

Dating the shock wave and thermal imprint of the giant Vredefort impact, South Africa

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ABSTRACT

U-Pb geochronology of single grains of zircon and monazite has been used to date an episode of intense postimpact metamorphism in the core of the deeply eroded Vredefort impact structure of South Africa. Results from two basement units exposed in the uplifted central region indicate that the impact and a later pyroxene hornfels metamorphic event were penecontemporaneous at 2020 ± 3 Ma. Discovery of a synimpact to postimpact dike of norite that intruded at 2019 ± 2 Ma is the first recognition of mafic igneous activity related to impact. The dike is either derived from a Sudbury-type impact melt layer (since eroded) or is the product of decompression melting of Kaapvaal mantle in response to the ablation of >15 km of crust at the center of the crater. The combined heating effects of the shock wave and impact-triggered magmas are thought to have created the 300 km² thermal imprint of the asteroid collision with Kaapvaal craton, and account for the nearly coeval timing relationship between core metamorphism and shock revealed by this study.

INTRODUCTION

The Vredefort structure in the Archean Kaapvaal craton of South Africa is widely regarded as the oldest (ca. 2.02 Ga; Spray et al., 1995; Kamo et al., in press) and largest recognized terrestrial impact structure, having an estimated original diameter of 300 km (McCarthy et al., 1990; Theriault et al., 1993). Exposures of middle crust in the center of the deeply eroded crater offer a unique opportunity to study the geologic consequences of major impact on continental lithosphere. Of specific interest is the cause and age of an intense thermal metamorphic event that recrystallized shock features in the deep-crustal gneiss uplifted by the impact (Grieve et al., 1990). Some workers propose that the heat source for recrystallization either is directly related to Bushveld-aged (ca. 2060 Ma; Walraven et al., 1990) magmatism (Stephens, 1990) or is the indirect result of above-average heat flow in the aftermath of the Bushveld event (Gibson and Wallmach, 1995). Others argue that annealing and recrystallization of the core zone was the consequence of meteorite impact processes alone (Grieve et al., 1990; Hart et al., 1991a). All interpretations are hampered by a lack of precise isotopic age data for postimpact metamorphic activity in the crater, and, to address this, results of single-grain U-Pb dating of zircon and monazite from the core of the Vredefort structure are presented.

GEOLOGIC SETTING AND SAMPLE DESCRIPTIONS

The Vredefort structure is located near the center of the Witwatersrand basin (Fig. 1), in the 2.7 Ga to 3.6 Ga Kaapvaal craton (de Wit et al., 1992). The remains of the structure consist of a 70-km-diameter, semicircular collar of upturned Proterozoic and Archean strata, surrounding a core of uplifted Archean granites and deep-crustal gneiss. Together, the units of the collar and core zones are thought to represent a cross

section through the craton (Slawson, 1976; Hart et al., 1981). The deepest structural levels are found in a 30-km-wide area at the center of the core zone (Slawson, 1976; Hart et al., 1991b). This poorly exposed region is underlain by the Inlandsee leucogranofels; subordinate amounts of mafic granulite, paragneiss, and recrystallized norite (Stephens, 1990); and rare harzburgite of possible upper mantle origin (Hart et al., 1991b). The ages of the gneissic units range between 3.5 Ga and 3.1 Ga, on the basis of whole-rock Rb-Sr and Th-U-Pb dating studies (Hart et al., 1981). Postimpact plutonic units in the core zone are rare and include a metre-scale pod of anatectic granite (Hart et al., 1981).

Preimpact granulite facies metamorphic assemblages in mafic gneiss and paragneiss indicate minimum paleopressures of ~ 7 kbar (Schreyer, 1983). Following impact, an intense low-pressure, high-temperature metamorphism caused dehydration and partial melting of felsic units, pyroxene hornfels metamorphism (Schreyer, 1983), and recrystallization of shock features, such as pseudotachylyte and planar deformation features in quartz, within a roughly circular, 20-km-wide area (Hart et al., 1991a; Grieve et al., 1990) (Fig. 1). Temperatures reached during this event were in excess of 900 °C at pressures of 3 kbar, based on the composition of pyroxenes near the center of the structure (Schreyer, 1983). Rapid cooling following the final metamorphism is indicated by granophyric textures in veinlets of partial melt in Inlandsee leucogranofels units (Schreyer, 1983). It has been proposed that the age of hornfels metamorphism coincides with formation of a pod of anatectic granite for which a Rb-Sr isochron age of 1950 ± 60 Ma (1 σ) has been determined (Hart et al., 1981).

