8].

The Chelmsford Formation, a turbidite deposit with nearly invariant bed thickness (1.2 m average), detrital composition, and high sand/mud ratio, was deposited by uniformly southwest-directed currents [9,10], and was part of a very large nonchannelized foreland basin turbidite system [11]. The lack of facies change in the northwest-southeast direction implies that the preserved Chelmsford strata were far from the original foreland basin margin or from a site of syndepositional tectonic disturbance. This suggests that the South Range Shear Zone [12], which probably had a geomorphic expression at surface, postdates the Chelmsford Formation and its lithification.

The combined sedimentary and structural evidence constrains the time of emplacement of the SIC and its consolidation. Turbidite complexes have sedimentation rates of 100–1000 m/m.y., with foreland basin-fill systems typically ranging 400–900 m/m.y.



**Pre-fold emplacement of the Sudbury Igneous Complex:**

Solid-state strain whithin the SIC with schistosity trajectories concordant to that of the sedimentary core

**Syn-fold emplacement of the Sudbury Igneous Complex:**

SIC with igneous-foliation trajectories concordant to schistosity trajectories of the sedimentary core

**Post-fold emplacement of the Sudbury Igneous Complex:**

SIC with igneous-foliation trajectories concordant to intrusive contacts

**Fig. 1.** Eastern Sudbury structure: SIC (shaded), Whitewater Group (white).