Geology, published online on 5 August 2011 as doi:10.1130/G31990.1

The newly confirmed Luizi impact structure, Democratic Republic of Congo—Insights into central uplift formation and post-impact erosion

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ABSTRACT

Rocks exposed within the uplifted central part of meteorite impact structures come from significant stratigraphic depths, in some cases as much as several kilometers. On Earth, central uplifts are commonly the final and only feature of an impact crater that remains after the rest of the structure is lost to erosion. However, the crater-forming process that results in the formation of intricate features such as central peak and peak rings is poorly understood. Much of our knowledge is based on extraterrestrial observations; as on Earth, there are very few unequivocal examples of impact craters with well-preserved peak and ring morphologies, because of erosion. In this study we describe the ~17-km-diameter Luizi structure (Katanga region, Democratic Republic of Congo), a moderate-sized complex crater, with an intermediate ring (~5.2 km in diameter), and an ~2-km-wide circular central ring around a central depression. For the first time, unique evidence of shock metamorphism, in the form of macroscopic shatter cones and multiple sets of microscopic planar deformation features in quartz and feldspar grains, is described, confirming the meteorite impact origin of the structure. Our observations at Luizi provide insights into the formation of mid-sized impact craters on Earth, adding to the evidence that, in the case of sedimentary target lithologies, structural ring structures within the central uplift may form by the collapse of an unstable central peak. Given the preservation state of the Luizi crater, it cannot be excluded that structural rings may be a common feature for mid-size craters developed in layered target rocks.

INTRODUCTION

Impact cratering is a fundamental and virtually instantaneous geological process that has contributed to the formation and evolution of our solar system (e.g., French, 1968; Shoemaker, 1977), involving extreme pressures, temperatures, and high strain rates (e.g., Stöffler, 1972; Melosh, 1989). Although millions of impact craters are known on Mars and the Moon, to date only 181 confirmed meteorite impact structures are currently recognized on Earth, only 18 of which are located in the African continent (Fig. DR1 in the GSA Data Repository[1]). In contrast to most other planetary bodies, Earth's surface is constantly renewed by plate tectonics and erosion, and a large part of it is not easily accessible, either because of the presence of oceans, dense vegetation, and/or the political situation in some regions of the globe. The recognition and confirmation of new hypervelocity impact structures, particularly complex craters (>2–4 km in size), is thus extremely important for improving our understanding of the terrestrial cratering record and for the improvement of our knowledge of impact cratering processes in general.

A unique result of complex crater formation is that material from depth is brought to the surface; the original position and distribution of the target rocks are modified when, because of gravitational instability of the transient cavity, inward and upward movement of the crater floor leads to formation of a central uplift (e.g., Melosh, 1989). Redistribution of rock can also occur during the subsequent collapse of an initially oversteepened and/or weak central uplift. The mechanics of central uplift formation remain unclear and there are large apparent differences between the behavior of sedimentary versus crystalline rocks. For many impact sites and on all other planetary bodies besides Earth, these central uplifts provide the only samples of the deep subsurface. The central uplift is also commonly on Earth the only remnant of an impact crater to be preserved following erosion, and thus represents the only material available with which to identify and characterize impact structures. Therefore, studying the formation of, and distribution of shock features within, a central uplift is crucial to further our understanding on the crater-forming process. Although these types of impact structures with intricate structural features are abundant on other planets, they are very rarely exposed and preserved on Earth.

Here we report on a detailed analysis of the Luizi structure, located in Democratic Republic of Congo, combining a remote sensing study with geological field observations and petrographic examination of rock samples collected during our 2010 field campaign. We demonstrate that this structure is a complex meteorite impact crater, the first one to be confirmed in Central Africa (Fig. DR1). Because of its size and its complex crater morphology, i.e., an inner ring and a central depression, together with its relatively simple geology, we propose that Luizi is an excellent site for contributing to our understanding of the formation of mid-sized impact craters on Earth and on other planetary bodies.