In an attempt to obtain a more precise age for core metamorphism, two samples were collected from a 15-m-wide outcrop near the geographic center of the Vredefort structure (Fig. 1). One of the samples is from a massive component of Inlandsee leucogranofels that makes up most of the outcrop. The gneissic fabric of this unit is defined

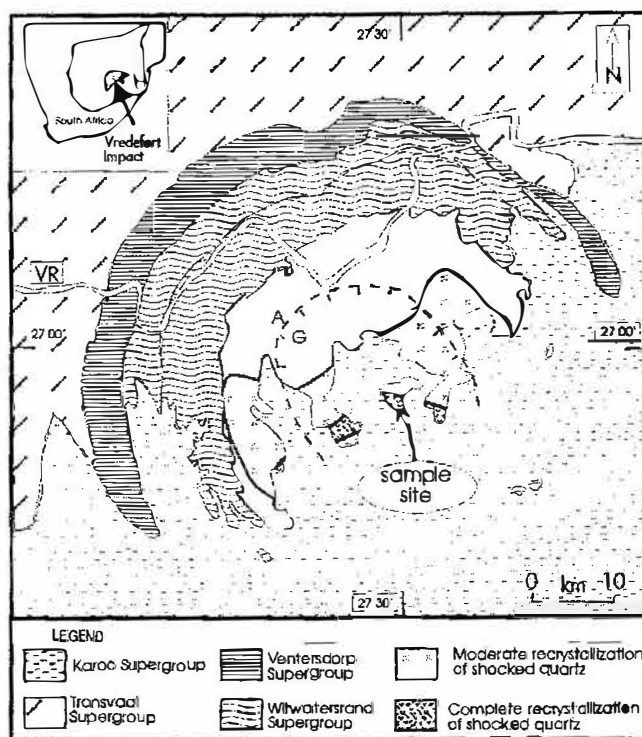


Figure 1. Generalized geologic map of Vredefort impact structure, near the center of Kaapvaal craton, showing upturned rim of strata of Witwatersrand basin, and interior zone of amphibolite (A) to granulite facies (G) Archean bedrock, and zones of moderate to complete recrystallization of planar features in quartz in core zone (modified after Bisschoff, 1982; Grieve et al., 1990; Stephens, 1990). Note sample site is located at center of recrystallized zone. VR = Vaal River.

by centimetre-wide, discontinuous leucocratic layers that in places form tight to open minor folds. The main component of the gneiss consists of granoblastic feldspar and quartz distributed in fine- and medium-grained centimetre-scale fabric units, and these host discontinuous granophyre veinlets. The second sample is from a homogeneous, medium-grained, 0.5-m-wide layer of recrystallized norite. This unit does not exhibit a gneissosity, but contains a pervasive foliation defined by anhedral ilmenite and elongate aggregates of fine-grained, anhedral, inverted pigeonite. The foliation is parallel to the poorly exposed contact with the Inlandsee leucogranofels.

METHOD

Zircon and monazite were separated using standard heavy liquid and magnetic separation methods. Different zircon types from each magnetic fraction were examined for planar features (a result of shock wave deformation; Bohor et al., 1993) with a scanning electron microscope prior to air abrasion and U-Pb analysis using low-contamination isotope dilution procedures (see Krogh et al., 1996). All uncertainties are reported at a 95% confidence level (Table 1).

RESULTS

Inlandsee Leucogranofels

Zircons from the Inlandsee leucogranofels sample have both prismatic and rounded forms, and all grains exhibit blunt and discontinuous planar features. In some cases they have been overgrown by a smooth clear layer of zircon several microns thick (Fig. 2A). Reflected light images of etched zircons in thin section reveal fine concentric zoning. A clear colorless short prismatic zir-

con containing a relatively low density of planar features and no overgrowth yields a $^{207}\text{Pb}/^{206}\text{Pb}$ age (minimum age) of 2819 ± 3 Ma. A larger, cracked long-prismatic crystal with turbid pink interior transitional to clear tips exhibits abundant, pervasive planar features and is highly discordant with a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2429 ± 2 Ma. The Inlandsee leucogranofels gneiss also contains abundant monazite, which occurs mostly as yellow, clear to cloudy anhedral fragments. Some single monazite grains are actually an aggregate of 5–10-mm-wide crystallites (Fig. 2B), a possible shock morphology not previously reported for monazite. Such grains are referred to here as polycrystalline monazite. A multigrain fraction of partly clear monazite fragments yields a discordant analysis with a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2090 ± 9 Ma, whereas the result for a large, single polycrystalline monazite lies on concordia at 2016 ± 7 Ma. The latter result lies at the lower intercept of a discordia line defined by all zircon and monazite analyses (MSWD = 2.1). The upper and lower intercepts of the line with concordia are 3292 ± 28 Ma and 2010 ± 7 Ma, respectively.

