Introduction: Given that impact cratering was a fundamental geological process in the early Solar System [e.g., 1], understanding how large impact structures cool is critical to understanding the thermal evolution of early crusts on Earth and other planetary bodies. However, few studies have reported direct measurements that constrain the crystallization and early cooling history of a large impact melt sheet.

The Morokweng impact structure, South Africa (Fig. 1) provides an exciting case study for assessing melt sheet crystallization, while also being a priority target for high-precision dating given its age near the Jurassic-Cretaceous (J-K) boundary [2,3].

Estimates for the diameter of the Morokweng impact structure have varied significantly and a consensus has yet to be reached. However, the observation of limited deformation in the KHK-1 borehole (Fig. 1) appears to constrain the maximum present-day diameter to about 75-80 km [4] and a diameter in this approximate range would also be consistent with initial interpretations that the M4 borehole (Fig. 1) appears to have intersected the peak ring [5].

In contrast to some of the largest impact structures on Earth (such as the heavily eroded Vredefort structure, deeply buried Chicxulub structure, and 1.85 Ga Sudbury structure), Morokweng hosts a melt sheet that has been intersected by a number of boreholes (Fig. 2) and is suitable for individual samples to be dated with extremely low absolute age uncertainties. However, it is important to note that the top of the melt sheet is an erosional surface (meaning that there may be a substantial section of melt missing) and there is also the possibility that gneisses intersected in the bottom of the M3 borehole do not represent true basement but may belong to a >100 m wide clast within the melt – similar to interpretations that the granite at the bottom of WF5 belongs to a boulder (Fig. 2).

Zircon from the melt sheet at Morokweng has previously given $^{206}$Pb/$^{238}$U ages of 145.2 ± 0.8 Ma (all data are 2σ) [2] and 146.2 ± 1.5 Ma [3], in agreement with less precise Ar-Ar ages for biotite of 143.5 ± 3.6 Ma [2]. In light of emerging data that the J-K boundary may as much as 5 Myr younger than the currently accepted 145 Ma age [6-8], a modern, high-precision age for the Morokweng impact melt sheet may offer insight into the relative timing of the impact and the boundary.

Here we aimed to assess the early stages of cooling in a large impact structure by constraining the length of time for an initially molten impact melt sheet to crystallize, while also placing high-precision constraints on the timing of the Morokweng impact event.

Materials & Methods: Zircon grains were separated from six samples from the M3 borehole (Fig. 2) and mounted in epoxy. The grains were analyzed for U-Pb isotopic age data and trace element composition by in situ laser ablation-inductively coupled plasma mass spectrometry (LA-ICPMS) at Boise State University. A selection of the grains from five samples were then plucked from the grain mount and analyzed by chemical abrasion-isotope dilution-thermal ionization mass spectrometry (CA-ID-TIMS). The aliquots were spiked with EARTHTIME isotope dilution tracer solution ET2535 and analyzed on an IsotopX Isoprobe-T mass spectrometer.
The stratigraphically highest sample (M3-1; 146.056 ± 0.018 Ma, MSWD = 1.08, probability of fit = 0.37, n = 7) and stratigraphically lowest sample (M3-6; 146.018 ± 0.017 Ma, MSWD = 1.47, probability of fit = 0.18, n = 7) are separated by 38,000 ± 25,000 years, indicating that zircon throughout the melt sheet took a maximum of 63,000 years to crystallize.

_Discussion:_ Our results indicate extremely fast cooling and crystallization of the presently preserved Morokweng impact melt sheet, with the lowest, most insulated portion of the melt having crystallized less than 65 kyr after higher levels. As the top of the melt sheet is an erosional surface, it is possible that the missing upper portion may have given an age younger than sample M3-1, thereby extending the apparent extent of crystallization. However, the fact that samples M3-1 to M3-4 give indistinguishable, tightly constrained ages suggests that the main body of the melt did indeed cool extremely quickly.

Our new ages for the melt sheet agree with previously published data [2,3] but are far more precise. Given that the melt sheet would have cooled from the top downwards, we interpret the age of the stratigraphically highest sample, M3-1, to most closely constrain the timing of the impact event. This age of 146.056 ± 0.018 Ma indicates that the Morokweng impact event did not coincide with the J-K boundary, which may be as young as 140 Ma [6-8].

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