THE PROTEROZOIC BUSHVELD COMPLEX, SOUTH AFRICA: PLUME, ASTROBLEME OR BOTH?

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The Bushveld Complex has been cited (1, 2,) as a possible example of a large (diameter 400 km, volume 10^6 km^3) igneous province generated by rapid decompression melting at the leading edge of a mantle plume, triggered by the impact of a large (d ≥20 km, v≥10 km/sec) iron bolide. This scenario would reconcile the widely accepted Bushveld plume model (3, 4) with the controversial proposal for an initial Bushveld impact (5, 6, 7). The evidence for an initial catastrophe comes from a group of extraordinary high-energy high-temperature debris flows at the base of the oldest Bushveld unit, the Rooiberg Group and from intense deformation bracketed between the end of pre-Bushveld shallow marine sedimentation (Transvaal Supergroup) and the coming-to-rest of the basal Rooiberg debris flows. Subsequent plume-related events are documented in the remaining 90+% of the Rooiberg Group and voluminous associated mafic and granitic units, and in a long period of structural instability that followed the initial event. A second catastrophe, documented by a zone of megabreccia blocks (diameter to 50 m) in the upper part of the Rooiberg Group, has been traced around the entire circumference of the Bushveld Complex (6, 8).

The Bushveld Complex is a unique association of (i) rocks of volcanic aspect (Rooiberg Group, diverse but predominantly siliceous, 0.1 x 106 km3) (9); (ii) anorthositic, mafic and ultramafic cumulates (Rustenburg Layered Suite, RLS, ~1.0 x 106 km3) (10, 11); and (iii) A-type granites (Lebowa Granite Suite, LGS, 0.1 x 106 km3) (12). Granophyres, developed as facies of these rocks or at contacts between them, constitute the Rashoop Granophyre Suite (13). Each of these has many subunits. RLS and LGS are the largest of their kind in the geological record. The principal units are sheet-like surface accumulations or sills (max. thicknesses: Rooiberg, 4.5 km; RLS, 9 km; LGS, 5 km. Max. cumulative thickness in one locality: ~12 km) (10). Zircon U-Pb dates for RLS and the upper part of the Rooiberg Group have converged at ~2,061 Ma. LGS activity may have continued for another 7 m.y. (14).

Discontinuous RLS outcrops outline the peripheries of three lobes or overlapping basins: eastern, western, and northern. They are truncated by erosion and their original extent is unknown. Contact metamorphism of underlying sedimentary units locally extends for tens of kilometers beyond the outcrop belt (15). The interiors of the basins are obscured by LGS granite or covered by younger sedimentary rocks, except for two 50-km inliers of pre-Bushveld rocks, respectively within the eastern and western basins (16). A large probable RLS outlier (Molopo Farms Complex; 17) is known from the subsurface of Botswana, 200 km to the west, and a small one (Losberg body; 18) crops out 100 km to the south. The total RLS volume of ≥1.0 x 106 km3 suggested by petrological calculations seems reasonable (11).

The Bushveld Complex is roofless (19), not intrusive in the usual sense. The later members intrude earlier ones but the entire complex cooled on the surface. The Rooiberg Group erupted in a previously stable tectonic setting but rests on a regional unconformity (20), probably enhanced by catastrophic scouring. This lower contact became the principal conduit for RLS and LGS sills. Consequently, the Rooiberg Group now forms the roof of the Bushveld Complex, of which it is itself a part. Upper units of the Rooiberg Group may have been synchronous with the later pulses of RLS and early LGS (3, 21). If so, siliceous flows piled up on top of the Rooiberg stack while sills invaded its bottom. With few exceptions, invasions of RLS and LGS have destroyed the critical basal debris flows by contact metamorphism and rheomorphic melting (22). Exceptions include the intrabasin inliers and a slice of the lowest unit of the Rooiberg Group (Dullstroom Formation) locally caught beneath the RLS in the southeastern Bushveld. The recognizable Dullstroom Formation has a limited distribution in the southeastern part of the Bushveld Complex (8). The basal debris flows are best preserved in scoured (?) paleochannels.

What kept the 12-km surface pile from collapsing? Rooiberg flows and RLS sills must have accumulated in a pre-existing basin many kilometers deep, even allowing for Rooiberg overflow. There could have been no significant subsidence until after the invasion of the third major RLS pulse, the Main Zone. Paleomagnetic data (23) showed the RLS as horizontal until that time. Gravity data by Cousins (23) indicated an annular RLS basin fed by ring intrusions, not the central vent for the gigantic lopolith (25) that still haunts our textbooks. Hamilton (5) and Rhodes (6) invoked quasi-simultaneous multiple impacts to create a three-lobed Bushveld crater and the smaller Vredefort dome, 250 km to the SSW, both surrounded by multiple rings. In Rhodes' view, Cousin's annular basin was the inner ring syncline. I interpret Cousin's ring dike as an impact-related deep fracture system (as seen at Chicxulub; 26), originally inward-dipping but now rotated to near-vertical by basin subsidence. It was partly filled with RLS mafic melts, released from a rising mantle plume by decompression and contaminated with crustal material (27).