Norite

The zircon population from the homogeneous, recrystallized norite body consists of both shocked and unshocked grains. The shocked zircons are the most abundant (80% of total population), exhibit varying densities of partly annealed planar features, and, in thin section, are observed as inclusions in inverted pigeonite and ilmenite. Most shocked grains are long prismatic crystals, or fragments thereof, and show signs of having undergone partial resorption prior to being covered with crystallites of clear zircon.

Etched cross sections through such zircons reveal highly deformed cores surrounded by a 10–30- μm -wide corona of unzoned and undeformed zircon. A small number of polycrystalline zircon fragments was also recovered. The result for an unabraded polycrystalline zircon (Fig. 2C) lies slightly below concordia and corresponds to a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2026 ± 3 Ma (Fig. 3), whereas a single long prismatic, partially resorbed grain yielded an older $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2163 ± 4 Ma. A line between the two results intercepts concordia at 2.8 Ga and 2.0 Ga. In general, planar features in shocked norite grains have undergone greater surface recrystallization and are surrounded by much thicker postshock overgrowths as compared to zircon from the Inlandsee leucogranofels sample.

Unshocked, gem-quality grains make up the remaining 20% of the zircons in the norite. These crystals are perfectly clear and undeformed tetragonal to tabular prisms with low-order crystal faces (Fig. 2D) and contain inclusions of Fe-oxide minerals and elongate bubble cavities. One such crystal was observed in a thin section of homogeneous norite, situated at the boundary of ilmenite and plagioclase grains. Three single-grain analyses of abraded crystals, and an unabraded multigrain fraction of 16 smaller prisms, yield concordant and slightly discordant ages, respectively. The weighted average of $^{207}\text{Pb}/^{206}\text{Pb}$ ages for the concordant points yields an age of 2019 ± 2 Ma (Fig. 3).

Age of Impact and Core Metamorphism

The polycrystalline zircon and planar features in zircon in the Inlandsee leucogranofels and norite samples are diagnostic of shock due to me-

TABLE 1. U-Pb DATA

Fraction number and description*	Mass [μg]	U [ppm] [†]	Pb _{com} [pg] [‡]	Th/U [§]	$^{206}\text{Pb}/^{204}\text{Pb}$ ^{**}	$^{206}\text{Pb}/^{238}\text{U}$ ^{††}	$^{207}\text{Pb}/^{235}\text{U}$ ^{††}	$^{207}\text{Pb}/^{206}\text{Pb}$ ^{††}	$^{207}\text{Pb}/^{206}\text{Pb}$ ^{††} age (Ma)
Inlandsee leucogranofels									
V58-2-Z1 [s, unabr, pf] D	18	90	3.9	0.71	12 697	0.4800 ± 32	13.177 ± 86	0.19909 ± 40	2819 ± 3
V58-2-Z2 [s, unabr, pf] F	60	95	7.8	0.49	18 834	0.4086 ± 14	8.872 ± 32	0.15748 ± 20	2429 ± 2
V58-2-M1 [11, an, frag] F	77	160	52.5	20.4	5 578	0.3740 ± 18	6.672 ± 28	0.12939 ± 32	2090 ± 4
V58-2-M2 [s, pxt] F	12	230	35.2	165	1 795	0.3659 ± 10	6.261 ± 32	0.12408 ± 52	2016 ± 7
Norite									
V58-1-Z1 [s, eu] D	25	25	2.1	0.63	7 076	0.3670 ± 14	6.290 ± 24	0.12431 ± 26	2019 ± 4
V58-1-Z2 [s, eu] D	8	45	1.2	0.77	6 932	0.3675 ± 08	6.300 ± 28	0.12433 ± 30	2019 ± 4
V58-1-Z3 [s, eu] D	24	20	2.3	0.54	4 406	0.3672 ± 12	6.299 ± 22	0.12441 ± 36	2020 ± 5
V58-1-Z4 [16, unabr] D	16	35	2.5	0.39	5 249	0.3645 ± 08	6.247 ± 18	0.12431 ± 20	2019 ± 3
V58-1-Z5 [s, unabr, pxt] D	4	160	1.8	0.59	8 060	0.3650 ± 10	6.278 ± 20	0.12477 ± 22	2026 ± 3
V58-1-Z6 [s, unabr, pf] D	60	15	8.1	0.83	2 524	0.385 ± 13	7.153 ± 24	0.13492 ± 28	2163 ± 4

