Morokweng, South Africa: A large impact structure of Jurassic-Cretaceous boundary age

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ABSTRACT
Geophysical, petrographical, and geochemical data indicate the presence of a large impact structure in the area around Morokweng, Northwest Province, South Africa, possibly up to 340 km in diameter. Drill cores from the center of the structure show a thick layer of impact melt rocks with high abundances of Cr, Ni, Co, and the platinum-group elements, consistent with the presence of up to 5% of a chondritic component. Ion probe dating of zircons extracted from the impact melt yielded a 206Pb/238U age of 146.2 ± 1.5 Ma and a 206Pb/232Th age of 144.7 ± 1.9 Ma; these are indistinguishable from the age of the Jurassic-Cretaceous boundary. Following the identification of the Chicxulub impact structure of Cretaceous-Tertiary boundary age, the discovery of a second large impact structure at a previously established major chronostratigraphic boundary strengthens suggestions that large impact events have been major factors in the evolution of the Earth.

INTRODUCTION
Over the past 15 years, the study of the events that led to the extinction of the majority of all life on Earth at the end of the Cretaceous Period (65 Ma) has implicated a large-scale asteroid or comet impact as the cause of this catastrophe. In Africa, only 15 impact structures were known as of 1994, but cratering rate estimates indicate that numerous, so far undiscovered, craters must exist in Africa (e.g., Koeberl, 1994). Considering the substantial importance of impacts for geology in general, and their possible influence on the evolution of life on Earth, impact craters deserve more extensive study. Another important aspect is the economic importance, especially of large impact structures, as two of the largest known impact structures on Earth—Sudbury and Vredefort—are associated with world-class nickel and gold deposits, respectively.

Recently, large, near-circular coincident magnetic and gravity anomalies, centered at 23°32'E and 26°31'S, were identified near Morokweng, Northwest Province, South Africa, close to the border with Botswana. Preliminary geophysical, petrological, and geochemical investigations led to the suggestion that these anomalies may represent an impact structure (Andreoli et al., 1996; Corner et al., 1996, 1997; Hart et al., 1997). Detailed geophysical studies by Corner et al. (1997) identified a circular positive magnetic anomaly of up to 350 nT above regional background. This anomaly forms a central near-circular area, 30 km in diameter, which is surrounded by a concentric, magnetically quiet zone 20 km wide. Refined processing of the gravity and aeromagnetic data reveal the presence of a much larger structure with a diameter of about 340 km (see Corner et al., 1997). These authors concluded that there is good evidence to argue that the Morokweng structure is at least 70 km and may be as large as 340 km in diameter, although confirmation of this size will require further geophysical studies.

Surface exposures are very rare in this largely sand- and calcite-covered part of the southern Kalahari desert. Locally, Transvaal (ca. 2.25–2.5 Ga) quartzite and ironstones occur to the northeast and west of the center of the structure, and about 40–70 km to the southeast, several outcrops of Archean granitoid basement rocks are known (Corner et al., 1997). Petrographic studies of surface samples (quartzite, chert, granitoids, etc.) from the Morokweng area resulted in the identification of shocked quartz grains with single and multiple sets of shock-characteristic planar deformation features (PDFs) in fragmental breccia of banded ironstone and in quartzite, indicating an impact origin of the Morokweng structure (Corner et al., 1997).

DRILL CORE STUDIES
Three boreholes in the south-central area of the aeromagnetic anomaly (MWF03, core depth 130.3 m; MWF04, 189.3 m; MWF05, 271.3 m) were logged (Fig. 1) and comprehensively sampled for the present study. They represent an ~5.5-km-long traverse from near the southern edge of the anomaly (core MWF03), via MWF05, to its approximate center (MWF04). All three boreholes went through a top layer of Tertiary and Holocene Kalahari Group calcrites, which is directly underlain by a dark-brown melt rock, with a thickness of about 125 m in borehole MWF05. Only in borehole MWF05 was the lower contact of the melt rock intersected, when granitic rocks were reached at 225 m depth, whereas the other holes bottomed in the melt rock unit.

