may have been a mantle plume, but, alternatively, it may have been triggered by an asteroidal impact. An impact fall-out layer with shocked debris has been reported at the Tr/J boundary in Italy [13]. The synchronicity of extrusion and extinction appear established as an event horizon independent of radiometric or fossil stratigraphy.

Of course, enthusiasm for impacts does not score points in the scientific forum, but the current evidence of their importance in shaping other terrestrial planets (Venus has 900 impact craters as well as 1500 volcanos) suggests that impacts need not be assigned a role of last resort.

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MOBILIZATION OF THE PLATINUM GROUP ELEMENTS BY LOW-TEMPERATURE FLUIDS: IMPLICATIONS FOR MINERALIZATION AND THE IRIDIUM CONTROVERSY.

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Geochemical investigations on the widely dispersed Late Proterozoic Acraman impact ejecta horizon and its host marine shales in the Adelaide Geosyncline provide strong evidence for low-temperature mobilization of the platinum group elements (PGE), including Ir. The ejecta horizon was formed when the middle Proterozoic dacitic volcanics in the Gawler Ranges, central South Australia, were impacted by a very large (ca. 4 km) meteorite. The resulting structure, now represented by Lake Acraman, is Australia's largest meteorite impact structure. Debris from the impact was blasted for many hundreds of kilometers, some falling into the shallow sea of the Adelaide Geosyncline, some 300 km to the east of the impact site.

The Bunyeroo Formation (~600 m.y.), which hosts the impact horizon, consists of monotonous deep-shelf maroon and green clay shales, with minor concretionary carbonates. The ejecta horizon is typically 0 to 40 cm thick and is composed of a basal clast layer that is poorly sorted, angular, and dominated by pebble-sized fragments. It is overlain by a thin shale layer that contains abundant coarse sand-sized clasts that is in turn overlain by a graded layer that fines up from coarse-medium sand to a fine muddy sand. The largest clast found to date is 40 cm in diameter. All the clasts and most of the sand-sized grains appear to have been derived from a pink to red porphyritic volcanic rock, similar to that currently exposed at the Gawler Ranges impact site. The ejecta horizon is almost invariably enveloped by green shales that range in thickness from a few millimeters to several meters.

Metal concentration along the horizon is anomalously high though variable, with values up to 300 times greater than average red shale background values [1]. Where the green shale envelope is most narrow, metal enrichment is lowest and the PGEs exhibit chondritic ratios. Sections of the ejecta horizon with a significantly wider green alteration envelope are variably enriched in Cu and frequently in Au. In these situations, both the ejecta horizon and the green shales that envelope it have strong PGE enrichments with Ir up to 100 times enriched and Pt up to 300 times enriched relative to the host red shales. Copper and Pt are well correlated with each other and the PGEs exhibit strong nonchondritic ratios.

Thin green shale layers that show no evidence of meteoritic contribution and occur at stratigraphic positions above and below the ejecta horizon in the red shale sequence are similarly enriched in Ir and Pt as well as Cu, V, Zn, and Ni. Isolated green reduction spots in the red shales also have PGE enrichments. All thin green shale horizons and green reduction spots analyzed have relatively high levels of K and other PGE regardless of their stratigraphic position.

The similar chemistries of the ejecta-associated green shales and green shales at other stratigraphic levels suggest a similarity in the enrichment process. The very high Pd/Ir, Pt/Ir, and Au/Ir ratios of the green shale and the Cu-enriched ejecta sample, together with the Cu-PGE correlation, are not totally consistent with an extraterrestrial origin. The ejecta horizon clearly has a meteoritic component as do the other thin green shale horizons and green reduction spots, which suggests that the elevated values are due to low-temperature transport.

The element associations and distribution are consistent with a PGE redox entrapment process. It is suggested that the ejecta horizon was an aquifer for low Eh fluids derived from deeper in the sedimentary basin. These fluids reduced ferric iron in the red shales to ferrous iron that was removed in solution, leaving the shales with their green color. Mixing of the reduced fluids flowing along the aquifer with oxidized fluids circulating in the red shales, from which they had leached Au, Cu, PGE, and other elements, caused metal deposition.

The discovery of significant PGE mobility by low-temperature oxidized fluids has several important implications: Ir, PGE, and Au anomalies may be associated with postdepositional processes, which is particularly significant given the K/T boundary Ir controversy. Further, it indicates that economically important accumulations of the metals might be anticipated in environments in which such solutions entered low redox environments. Examples of such environments include red-bed Cu and roll-type U deposits.

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DOES THE BUSHVELD-VREDEFORT SYSTEM (SOUTH AFRICA) RECORD THE LARGEST KNOWN TERRESTRIAL IMPACT CATASTROPHE?