LUIZI STRUCTURE

Previous Work

The Luizi structure, centered at 10°10′13.5″S and 28°00′27.0″E on the Kundelungu Plateau of the Katanga province, lies in an underexplored region of the southeastern Democratic Republic of Congo (Fig. 1). The first and only field geological report on the Luizi structure appeared in Grosse (1919), in which the author described an ~20 km semicircular basin, with the dominant rocks consisting of more or less fractured thick-bedded quartzitic arkose, dipping from 5° to 20° at the basin edge and from 60° to 90° in the inner basin. Since that time, owing to the political situation and logistical challenges of working in Democratic Republic of Congo, the study of Luizi has been restricted to remote sensing techniques. As such, we identified this structure as an analogue for planetary exploration, where only satellite imagery is available. Our motivation to study the Luizi structure came from a brief note in a publication by Dumont (1990), in which an impact origin was suggested for Luizi purely on the basis of its circular morphology. Given that other terrestrial geological processes, such as magmatism, salt diapirism, caldera collapse, or sinkhole formation, are also capable of producing more or less circular features, unambiguous shock deformation features, such as planar deformation features (PDFs) in quartz, or traces of extraterrestrial matter (e.g., siderophile element anomalies), are essential to confirm the impact origin of a structure (French and Short, 1968; Stöffler,

[1]GSA Data Repository item 2011247, Figure DR1 (distribution map of the confirmed meteorite impact structures on Earth) and Table DR1 (universal-stage microscope data), is available online at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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1972; Stöffler and Langenhorst, 1994; French and Koeberl, 2010), and thus field investigations and sample collection are mandatory.

Remote Sensing Study

Prior to field work, we conducted a remote sensing study using available imagery and topographic data (Fig. 1) that revealed the dominant morphological features of the structure. Luizi exhibits, from the periphery to the center of the structure, a rim elevated up to ~300–350 m above the crater interior, an annular depression, an intermediate ring with a diameter of ~5.2 km, and an ~2-km-wide circular central ring around a central depression (Fig. 1). All these features are well defined and can be easily recognized because of their sharp local topographic gradients. Using a digital elevation model (DEM) and derived cross sections, we estimate the rim diameter of the structure to be ~17 km (Fig. 1). A large fault zone oriented NNW-SSE (at least 100 km long) is apparent on the right part of the Landsat image and on the DEM (Figs. 1B and 1C); it marks the eastern limit of the Kundelungu Plateau. This fault zone cuts the impact crater and is therefore likely post-impact in age.

Field Observations

Following these preliminary remote sensing studies, field investigations were conducted by two of us (Ferrière and Kaseti). Because of the lack of road access or facilities and challenging field conditions, only part of the structure could be explored, including a NNW-SSE transect from the periphery to the center of the structure. More than 30 outcrops, principally along rivers, were documented, including structural measurements and collection of rock samples. It is apparent that the structure formed in tabular massive arkosic sandstone beds, of centimeter to decimeter thickness, with intercalated laminated argillaceous sandstones, locally displaying cross-laminations. These formations correspond to the Biano Subgroup, late Neoproterozoic in age, capping the Kundelungu Group succession (Master et al., 2005). Our structural measurements show that sandstone beds dip from ~5° to 25° at the perimeter and from 50° to nearly vertical in the inner part of the structure. We were able to immediately confirm the impact origin in the field due to the presence of in-situ well-developed shatter cones in sandstone (Fig. 2). Shatter cones are the only macroscopic diagnostic evidence of hypervelocity impact (e.g., Dietz, 1960; French and Koeberl, 2010). These mesoscale to macroscale features consist of conical striated fracture surfaces forming partial to complete cones. Shatter cones occur usually below the crater floor or in the central uplifts of complex impact structures, and it is generally accepted that they form at shock pressures as low as ~2 GPa (e.g., French and Koeberl, 2010). At Luizi, they formed in arkosic sandstone and they are up to 40 cm in size. Shatter cones were mostly observed in situ and a few were also found in float samples along rivers, but no isolated fragments were observed in impact breccia units. Even though shatter cones occur at several locations within the central part of the structure, they appear to be restricted only to the inner 3.2 km of the structure. In addition, monomict lithic breccia

