COMPOSITIONAL CRITERIA FOR IDENTIFYING IMPACT MELT SHEETS: ASSESSING THE BUSHVELD IGNEOUS COMPLEX AND THE SOUTH POLE-AITKEN BASIN FLOOR.

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Introduction: How can the site of a meteorite impact be conclusively identified [1]? Topographic or structural features (such as craters or ring synclines) alone are suggestive but inconclusive, as endogenous processes can produce striking counterfeits (*e.g.*, Hole-in-the-Ground, Oregon [2]). Certain byproducts of the meteorite impact process, such as the deposition of meteorites or the metamorphism of target rock by shock waves, have no counterpart in endogenous processes (meteorites are necessarily extraterrestrial; the pressures achieved in volcanic explosions are limited by the tensile strength of rock, ~10 MPa, whereas the pressures achieved in meteorite impacts, as inferred from impedance matching of Hugoniot curves of geologic materials with an initial velocity difference corresponding to likely meteorite impact velocities, are at least 10^3 times larger). The presence of meteoritic material or shock-metamorphic features is therefore conclusive evidence for meteorite impact.

However, the absence of meteoritic material or shock-metamorphic features is equivocal. Meteoritic material rapidly weathers—indeed, when the presence of meteoritic material was the only known criteria for conclusively identifying impact structures, only small, young impact craters were conclusively identified [3]. Shock-metamorphic features, while comparatively permanent, are often elusive: it took 25 years to identify such features at the Upheaval Dome impact structure in Utah [4]. Moreover, post-shock annealing of metamorphosed target rock can destroy shock metamorphic features: *e.g.*, planar deformation features in quartz start to anneal at temperatures of ~1200–1300°C [5]. Since large impacts induce rapid stratigraphic uplift of hot, deep rocks, it is conceivable that a very large impact might cover its tracks by annealing its shock-metamorphosed target (though unlikely: shock-metamorphic features persist in the Vredefort impact structure [6], the largest known impact structure on Earth; even the formation of an enormous ~500 km diameter terrestrial crater and consequent stratigraphic uplift of ~50 km is just barely sufficient to bring mantle peridotite to the surface at its low pressure solidus temperature of 1100°C [7]—still several hundred degrees Celsius too cool to anneal planar deformation features in quartz).

Given that meteoritic material and shock-metamorphic features may be absent even in true impact structures, additional criteria for conclusively identifying the sites of meteorite impacts are desirable.

Large meteorite impacts (at the high impact velocities characteristic of impacts on planets) produce large volumes of melt [8] which crystallize to form bodies of igneous rock known as impact melt sheets. The presence of an impact melt sheet is conclusive evidence for meteorite impact. Impact melt sheets are more permanent and prominent than ether meteoritic material or shock-metamorphic features. Unfortunately, endogenous magmatic processes also produce bodies of igneous rock (sometimes of comparable or larger volume: the Sudbury Igneous Complex, an impact melt sheet, is ~8,000 km^3; the endogenous Stillwater Igneous Complex is >20,000 km^3) which can be difficult to distinguish from impact melt sheets. In this abstract, we consider the question: *What compositional criteria can be used to determine whether a large body of igneous rock is endogenous or an impact melt sheet?* We then apply these compositional criteria to assess putative impact melt sheets in the Bushveld Igneous Complex and the floor of the lunar South Pole-Aitken Basin.

Compositional criteria for distinguishing impact melt sheets from endogenous igneous bodies:

Bulk composition. A high-velocity impact completely melts a volume of its target. The composition of this melt is a mixture of the compositions of target lithologies contained in the melt volume. Therefore, it is possible to predict the bulk composition of an impact melt sheet given the characteristics of the impact that formed that melt sheet as well as the composition and distribution of target lithologies. This predicted bulk composition can be compared to the observed bulk composition of an igneous body to assess if it is an impact melt sheet. We now estimate the bulk composition of melt in the largest known terrestrial craters.

On a planetary body like the Earth or Moon where composition becomes increasingly mafic with depth, the bulk composition of an impact melt sheet ought to become more mafic with increasing crater diameter, since larger impacts melt deeper [8]. We take the relationship betweeen depth of melting D and the melt volume V (given as a function of crater diameter in [8]) to be $D = \sqrt[3]{3V/2\pi}$, since impact at an angle of 45° (the most probable impact angle) produces a hemispherical melt volume [9]. For a very large impact the size of Sudbury or Vredefort which produces ~10^4 km^3 of impact melt, the depth of melting is ~15 km—essentially the thickness of Earth's upper continental crust. The implication is that the melt sheets of the largest known terrestrial impact structures ought to have a bulk composition similar to that of the upper continental crust (granodiorite). Indeed, the bulk composition of impact melt at the Sudbury, Vredefort, and Morokweng impact structures is similar to that of the upper continental crust (Table 1). The average composition of the upper continental crust is determined from sedimentary deposits (such as marine sediments, glacial sediments, and loess) formed by erosional processes that homogenize large volumes of heterogeneous target rocks. Impact melting and subsequent mixing is also a homogenizing process, so impact melts too can be used to assess average crustal composition.

