BUSHVELD COMPLEX, SOUTH AFRICA: IMPACT AND PLUME MODELS RECONCILED. W. E. Elston, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131-1116, U.S.A., weelston@earthlink.net.

Introduction: The (unpopular) impact model for the Bushveld Complex [1, 2] is based on evidence for an initial catastrophe, preserved in extraordinary high-temperature, high-energy debris flows at the base of its oldest unit (Rooiberg Group, ~2,061 Ma) and on intense deformation bracketed between the end of pre-Bushveld marine sedimentation and the coming-to-rest of the basal debris flows. The alternative (popular) mantle plume model [3, 4] is based on a long sequence of subsequent events related to sequential partial melting of mantle and crust: Evolution of the Rooiberg Group from diverse predominantly mafic flows to homogeneous siliceous flows of increasingly conventional volcanic aspect, overlapping with intrusion (into the base of the Rooiberg Group) and quiet differentiation of massive mafic cumulate sills (Rustenburg Layered Suite, *RLS*), followed by sills of A-type granite (Lebowa Granite Suite, *LGS*). The hydrodynamic model of Jones et al. [5] for an impact-triggered long-lived mantle plume promises to reconcile the two Bushveld models. It cites the Bushveld Complex as a possible example of a large igneous province generated by decompression melting at the leading edge of a shallow mantle plume, triggered by impact of an iron bolide (d ≥20 km, v ≥10km/sec).

Plume Criteria: Jones et al. [5] distinguished shallow impact-triggered (I-type) plumes rooted in the upper mantle from endogenic hot-spot (H-type) plumes, deeply rooted at the core-mantle boundary. The Bushveld Complex meets their criteria for a large igneous province generated by an I-plume: Melt volume $\geq 10^6$ km^3, crater "auto-obliterated" by melts, high rate of eruption, no initial doming, "plume-like geochemical signature," "no deep geophysical fingerprint." A modest modification involves substituting mafic flows in the lower 2,000 m of the Rooiberg Group for initial "low-viscosity peridotitic melts."

Distinctiveness of the Bushveld Complex: In its early impact-dominated stage, the Bushveld Complex conformed generally to the to a model developed for Chixculub [6]. It is proposed that three quasi-simultaneous impacts resulted in (i) an outward-collapsed central peak, (ii) a melt sheet inside a three-lobed transient cavity, ~150 km in diameter, surrounded successively by (iii) a peak ring and zone of inward collapse, (iv) a deep three-lobed basinal outer ring, 250-km diam. (=ring syncline [1]) and (v) a 400-km diam. exterior ring (= ring anticline [1]; = chain of uplifts [7]). The Bushveld then diverged from the Chixculub model during the I-plume stage. As predicted, intrusions by crustal melts of LGS granite auto-obliterated the transient cavity except for two 50-km windows, in which segments of its wall are exposed. The Bushveld Complex and two other proposed Proterozoic multi-ring impact structures, Vredefort and Sudbury, can be interpreted as a denudation series: Vredefort has been eroded to the sub-crater basement. Only dikes injected into the basement remain of its melt sheet [8]; no ejecta remains in its ring basins. Sudbury preserves basement and a segment of crater floor, melt sheet and impactite crater fill. No ouflow is preserved in the ring basins. In the Bushveld Complex, the Rooiberg Group and RLS are entirely preserved in the basinal outer ring, with a maximum thickness (including LGS) of ~12 km. No crater fill, crater floor, or basement has been documented to date. The Bushveld Complex is topless; its earliest member, the Rooiberg Group caps subsequent RLS and LGS sills. A 300-km westward RLS tail, ending in the buried Molopo Farms Complex (Botswana), suggests that the plume was affected by a deep E-W lineament. A small RLS outlier, the Losberg body, lies in a ring of the Vredefort impact structure, 100 km to the south.

The Impact Stage: Evidence for the proposed impact is seen in the two windows exposing the transient cavity wall. They are located, respectively, in the eastern and western Bushveld lobes. Each consists of two *fragments*, in fault contact: *deformed,* interpreted in terms of the outward collapse of a central peak; and *undeformed,* interpreted by inward collapse of the unstable walls of an enlarging transient cavity.

Deformed fragments. In the deformed fragments, pre-Bushveld rocks (Transvaal Supergroup), intensely sheared, tightly (even isoclinally) folded and metamorphosed to pyroxene hornfels facies [9], are interpreted as segments of a collapsed central peak [6], ramped against the cavity wall. Deformation of this intensity is not known elsewhere in the Transvaal Supergroup or worldwide in any volcanic setting.