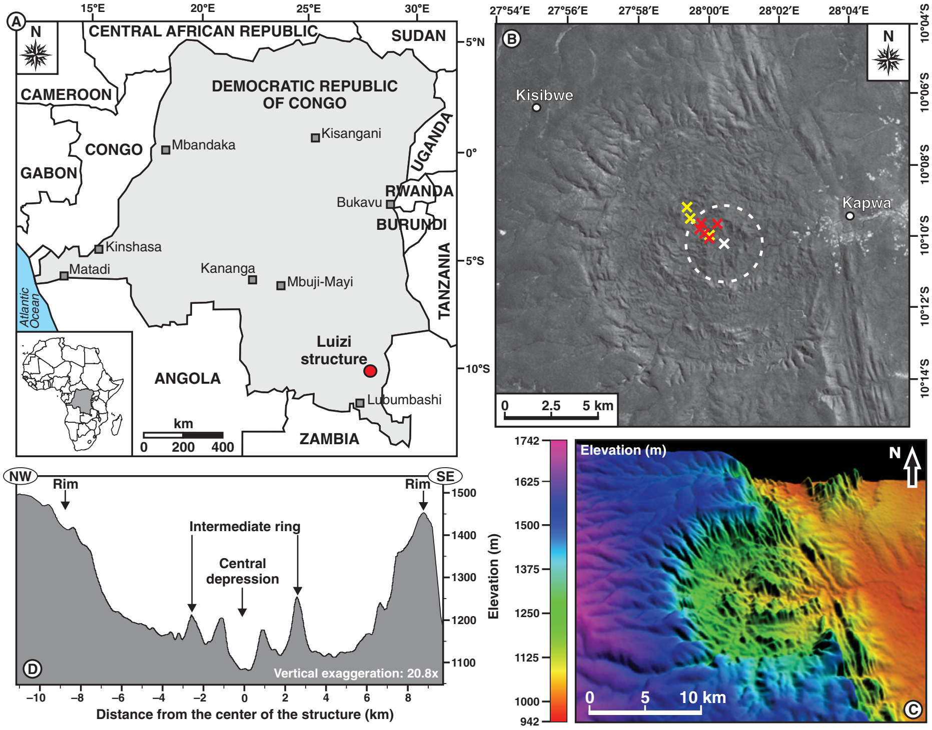

Figure 1. A: Location map of Luizi crater in southeastern part of Democratic Republic of Congo. B: Landsat image of Luizi structure with location of main shatter cone and monomict breccia dike sampled outcrops (red and yellow crosses, respectively); limit of shatter cones occurrence (dashed line) and structure center (white cross) are indicated. C: Digital elevation model (DEM) showing morphology of structure and surrounding region. D: Cross section (profile from northwest to southeast, starting at 10°05′07.56″S, 27°57′08.11″E and ending at 10°14′26.27″S, 28°03′29.05″E) of Luizi crater, based on Shuttle Radar Topography Mission (SRTM) data. Near-circular morphology of structure and large fault zone (oriented NNW-SSE) are apparent on DEM (left). Central ring and central depression are evident on the cross section extracted from DEM (right); approximate location of apparent rim is also given. SRTM data are available online (http://www2.jpl.nasa.gov/srtm/).