This rock appears fresh and homogeneous except for a large number of lithic clasts. The clast population is dominated by gabbro fragments, but microscopic studies reveal that felsic, clearly granitoid-derived clasts are also abundant. Besides mafic lithic clasts, numerous platy, sometimes poikilitic, clinopyroxene clasts—many of which have corroded margins (perhaps due to absorption by melt)—are also significant. All pyroxene crystals analyzed contain significant amounts of Ni. However, the small matrix pyroxenes, at about 0.20 wt% NiO, are relatively enriched in comparison with the platy clinopyroxenes, which on average have about 0.12 wt% NiO. The matrix, which constitutes >90 vol% of the rock, is dominated by lathly or bladed plagioclase crystals, set between generally smaller, short-prismatic orthopyroxene and ubiquitous, but variably abundant, granophyric intergrowths of plagioclase, alkali feldspar, and quartz.

Individual samples are completely composed of micropegmatite (Fig. 2, A and B). Subordinate clinopyroxene, as well as even rarer amphibole,
occurs as well. Opaque minerals are relatively abundant in the Morokweng melt rock and include magnetite, ilmenite, and trevorite (containing about 25 wt% NiO). Some samples contain significant amounts of biotite, often displaying cores of an older generation with overgrowths of a later one. Many samples display textural variation that is remarkably similar to the textures of the Vredefort Granophyre (e.g., Therriault et al., 1996). The grain size of matrix minerals is variable from medium to fine grained, and the more clast-rich samples have typically a finer-grained matrix. The overwhelming proportion of felsic clasts is completely recrystallized, but we observed a small number of unannealed relics with unequivocal remnants of PDFs. Other quartz or quartz-bearing clasts contain densely-spaced planar trails of microinclusions, which most likely are remnants of PDFs.

The granites drilled below the melt body in core MWF05 are locally brecciated and pervasively recrystallized. In places, however, primary minerals are preserved and often display shock deformation. PDFs were observed in quartz, plagioclase, alkali feldspar (Fig. 2C), and K-feldspar (Fig. 2D). Several samples contained diaplectic quartz glass or ballen quartz, which is thought to represent a pseudomorph after diaplectic quartz glass (Carstens, 1975). Thin (at maximum 10 cm wide) breccia veins occur sporadically in the granitoids of drill core MWF05. These breccias could be injections of melt or in part recrystallized, locally produced, cataclastic material. It is not clear yet whether granitoid basement has been reached at the bottom of drill core MWF05, but it is quite possible that a (mega?)breccia zone below the melt rock and above the basement was intersected.

**GEOCHEMISTRY OF MELT ROCK**

Detailed geochemical studies were made of 60 drill-core samples, covering all three cores and representing impact melt rocks from various depths, as well as granites and breccias from below the melt-rock unit in core MWF05 and a variety of clasts within the melt rocks. Excluding a few altered samples that have high carbonate contents, the samples of impact melt rock have a remarkably uniform composition. The average melt rock composition is, in weight percent of the oxides, Si 65.75, Ti 0.49, Al 13.48, Fe 5.87, Mn 0.08, Mg 3.70, Ca 3.41, Na 3.89, K 2.15, P 0.12, with variations of mostly 2–5 relative percent.

The most remarkable result of the trace element analyses was the discovery of a uniformly high content of the siderophile elements, mainly Cr, Co, Ni, and Ir, in the melt rock samples. The values determined were up to 440 ppm of Cr, 50 ppm of Co, 780 ppm of Ni, and 32 ppb of Ir, with little variation (less than a factor of 2) in the melt rock samples. No correlation between the trace element contents and the sample depth was observed, and the contents are uniform between the three cores. Although the high contents of Cr, Co, and Ni may to some degree be due to a mafic component in the target rocks, this interpretation is implausible in the case of Ir, as Ir contents in mafic and ultramafic rocks are mostly <5 ppb Ir. Thus, contents of 15–32 ppb of Ir cannot easily be explained from such sources. Mantle sources are also excluded by our Rh-Sr and Sm-Nd isotopic
analyses (cf. Koeberl et al., 1997), which indicate a dominantly crustal composition of the melt rock. Mixing calculations with granites and other plausible target rocks were performed to reproduce the composition of the impact melt rock, with the additional aim of determining and subtracting the indigenous siderophile contribution from the target. The results of the mixing calculations indicated 40% of a mafic component (best results were obtained for Karoo, Kraaipan, and/or Venterbos components; compositions from Cornell et al., 1996; Pybus, 1995; Zimmermann, 1994; and references therein), leading to a correction for the indigenous Cr, Co, and Ni contents of between 10 and 30 relative percent, leaving a near-chondritic abundance range (Fig. 3A).

