Zircon-based identification of mafic impact melt bodies at the center of the Vredefort dome–remnants of the lost melt sheet

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Introduction: The Vredefort impact structure in South Africa is among the oldest and largest terrestrial impact basins. Impact modelling predicts that it was overlain by a melt sheet several kilometers thick [1], similar to that of the Sudbury structure. The current belief is that all components of the Vredefort melt sheet have been removed by 2.02 Gyr of erosion. To date, evidence of impact melt bodies has been restricted to the Vredefort Central Anatectic Granite dated at 2017 ± 5 Ma [2], and the granophyre dykes [3]. A third melt type, a foliated norite dyke, which has zircon ages of 2019 ± 2 Ma has been reported [4], but it has since been proposed that the unit is a mafic pseudotachyllite and the impact age zircons are the result of post impact metamorphism [5]. The prospect has also been raised that the impact age of the zircons from melt are a consequence of shock and thermal resetting of pre-impact grains, and does not correspond to primary crystallization. We have further investigated zircon grain morphologies and internal structures in the type norite (now, consequent to further petrographic analysis, reclassified as a gabbro-norite) and conducted detailed field mapping to assess a metamorphic versus igneous origin for the impact age zircons. Our new and previous microstructural data [6], together with new Ti-in-zircon thermometry and SHRIMP U-Pb dating of unshocked grains, are consistent with gabbro-norite crystallization from a high temperature impact melt analogous to mafic phases of the Sudbury igneous complex. Our mapping also shows that the gabbro-norite lithology is more extensive in the Vredefort dome than previously recognized.

Background: The Vredefort impact structure is located 120 km southwest of Johannesburg and is estimated to have had an original crater diameter of 250-300 km [7]. The physiographic expression of the original transient crater is a semi-annular exposure of upturned sedimentary strata 80 km in diameter consisting of a 12,350 m section of volcanics and sediments from the Witwatersrand, Ventersdorp and Transvaal systems that are Late Archean to Early Proterozoic in age [5]. The central uplift is comprised of predominantly granitic and gneissic Mesoarchean units often referred to as the Vredefort dome. The amount of post-impact erosion is estimated to be 8-10 km [5]. We investigated an area near the centre of the dome in the region of a seasonal lake, the Inlandsee Pan.

Methods: Detailed mapping at 10 m grid spacing was initially carried out in the area of the 'type' gabbro-norite dyke [4], which led to the identification and sampling of dm-scale bedrock exposures of the same rock type. Geochronology mineral separation was conducted at the Jack Satterly Geochronology lab at the University of Toronto using standard procedures. Zircons were cast in epoxy mounts at the Stanford/U.S.G.S. SHRIMP-RG facility. Electron nanobeam techniques including cathodoluminescence (CL) and Energy Dispersive Spectroscopy (EDS) were performed with a Hitachi SU6600 VP-FEG-SEM at the University of Western Ontario, Zircon and Accessory Phase Laboratory (ZAPLab). Mineralogic composition was determined by optical microscopy and EDS analyses of petrographic thin sections. SIMS U-Pb isotopic analysis and Ti-thermometry was conducted at the Stanford/ U.S.G.S. SHRIMP-RG facility according to previously published procedures [8], and referenced to internal zircon geochronology standard VP-10.

Results and Discussion:

Mapping: Two areas containing dm-wide, moderately foliated to massive gabbro-norite dykes and lenses were identified. The first area is within the vicinity of the 'type' site locality. The second area is 1.4 km from site 1 and has an areal extent of 900 m^2. Both occurrences are within the Mesoarchean Inlandsee Leucogranofels unit.