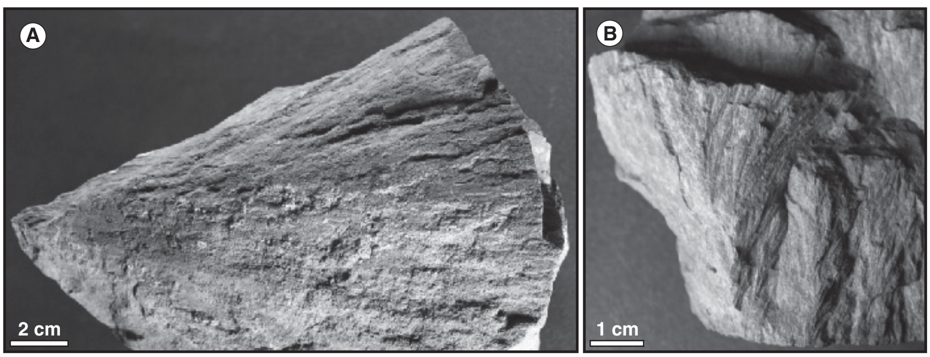

Figure 2. Photographs of shatter cones from Luizi impact structure. A: Large well-developed almost complete shatter cone in arkosic sandstone with typical striations that radiate outward from apex of cone (sample LUI10-20a; collected ~1.5 km from center of structure). B: Excellent finely detailed small cone in arkosic sandstone. Subsidiary horsetailing striations are barely visible on upper part of cone surface (sample LUI10-23; collected ~1 km from center).

dikes, up to ~2 m in thickness, and crosscutting sandstone beds, occur up to ~3 km from the center of the structure. Other monomict lithic breccia occurrences were noted locally, most probably corresponding to in situ brecciated target rocks. More or less abundant pervasive fractures were also documented at numerous outcrops, generally perpendicular to the bedding of the sandstone, and occurring up to ~6 km from the center of the structure. Considering that sandstones from outside the structure are not deformed, this fracturing must have been induced by the impact; however, no obvious trend in fracturing with distance from the center was observed.

Petrographic Investigations

The petrographic characterization of 25 samples has resulted in the detection and characterization of microscopic shock metamorphic features in minerals from shatter cone, as well as from sandstones collected within the central depression, substantiating the meteorite impact origin of the Luizi structure. No shocked grains were detected in any of the three investigated monomict lithic breccia dike samples. Shock-metamorphic effects in minerals include abundant PDFs in quartz (Fig. 3) and rare shock deformations in feldspar, notably in perthitic alkali feldspar grains, in which PDFs oblique to the perthite exsolution lamellae are noticeable. These features form upon shock compression and in nature are uniquely associated with shock metamorphism (Stöffler, 1972; French and Short, 1968; Stöffler and Langenhorst, 1994; French and Koeberl, 2010). PDFs are composed of narrow, individual planes of amorphous material that are <2 μm thick, comprising straight, parallel sets, spaced 2–10 μm apart, and oriented parallel to rational crystallographic planes (French and Short, 1968; Engelhardt and Bertsch, 1969; Stöffler and Langenhorst, 1994; French and Koeberl, 2010).

Kink banding in muscovite grains is also common in most of the studied samples, even in the ones collected several kilometers from the center; kink bands are also observed in micas from nonimpact settings, such as in tectonically deformed rocks, so they cannot be used as diagnostic criteria (e.g., French and Koeberl, 2010). Quartz grains with up to five different PDF sets were identified under the universal stage (U-stage) microscope. The decoration of many of the PDFs with fluid inclusions (Fig. 3) indicates that these originally amorphous shock features (see, e.g., Alexopoulos et al., 1988; Goltrant et al., 1991) were altered by post-impact processes. In order to estimate the peak shock pressure recorded by the target rocks cropping out in the central part of the structure (and to confirm the shock origin of the PDFs), the crystallographic orientations of 185 PDF sets in 104 quartz grains were measured in the shatter cone sample showing the highest abundance of shocked grains, using the U-stage microscope (Fig. 4; Table DR1 in the Data Repository). Because specific crystallographic orientations of PDFs are formed at different shock pressures (e.g., Hörz, 1968; Huffman and Reimold, 1996), peak shock pressure for a given sample can be estimated using the U-stage microscope. On the basis of the results, which show the dominance of PDF orientations parallel to $\omega\{10\bar{1}3\}$ and the occurrence of a few PDFs parallel to $\pi\{10\bar{1}2\}$ (Fig. 4), we can estimate that the more heavily shocked exposed target rocks have experienced peak shock pressure slightly above 20 GPa. Because no PDFs in quartz were detected in samples collected at distances >~2 km from the center of the structure, our investigations confirm the rapid attenuation of the spherical shock wave with increasing distance from the point of impact (Robertson and Grieve, 1977; Ferrière et al., 2008). Further out, shock pressures were not high enough to induce the formation of shock deformation features in rocks and minerals, and thus were probably <~1–2 GPa.