Isotopic homogeneity. Pb and Sr isotopes vary little across the thick norite and granophyre layers of the Sudbury Igneous Complex, differentiates of a massive impact melt sheet [15]. Given the high initial temperatures and slow cooling times inferred for massive impact melt sheets, isotopic homogeneity should be a feature of all large impact melt sheets (but not a feature of large endogenous igneous complexes, which comprise multiple magmas that have assimilated varying degrees of wall rock). Initial isotope ratios of the melt sheet should correspond to a mixture of isotope ratios (those prevailing at the time of impact) of target lithologies contained in the melt volume.

Assessing the Bushveld Igneous Complex: In response to Robert Dietz's claim that the Vredefort dome in South Africa is an impact structure [6], geologist Walter Bucher [16] showed that Vredefort was collinear with the massive Bushveld Igneous Complex (henceforth the BIC, an enormous layered igneous complex some ~10^6 km^3 in volume) and the Great Dyke of Rhodesia (Zimbabwe). What are the odds, Bucher asked, that an impact structure would occur on the same axis as these two igneous bodies? Coincidences happen, replied Dietz [17], who noted that the Barringer Meteorite Crater, almost certainly an impact crater, occurs at the edge of the San Francisco Volcanic Field (only ~35 km SE of a maar, Rattlesnake Crater): "Landing amidst this full span of volcanic effects was a most confusing thing for a meteorite to do but, with the perversity of nature, it apparently did so anyway."

An alternate explanation for the collinearity of Vredefort and the BIC (invoking no coincidences) was proposed by Rhodes [18] in 1975: the Bushveld Igneous Complex itself was hosted in an impact structure, or, more precisely, three impact structures, which formed with Vredefort in four simultaneous hypervelocity impacts. Certain felsic lithologies of the BIC (the lower members of the Rooiberg Group) were supposed to represent an impact melt of the crust; the remainder of the BIC was endogenous, perhaps formed by impact-induced decompression melting.

The intervening ~40 years have not been kind to this hypothesis: not only have several extensive searches (*e.g.*, [19]) failed to turn up shock metamorphic effects, but it also turns out that the BIC is about 50 Ma *older* than the Vredefort structure. Nevertheless, as discussed above, the apparent absence of shock metamorphic features is equivocal; moreover, separate impacts which are nearly coincident in space and time are possible, if unlikely (*e.g.*, the Lake Wanapitei impact structure occurs very near the Sudbury impact structure). Revised Bushveld impact scenarios can accomodate recent discoveries [20]. Did a giant impact take place in the Bushveld?

If a giant impact did take place in the Bushveld, it is unlikely that the Rooiberg Group is its impact melt sheet, as it does not meet our compositional criteria for impact melt sheets. First, the volume of the Rooiberg Group is ~300,000 km^3; if the Rooiberg Group is an impact melt sheet, it melted at least ~50 km deep into the Earth. Yet its composition is on average more felsic than that of the *upper* crust (Table 1). Second, the Rooiberg Group is isotopically heterogeneous [13]. We agree with the conclusion of [13]: "The presence of volcanic strata of several distinct geochemical compositions, interbedded with sedimentary units, throughout the Rooiberg group, precludes the interpretation of the lower Rooiberg group as a uniform sheet of impact melt breccia."

Assessing the South Pole-Aitken Basin floor: We have previously suggested that the feldspathic floor of the lunar South Pole-Aitken Basin (henceforth SPA) is the top of a massive differentiated impact melt sheet [21] rather than lunar primary crust. If this is the case, the crystallization age of SPA floor samples is the essentially the formation age of SPA. How can samples of the SPA floor be used to test this idea? For that matter, how is it possible to distinguish feldspathic SPA melt from allochthonous feldspathic crust? Our suggestion is that isotopic homogenization in a massive, mantle-dominated SPA impact melt sheet gives feldspathic SPA melt a LREE-depleted mantle component (contrasting with higher LREE abundances in primary crust). SPA sample return can test this possibility.

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	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Reference
Sudbury	64.57	0.81	13.79	1.80	4.84	0.09	2.12	3.79	3.41	2.87	[10]
Vredefort	67.50	0.50	12.70	7.21	–	0.14	3.50	3.80	2.54	2.14	[11] (BG-4)
Morokweng	63.59	0.51	13.27	2.77	3.35	0.09	3.82	3.74	4.09	2.05	[12]
BIC (Dullstroom)	66.30	0.63	13.20	6.69	–	0.12	1.95	4.37	3.08	2.57	[13]
BIC (Damwal)	69.20	0.56	11.90	7.36	–	0.13	0.35	2.01	3.24	4.32	[13]
Upper crust	66.60	0.64	15.40	–	5.04	0.10	2.48	3.59	3.27	2.80	[14]

Table 1. Major element composition of large terrestrial impact melt sheets [10-12], members of the Rooiberg Group of the Bushveld Igneous Complex [13], and the average upper continental crust of the Earth [14].