*[38] = number of grains in a multigrain fraction; s = single-grain fraction; eu = euhedral; sb = subhedral; an = anhedral, subrounded; frag = fragment(s); pxt = polycrystalline; pf = planar features; unabr = not abraded; D = Daly detector used; F = Faraday detector used.

[†]U concentrations known to better than 5% for sample weights over 50 μg and about 50% for sample weights below 2 μg .

[‡]Total common Pb, including blank; corrected for fractionation and spike.

[§]Model Th/U inferred from $^{206}\text{Pb}/^{206}\text{Pb}$ and age.

^{††}Corrected for fractionation and spike.

^{†††}Corrected for fractionation, spike, blank and initial common Pb; initial Pb composition estimated using Stacey and Kramers (1975) model. Uncertainty estimated with an error propagation procedure that takes into account measurement errors, blank uncertainties and reproducibility of Pb and U standards, and the effect of an uncertainty of $\pm 2\%$ on the initial Pb composition and 1% on the blank Pb composition. Errors on isotopic ratios are 2σ .

teonite impact (Bohor et al., 1993), and their presence affirms an origin for the Vredefort structure by meteorite collision. The primary age of the Inlandsee leucogranofels unit is approximated by the 3292 ± 28 Ma upper intercept of the discordant array of zircon and monazite data. Discordancy is due to an event that caused greater Pb loss from monazite than from zircon. The data point for the single polycrystalline monazite grain lies at the lower intercept of the discordia line, indicating that it lost virtually 100% of its radiogenic Pb at 2016 ± 7 Ma. This Pb loss event could be related to the impact event itself, or to the subsequent postimpact metamorphism. The results do not resolve which of these mechanisms

caused Pb loss, but the fact that results for zircon and monazite are colinear indicates that the two events were penecontemporaneous. The concordant monazite age of 2016 ± 7 Ma is, by itself, the best constraint on the timing of these events.

The shocked zircon data for the norite lie on a line with an upper intercept with concordia of 2.8 Ga (Fig. 3), indicating that these shocked crystals are likely Archean grains that underwent extreme Pb loss at ca. 2 Ga. The degree of Pb loss displayed is correlated to shock morphology, the single polycrystalline zircon having undergone the most extreme resetting. The 2026 ± 3 Ma age for this polycrystalline grain is thus a maximum age for the impact, and the coeval metamorphism

of the core zone. The gem-quality population of zircons in the norite clearly crystallized after the shock event, and their concordant 2019 ± 2 Ma age is therefore a minimum age for shock deformation. The difference between the ages of shocked and unshocked grains constrains the time of impact and subsequent core metamorphism to 2023 ± 6 Ma. The intersection of this age bracket with the 2016 ± 7 Ma age estimate from the Inlandsee leucogranofels data leads to a value of 2020 ± 3 Ma for the time of impact and metamorphism at the center of the Vredefort structure. This compares favorably with previous estimates for the age of the shock wave of 2018 ± 14 Ma (Spray et al., 1995) and $\geq 2023 \pm 4$ Ma (Kamo et al., in press) based on dating studies of pseudotachylyte in the crater.

CAUSES OF THE THERMAL IMPRINT

Significant, pervasive heating in the immediate aftermath of the shock wave resulted in partial annealing and/or overgrowth of planar features in all shocked zircon in the core samples, and moderate to complete annealing of planar deformation features in quartz within the 20-km-wide core zone (Grieve et al., 1990) (Fig. 1). Suggestions that Bushveld-age mafic magmas were the source of heat can be ruled out because the dating indicates clearly that metamorphism postdated the main Bushveld intrusive event by ~35 m.y. The gneissic Inlandsee leucogranofels sample shows no evidence of Bushveld-age remobilization or isotopic resetting, making it unlikely that the lingering effects of Bushveld-age deep-crustal metamorphism are the primary cause of postimpact recrystallization in the uplifted gneiss. The shock wave itself is thought to have raised temperatures in the core zone by 150°C to 250°C (Grieve et al., 1990). An additional source of heat is therefore required to account for the $>900^\circ\text{C}$ temperatures (Schreyer, 1983) reached in the core "hot-spot" (Bisschoff, 1982). The results for the norite suggest that impact-related igneous activity may be responsible.