Undeformed fragments. In the studied eastern undeformed (Stavoren) fragment, unmetamorphosed and unfolded Transvaal quartz-sericite arenite is cut by breccia zones and overlain by tens of meters of an unbrecciated basal Rooiberg debris flow. The debris flow superfically resembles rhyolite studded with m-size quartzite xenoliths in every stage of deformation, recrystallization, and dissolution. In petrography and chemistry, its matrix turns out to be comminuted and partially melted quartz-sericite arenite. The rock, of local and shallow provenance, is interpreted as derived from the overturned crater rim. Its quartz grains inverted in the solid state into ordered and disordered forms of high-tridymite [10]. Late-stage tridymite needles to 5 mm crystallized directly from quenched interstial melt. Although larger, they resemble needles in a 60-m quartzite breccia at the base of Onaping impactite at Sudbury [11]. In a >10 m metamorphic zone below the debris flow, quartzite inverted to massive tridymite. On cooling, all forms of tridymite inverted back to paramorphous quartz. The entire squence is unknown in volcanic environments. The closest analogs to the solid-state inversions occur in silica-brick furnace linings, heated to 1,200-1,370°C [12]. Further evidence for extraordinary temperatures comes from the absence of zircon [13] in transformed arenite with 191-304 ppm Zr. Melting and high-T low-P sanidinite-facies metamorphism account for the absence of high-P SiO_2 polymorphs and PDFs.

Origin of the undeformed fragments. The undeformed fragments are interpreted as gigantic gravity slide blocks that encountered debris flows on their way into the enlarging transient cavity. At the strike-slip fault contact with the neighboring deformed (Marble Hall) fragment, the Stavoren fragment broke into overturned quartzite slabs, tens to hundreds of meters long, that became engulfed in the debris flow.

. *Other debris flow occurrences*. Aside from the undeformed fragments, the basal debris flows of the Rooiberg Group have generally been destroyed by metamorphism and rheomorphic melting at contacts with intruding RLS and LGS sills. Only along the SE margin of the Bushveld Complex (Dullstroom area) was a 2,000-m slice of Rooiberg rocks preserved *beneath* the RLS. At their base, up to 300 m of debris flows were preserved in three (scoured ?) paleochannels [14]. Inflated hot flows deposited sand-size quartz grains in a fine mafic matrix, cm-size lithic clasts metamorphosed *in situ* to amphibolite hornfels, and m-size blocks of shattered quartzite. An ignimbrite-like transport mode is indicate by basal surge deposits, lag deposits of boulder-size clasts, and an interlayered mafic ash-cloud deposit. Overlying rhyolite-like lavas consist of the same material, melted.

The I-Plume Stage: The I-plume dominated the well-documented petrochemical evolutions of the Rooiberg Group above the basal debris flows, RLS and LGS (3, 4, 15, 16). The initial melt sheet was augmented by partial decompression melts from the head of the rising plume. As a result of explosions triggered by periodic influxes of water, up to 4.5 km of Rooiberg rheoignimbrite flows, interlayered with high-energy sedimentary and pyroclastic deposits, accumulated in the basinal outer ring. Based on the Chixculub model [6], an inward-dipping fault from the outer ring to the Moho may have acted as a conduit for RLS mantle melts contaminated with crustal material. They formed sills up to 9 km thick at the base of the Rooiberg Group, as late-stage siliceous Rooiberg flows continued to pile on top. Those RLS sills that yielded consistent paleomagnetic orientations were horizontal at the time of crystallization (17). Collapse to form the present three Bushveld basins may have coincided with emplacement of sills of LGS crustal melts, up to 5 km thick, into basin fill and the Rooiberg-RLS contact. LGS granite nearly engulfed the undeformed fragments, probably by invading the soles of the slide blocks. Subsidence of the basins tilted RLS sills into present inward-dipping positions and rotated their feeders closer to vertical. The outward-verging recumbent folds of the deformed fragments rotated toward the vertical and the outward-dipping undeformed fragments toward the horizontal. Collapse may have been the cause of a second catastrophe, recorded in the upper part of the Rooiberg Group. It emplaced megabreccia blocks up to 50 m around the entire circumference of the Bushveld Complex [1, 18]. The blocks, and mm-sized xenoliths in their ignimbritic matrix, show moderate shock effects (cataclasis, deformation twins and lamellae, *not* PDFs). Spherules, mm sized, formed in this stage and are also imbedded in the matrix. Minor siliceous magmatism and structural adjustments continued into post-Bushveld time.

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