The present interpretation evolved from Rhodes', who regarded the two intrabasin inliers as central uplifts. From available maps (16) and a seismic profile (28), I reinterpret them as wall segments of a transient impact cavity. Each inlier consists of two fragments, in fault contact: deformed and undeformed. Deformed fragments are interpreted as either parts of the transient cavity wall or of a collapsed central uplift, ramped against a cavity wall (29). Rocks of the Transvaal Supergroup are tightly folded and metamorphosed, up to pyroxene hornfels facies (16). On a microscopic scale, shearing is intense. Compressional deformation on this scale is unknown in Transvaal rocks elsewhere. Neither is it known from any volcanic terrain; extension is the rule for large calderas (30). The undeformed fragments are interpreted as gigantic Transvaal blocks that slid into the unstable transient cavity, meeting the emerging debris flows. The present study has concentrated on the eastern (Stavoren) fragment. There, unmetamorphosed Transvaal rocks (Makeckaan Subgroup) have low (<10°) dips and brecciation is confined to fault zones. Only a few tens of meters of overlying debris flows are preserved. Elsewhere, large gravity slides have been related to the western Bushveld basin in Botswana (31).

Rhodes regarded the entire Rooiberg Group as impactite crater fill. It is here interpreted as outflow; there are as yet no documented outcrops of crater fill or signs of an eruptive source. In the present interpretation only the basal debris flows are impact-related; subsequent Rooiberg, RLS and LGS rocks are interpreted as plume-related. Three facies of the basal Rooiberg debris flows were studied: Proximal, in the undeformed Stavoren fragment, intermediate in the annular basin, and distal in the Dullstroom slice beneath the RLS. Superficially, the proximal facies resembles spherulitc rhyolite lava studded with relict quartzite blocks, some exceeding 10 m, in every stage of shearing, comminution, recrystallization, melting, and obliteration. In a paleochannel, the base rests on a polished and grooved surface, resembling a glacial pavement. Along the fault that juxtaposes the undeformed Stavoren fragment against the neighboring deformed (Marble Hall) fragment, the Stavoren fragment broke up. Overturned slabs of Makeckaan quartzite, tens to hundreds of meters long, were engulfed in a debris flow of hot quartz sand, now recrystallized (formerly identified as felsite).

Proximal-facies debris flows, derived from quartz arenite, have sedimentary mineralogy and chemistry (up to 90% SiO2) (6, 9). They contain 191-304 ppm Zr (9) but no zircon (32). Apparently the temperature was above the stability range of zircon. It was high enough to partially melt quartzites with varying amounts of interstitial sericite. Quartz inverted to high-temperature polymorphs of SiO2, probably ordered and disordered forms of high tridymite (33), which became the dominant phases. This was recognized 70 years ago (34) but the entire sequence of stages has not been previously described: (i) Solid-state inversion of quartz into a network of needles with optical continuity, confined within single quartz grains. (ii) Solid-state inversion of relict quartz grains into stout lath-shaped crystals ("stubbies"). (iii) Partial melting, leaving pseudospherulites (rounded mm-sized remnant aggregates of stubbies and relict quartz) in a matrix of melt. (iv) Quenching of melt, with rapid growth of mm-sized needles, some swallow-tailed, in a glass matrix. (v) Inversion of all previous forms into paramorphous quartz. Stage (i) also transformed >10 m of underlying quartzite and subgraywacke. Such sanidinite-facies contact metamorphism is unknown below volcanic rocks but occurs in cm-sized quartzite xenoliths in gabbro (35). The closest analog is tridymite formed in silica-brick linings of high-temperature industrial furnaces between 1,200 and 1,370°C (36). At Sudbury, in a 60-m quartzite breccia at the base of the Onaping impactite, tridymite of stage (iv) formed in interstial melt between quartz grains (37).