The petrologic characteristics for the 0.5-m-wide norite body are consistent with its origin as a dike that intruded immediately following im-

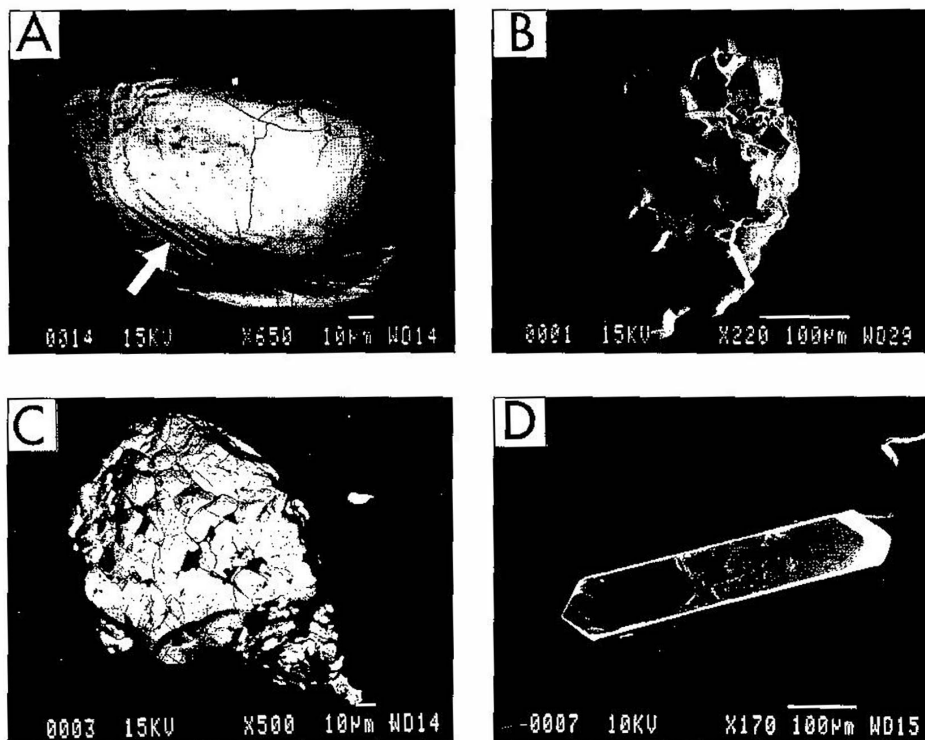


Figure 2. Scanning electron microscope images of shocked monazite and/or zircon. A: Deformed zircon from Inlandsee leucogranofels unit; note surface traces of radiating fractures (arrow) that underlie micron-thick overgrowth. B: Fragment of polycrystalline monazite from Inlandsee leucogranofels unit. C: Tip of euhedral Archean zircon grain from norite, converted to polycrystalline aggregate by intense shock and heat. D: Gem-quality 2019 ± 2 Ma zircon prism from the norite (note larger size relative to shocked zircons).

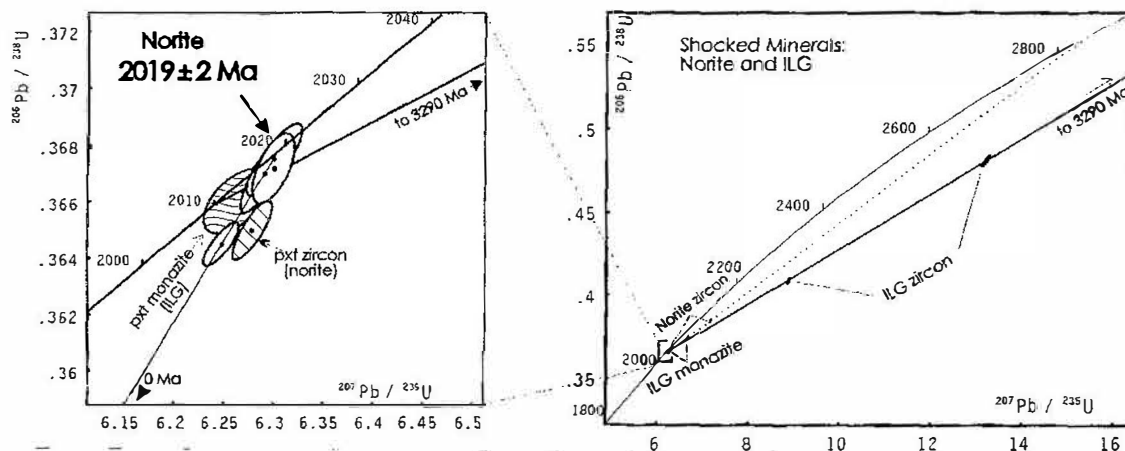


Figure 3. U-Pb concordia plots showing data for shocked monazite, and shocked and unshocked zircon, from units of Inlandsee leucogranofels (ILG) and norite (pxt = polycrystalline).