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The unique 2.05-Ga Bushveld and Vredefort complexes cover 100,000 km^2 (diameter 400 km) on the otherwise stable Kaapvaal craton. Since the 1920s, workers have recognized that they are bracketed by the same units and were probably formed by related processes. Modern field studies and radiometric dates have provided no compelling evidence for different ages. Hall and Molengraaff [1] and Daly [2] invoked magmatic upthrust. Daly [3] later attributed Vredefort to impact, but never applied his concept to the

Bushveld. Subsequently, Vredefort yielded shatter cones [4], coesite and stishovite [5], and planar features [6]; pseudotachylite (indistinguishable from Sudbury) had long been known [7]. Dietz [8], Hamilton [9], and Rhodes [10] concluded that at least four simultaneous impacts caused the Bushveld-Vredefort system. Three impacts formed overlapping Bushveld basins; the fourth made the Vredefort dome. If so, why has the Bushveld yielded no unequivocal shock phenomena? The nature of intra-Bushveld "fragments" and the properties of Rooiberg Felsite offer clues.

Cratering of this magnitude would intersect the ambient-pressure liquidus isotherms of both granite and gabbro. As a result, the Bushveld Complex generated successively the most voluminous siliceous flows, the greatest accumulation of layered gabbro, and the largest masses of A-type granite on Earth, in a setting of complex and long-continued structural adjustments. Gabbroic sills (Rustenburg Layered Suite, RLS), collectively up to 9 km thick, outline the Bushveld basins. Up to 4.5 km of earlier Rooiberg Felsite forms its intruded roof and locally (as Dullstroom Formation) its floor [11], analogous to the Onaping-sublayer relationship at Sudbury. Late-stage Lebowa Granite occupies interiors of Bushveld basins and invades the RLS-Rooiberg contact as sills up to 2 km thick.

This simple scheme is disturbed by deformation of pre-Bushveld rocks around the periphery of the complex [12] and, especially, in 50-km "fragments" within the western and eastern basins [13]. Deformation occurred prior to emplacement of Rooiberg Felsite and its equivalent "bronzite granophyre" dikes [14] at Vredefort. Hamilton [8] and Rhodes [9] interpreted "fragments" as central uplifts, which led to fruitless searches for shock phenomena [15,16]. Based on seismic [17] and field [12] evidence, I interpret the "fragments" as part of a zone between the central initial (transient) cavities (rebounded into Vredefort-type domes) and the present rim of the Bushveld basins. It is suggested that the Bushveld basins became enlarged beyond the initial cavities by collapse, in response to withdrawal of subsurface magma. Today, the central domes are totally obscured by Lebowa granite or covered by younger sediments. All exposures of RLS and Rooiberg Felsite are on the perimeters of the enlarged collapse basins, too distant from inferred central domes for shock phenomena.

In the eastern "fragment," the central (Marble Hall) segment exposes pre-Bushveld rocks that are intensely folded, faulted, metamorphosed, and boudinaged or brecciated. They are interpreted as part of the deformed collar around a transient cavity. In the northern (Stavoren) segment, basal Rooiberg-Dullstroom Felsite, conformable on unfolded pre-Bushveld quartzite, is interpreted as outflow that slid into the expanding collapse basin, probably during emplacement of Lebowa Granite (in the manner of collapse megabreccias of ignimbrite calderas [18]). The pre-Bushveld granitoid core of the southern (Dennilton dome) segment remains enigmatic. In the western "fragment," the southern deformed (Crocodile River) segment and the northern undeformed (Rooiberg) segment play roles similar to the Marble Hall and Stavoren segments respectively.

No source is known for Rooiberg Felsite, interpreted as several lithospheric melts [19]. Chemically and physically it differs profoundly from all known volcanic rocks. As a result of quenching from extraordinary temperatures, its feathery textures are more appropriate for komatiite than rhyodacite. It incorporates large amounts of sedimentary material, from relict quartz grains to large (up to 50 m) quartzite blocks, commonly brecciated before engulfment by "felsite" melts. The basal high-temperature Rooiberg-Dullstroom flows grade into high-energy debris avalanches. Quartz grains in partly digested sandstone clasts were recrystallized to tridymite needles at temperatures ≥1175°–1200°C [20,21] and inverted back to quartz ~1100°C [22]. Recrystallization at these temperatures would destroy all shock phenomena. Up to 30 m of quartzite beneath Rooiberg-Dullstroom flows also inverted to quartz needles and laths, paramorphs after tridymite [23]. Similar ex-tridymite quartz needles occur in the transition from micropegmatite to basal Onaping quartzite breccia at Sudbury [24].

The Bushveld lacks "smoking gun" shock phenomena because all *in situ* exposures are peripheral and all ejecta is recrystallized or melted. In Bushveld-sized impacts, heat effects overwhelm shock effects. A deeply eroded shocked core is exposed only in the smaller and nearly amagmatic Vredefort dome. The Bushveld-Vredefort event probably was the largest known multiple impact on Earth. The alternative would be an as-yet-unknown and unique endogenic catastrophe. The event may have had global effects. It coincides with the biogenic transition from reducing to oxidizing atmosphere [25] and may correlate with a worldwide $\delta^{13}C$ anomaly [26–28], greater than those at the Proterozoic-Cambrian, Permian-Triassic, and K-T boundaries [29–33].

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