The intermediate facies is barely preserved in the type section of the Rooiberg Group, at Loskop Dam (38). Most of it was obliterated at the RLS contact. The rock is black quartzite with a matrix of glass and devitrified glass. Coexistence of delicate uncompressed glass shards and lithic clasts suggests inflated ignimbrite-like transport. This exceedingly complex rock requires more study. In the distal facies, 300 m of melt rock and several flows of black quartzite are preserved in three paleochannels at the base of the type-Dullstroom section (9). From a distance, the black quartzite could be taken for ignimbrite with lithic clasts, black fiamme, and basal sand-wave and planar surge deposits. However, it contains no pumice, shards, glass, devitrification features, or phenocrysts. Rounded quartz sand grains are supported by a dark matrix of fine amphibole, chlorite, plagioclase and quartz. Chemically, the rock is a mixture of quartz and a mafic component. The lithic clasts are hornfels and the "fiamme" are cm-size zoned lenses with cores of pyrite, surrounded by zones of carbonate-epidote and actinolite and a reaction rim of fine quartz. These clasts were evidently metamorphosed to amphibolite in situ. The rock could also be taken for a quartzose suevite variant, in which amphibolite lenses take the place of glass lenses. In one locality (Kwaggaskop), m-size brecciated quartzite blocks are plastered against the wall of the paleochannel. Ignimbrite-like inflated transport of a hot debris flow is indicated. In another locality (Messchunfontein) accumulations of lithic clasts up to 50 cm resemble co-ignimbrite lag deposits. Dark matrix material, concentrated in a finely laminated interbed, resembles a co-ignimbrite ash-cloud deposit. Chemically similar material (low-Ti basaltic andesite) forms flows with quench textures. Above the debris flows, a rhyolite-like lava flow with m-size relict boulders and contorted flow bands has the same amphibolite lenses as the debris flows and similar chemical composition. It is the same material, hot enough to have partially melted. Some samples have microscopic quartz-tridymite paramorphs (9).

Aside from the basal debris flows, the Rooiberg Group is here interpreted as outflow from one or more melt pools created by impact but rapidly replenished by mafic melts released from a decompressing mantle plume. This can explain the abundance of diverse mafic lavas in the ~1,200 m Dullstroom Formation. In time, the pools coalesced and increasingly homogeneous siliceous melts developed by differentiation and crustal assimilation (3, 4). They increasingly resembled conventional volcanic rocks. Quench textures and scarcity of phenocrysts testify to continuing superliqidus temperatures. Repeated influxes of water triggered explosive eruptions of ignimbrite-like flows, interspersed with high-energy influxes of cold sediment, with exotic clasts from distant sources, and hot outflows (39). Concurrently, mafic plume-related RLS sills invaded the base of the Rooiberg Group, followed by LGS crustal melts. Return to stability allowed segregation of RLS cumulate zones traceable over hundreds of km, even as crustal diapirs locally rose into the RLS (40). During the second catastrophe (collapse of the present basins during LGS invasion?), an inflated flow carried both 10+-m quartzite blocks and delicate mm-size glass spherules. Tilting during basin subsidence turned horizontal RLS sills in Cousin's annular ring (24) into the inward-dipping sheets of a more recent gravity model (41). As the lithosphere readjusted, faulting and minor siliceous magmatism continued into post-Bushveld time (15, 42).

Objections to the proposed initial catastrophe have been raised by authors (4, 43) who dismissed the basal Rooiberg debris flows as conventional rhyolite and sandstone. The present combined impact-plume model reduces the volume of impactite, previously considered excessive. Other authors have cited he absence of shock criteria (planar deformation features, high-density polymorphs and glass, shatter cones, pseudotachylite). The rocks discussed here were either recrystallized or melted and were far from the proposed impact point. Inversion of quartz to tridymite occurs only under low-P, high-T conditions (36), outside the high-P, high-T stability field of coesite and stishovite. Indications of moderate shock (46) in contact metamorphosed rocks and in clasts of debris flows include mosaicism, deformation lamellae and twins, and cataclasis.

The Vredefort dome, which has all of the diagnostic impact criteria, is bracketed by the same stratigraphic units as the Bushveld Complex. To date, no unequivocal field evidence has proved a difference in ages. If the difference in zircon U-Pb dates between Bushveld (~2,060 Ma) and Vredefort (~2,020 Ma; 47, 48) could be resolved, a multiple Bushveld-Vredefort impact event would be plausible. Closure dates from quenched rocks in the upper part of the Rooiberg Group are close to times of emplacement. The thermal history of exhumed Vredefort rocks is more complex and controversial (49, 50). Gibson and Stevens (49) interpreted two stages of metamorphism by impact into a site preheated by a Bushveld-age plume, so "that parts of the granulite-facies terrane were still at temperatures above the granite solidus at the time of impact."

Could this sequence be reinterpreted as impact-plume-exhumation? Roberts and Finger (51) concluded that, in the presence of melt, zircon U-Pb dates of granulites "rather than representing the age of high-pressure metamorphism,..most likely date a stage where the rocks had already been exhumed to medium-pressure levels." For the Paleozoic granulites cited by (51), the time lag was 30 m.y. A Vredefort 40-m.y. impact-plume-exhumation lag would also have affected 39Ar/40Ar dates (52). It may be significant that Archean granulite from a locality near the north side of he Bushveld Complex yielded a "Vredefort" zircon U-Pb date of 2,027±6 Ma (53).

The Bushveld Complex meets most of the criteria for an impact-triggered plume, as set by the hydrodynamic model of Jones et al. (1): Melt volume ~106 km3, crater auto-obliterated by melts, high rate of eruption (11), no initial doming, "plume-like geochemical signature," and no "deep geophysical fingerprint." It differs from the prediction that "melt extrusion would start with...low-viscosity peridotitic melts" but the mafic components of the Dullstroom Formation may qualify.

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