pect. The presence of inverted pigeonite indicates that the unit had reached "igneous temperatures" (Schreyer, 1983) and cooled rapidly (i.e.; at shallow depths) relative to the surrounding granulite facies Archean gneiss, suggesting that the norite crystallized after uplift of deep-crustal core gneiss to upper crustal levels. Derivation of the norite by total fusion of a mafic Archean protolith is possible, but highly unlikely, given that surrounding rock types with lower melting temperatures preserve preimpact gneissosity and structure and therefore were not reconstituted by total melting.

That the norite is the only sample to yield unshocked, gem-quality zircon (Fig. 2D) further supports the interpretation that it is a postimpact intrusion. Although a metamorphic origin for the unshocked grains must be entertained, their morphology shares no similarity with the small round, multifaceted crystals that result from solid-state growth in mafic rocks (Krogh, 1993) but is typical of zircon crystallized from a mafic to intermediate magma (Pupin, 1980). When it is also considered that they are present in a rock containing no secondary veins or segregations, the simplest interpretation is that these crystals are part of the primary crystallization assemblage of the rock, and that their 2019 ± 2 Ma age dates the postimpact emplacement of the norite. The abundant shocked zircons in the norite are seen as Archean xenocrysts included during rapid injection of the dike. This is consistent both with their occurrence as inclusions in mafic minerals and their more advanced state of deformation and recrystallization relative to the shocked zircons in the Inlandsee leucogranofels. Solidification of the norite dike was accompanied or followed by a dynamothermal event that resulted in the planar alignment of mafic minerals. This texture is shared by the adjacent Inlandsee leucogranofels gneiss (glomerular texture, Schreyer, 1983) and indicates pervasive subsolidus deformation after the peak of core metamorphism.

Exposure in the core zone is poor, but limited borehole data suggest that mafic and ultramafic rocks may underlie >50% of the core zone (Hart et al., 1990). Further dating is required to establish the extent of postimpact norites. If, as suspected, such units are widespread, they would account for the "missing" heat source for post-impact thermal metamorphism of core gneiss, and the "anomalous" recrystallization of high-pressure shock features in their quartz (Grieve et al., 1990) and zircon (this study).

The most likely source region for the norite magma was either an overlying impact melt sheet or the mantle directly beneath the impact site. A possible example of the first mechanism can be seen at Sudbury, Canada, which is a less deeply eroded impact structure of approximately the same scale, age, and geologic setting as Vredefort. Archean basement gneiss in the rim of the Sudbury impact structure host massive mafic

bodies of the same age (F. Corfu, 1996, personal commun.) as the overlying 3-km-thick impact melt layer (Faggart et al., 1985), and these may be analogous to the norite dike identified in this study. A notable difference, however, is that the Vredefort dike is foliated. This contrasts with the undeformed state of bronzite granophyre dikes (impact melt; French and Nielsen, 1990) that occur in the outer regions of the Vredefort structure, suggesting that postimpact deformation was localized in the core zone.

A second plausible source for postimpact mafic magmatism is the mantle lithosphere beneath the impact. The presence of harzburgite several hundred metres away from the sample site is evidence that the mechanical effects of impact extended to upper mantle depths, and that the magnitude of impact-induced uplift may have been 25 to 30 km in the center of the crater (Hart et al., 1991b). The resulting pressure release of ≥ 5 kbar, and thermal input from the shock wave, would be sufficient to cause decompression melting of upper mantle (Green, 1972; Grieve, 1980), and the norite may be a component of such a melt, which was injected into deep-crustal gneiss during rapid ascent to the upper crust. The heat supplied by such impact-triggered intrusions, combined with heat from the shock wave, caused the recrystallization and pyroxene hornfels metamorphism at the center of the impact crater, imposing a 300 km² thermal imprint of asteroid collision on the Archean Kaapvaal craton.

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