Zircon microtextural descriptions: The zircons from both the type locality and the newly discovered area tend to be anhedral to subrounded, with the optical colouration of the grains ranging from clear to pale yellow to orange-red. The size of the grains varies from sample to sample (~50-200 μm in the long dimension) and the majority of the zircon grains contain inclusions. Zircon populations from three samples were examined. In the 'type' gabbro-norite dyke zircons with uneven microfaceted exteriors are more abundant than clear, euhedral to subhedral prisms. In two samples from the largest, foliated to massive body in the second area, clear subhedral to euhedral grains are dominant. Shocked grains were clearly distinguished by irregular to chaotic CL patterns and a higher abundance of inclusions (Fig. 1) as documented previously [9]. These are considered to be shocked xenocrysts inherited from the host felsic gneiss. The internal CL images of the clear optically continuous grains show sharp oscillatory concentric planar growth bands (Fig. 1) typical of igneous zircon [10].

Zircon Geochronology and Ti Thermometry: SHRIMP-RG U-Pb analyses of igneous zircon from the type gabbro-norite site are concordant at 2036 ± 45 Ma overlapping the published ID-TIMS age of 2019 ± 2 Ma from the type locality [4]. Igneous zircons from the large body, which are texturally identical to zircons from the type gabbro-norite, yield concordant to slightly discordant results with an upper intercept age of 2039 ± 33 Ma, overlapping the age of impact. Ti-in- zircon thermometry gives temperatures for zircon crystallization of 954-809˚C. This temperature range is high for normal crustal melts [11], but falls within the range of the mafic units at the base of the Sudbury igneous complex [12]. Zircon trace element chemistry and U/Yb ratios suggest a crustal source for the mafic magma.

Conclusions and Future directions: Detailed field mapping and petrographic analysis has led to the identification of mafic igneous bodies within the Vredefort dome. Microstructural analyses of zircon from these units allows us to distinguish igneous from shocked grains. SHRIMP-RG U-Pb isotopic results support the interpretation that the igneous zircons crystallized at the time of the Vredefort impact. Trace element analyses indicate that Ti-in - zircon crystallization temperatures are similar to those of the mafic base of the Sudbury igneous complex. We interpret these bodies to be basal elements of the Vredefort impact melt sheet that have been otherwise, largely been removed by erosion. Further analyses including Lu-Hf and oxygen isotope analysis of the igneous zircons are under way to better resolve the magma source and emplacement history of this unit, and help researchers gain a better understanding of the melt-crater interface of one of the largest known terrestrial impacts.

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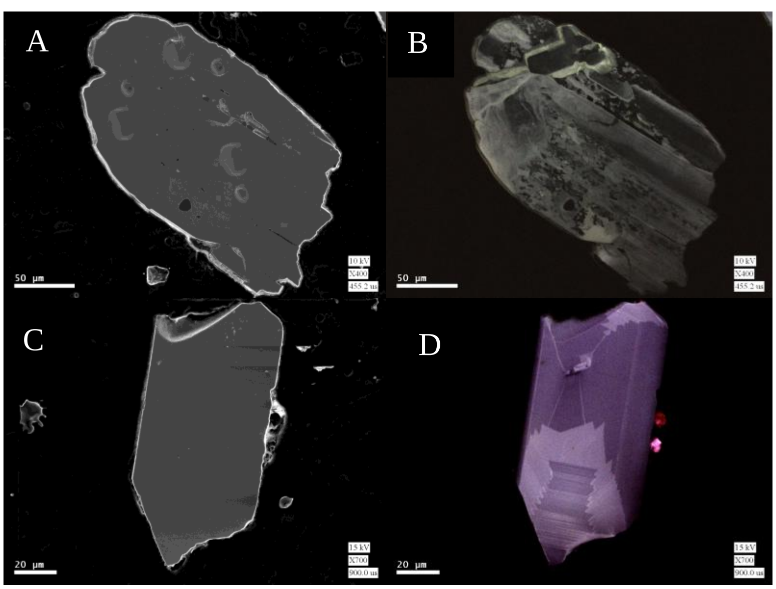

Figure 1: Sectioned, polished zircons from a gabbro-norite body near the center of the Vredefort dome showing the difference between shocked and unshocked grains. (A & B) SE and CL images of a grain that has been shown to have been shocked and recrystallized using CL and electron backscatter diffraction strain mapping [9]. (C & D) SE and CL images, respectively of an unshocked, igneous grain from the largest body of gabrro-norite with typical oscillatory planar growth banding and sector zoning.