The high Ir contents and the near-chondritic distribution pattern of the siderophile elements give a clear indication of the presence of an unusually high amount of a meteoritic component. Commonly, extraterrestrial components in impact melts amount to <1 wt%, which is usually difficult to determine (e.g., Palme, 1982). Only in very few cases, e.g., at the Clearwater East and Chicxulub structures, have higher contents been found, but they often show inhomogeneous distributions (e.g., Palme, 1982). In contrast, the meteoritic component is high and uniformly distributed in the Morokweng impact melt rocks. An iron meteorite is excluded as the source because of the high Cr contents in the impact melt rock (cf. Palme, 1982). To further confirm the presence of a meteoritic component and to obtain some information on the nature of this component, the abundances of the platinum-group elements (PGEs) were determined by radiochemical neutron activation analysis. The results confirm the presence of a chondritic component (Fig. 3B).

AGE DETERMINATION
To determine the age of this intriguing impact structure, zircons were extracted from a composite sample of several coarse-grained drill core sections from core MWF04, obtained at depths of between 75 and 115 m. The zircons, with euhedral shapes (or fragments thereof), were analyzed for their U-Th-Pb isotopic compositions on the ion microprobe SHRIMP I at the Research
School of Earth Sciences (RSES), Australian National University, following the techniques described elsewhere (e.g., Williams and Claesson, 1987; Claoué-Long et al., 1995). Ages are reported as weighted means (with 95% confidence limits), with corrections for common Pb made by using the measured 206Pb/208Pb and 206Pb/238U values (cf. Claoué-Long et al., 1995, and references therein). For the present samples, the average common 206Pb content, expressed as a percentage of the total 206Pb in the analysis, is 0.1%, which translates into an average correction of the calculated 206Pb/238U ages of less than 0.2 m.y. Thus, the correction for common Pb is negligible for the calculated ages.

The 19 separate zircons analyzed have simple isotopic compositions (Table 1). All but two conform to a single population from which a 206Pb/238U age of 146.2 ± 1.5 Ma can be obtained from standard statistical calculations, as shown in the Tera-Wasserburg concordia plot in Figure 4. Similarly, a 208Pb/232Th age of 144.7 ± 1.9 Ma can be calculated from this data set and is interpreted with confidence as the crystallization age of zircons in the melt. This age is statistically indistinguishable from the 206Pb/238U age calculated. Both age calculations exclude the analyses of grains 1 and 19, which represent outliers. (Although inclusion of these dates would not alter the final age significantly, they are excluded from the age calculation for standard statistical reasons.)

The obtained age is indistinguishable from the age of the Jurassic-Cretaceous (J-K) boundary, which is placed at the base of the Berriasian Stage at 145 Ma (Harland et al., 1990; Gradstein et al., 1994). In contrast to other boundaries, especially the Cretaceous-Tertiary boundary, the J-K boundary is still poorly defined, and little attention has been paid to impact signatures (Rampino and Haggerty, 1996), supporting similar conclusions recently obtained by Hart et al. (1997). Also, limited information on the biological significance of this boundary is available; however, some marine extinctions seem to have occurred at that time, and a marked peak in the extinction of reptiles (including dinosaurs) was reported (Rampino and Haggerty, 1996, and references therein). So far, the association of the large Chicxulub impact structure with the Cretaceous-Tertiary boundary could have been viewed as a coincidence. However, the existence of another large impact structure with an age that is indistinguishable from that of another major geological boundary supports the view that there is a connection between impact events and the geo(logic and biologic) evolution of the Earth.

ACKNOWLEDGMENTS
Supported by the Austrian Fonds zur Förderung der wissenschaftlichen Forschung (to Koeberl) and the Foundation for Research Development, South Africa (to Reimold). We are grateful to the Council of Geoscience, Pretoria, South Africa, for access to the Morokweng drill cores, and to J. D. Blum and R. R. Anderson for helpful reviews.

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Manuscript received March 26, 1997
Revised manuscript received May 12, 1997
Manuscript accepted May 29, 1997

734 Printed in U.S.A.
GEOLOGY, August 1997