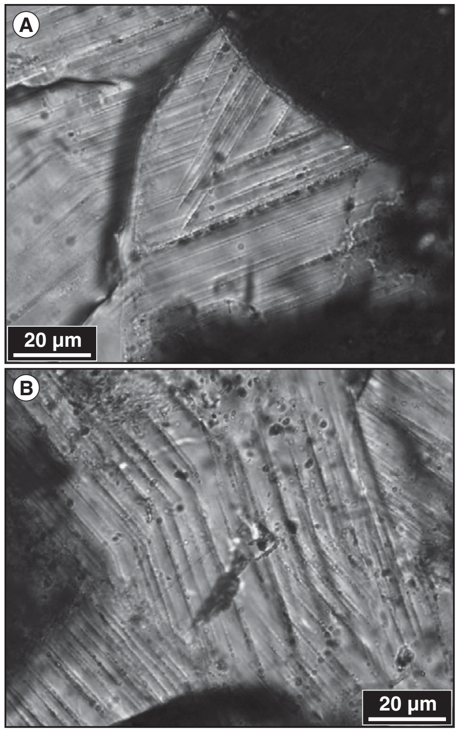

Figure 3. Thin-section photomicrographs (crossed polars) of shocked quartz grains in shatter cone sample LUI10-09-05, from Luizi impact structure. A: Small quartz grain containing two sets of planar deformation features (PDFs) with $\omega\{10\bar{1}3\}$-equivalent orientations. Relatively few, and very tiny, fluid inclusions occur along PDFs. B: Quartz grain with two sets of decorated PDFs; both PDF sets with $\omega\{10\bar{1}3\}$-equivalent orientations.

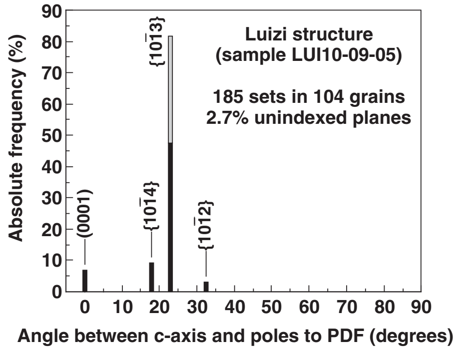

Figure 4. Crystallographic orientations of planar deformation features (PDFs) in quartz grains from shatter cone sample LUI10-09-05, collected 1 km from center of Luizi impact structure. Histogram showing absolute frequency percent of indexed PDFs versus angle between c-axis and poles of PDFs. PDF planes that fall into overlap zone between $\{10\bar{1}4\}$ and $\{10\bar{1}3\}$ crystallographic orientations are considered as $\{10\bar{1}3\}$ orientations in this figure, as suggested by Ferrière et al. (2009), but are reported in gray on top of indexed $\{10\bar{1}3\}$ orientations.

Unfortunately, no melt-bearing impact breccias, neither impact melt rock or pseudotachylitic breccias, were found, and thus none of the commonly used radiometric dating techniques can be employed to precisely constrain the formation age of the structure. Therefore, only a maximum Neoproterozoic age of ca. 573 Ma (the maximum age of sedimentation of the target rocks; Master et al., 2005) can be established for the structure.

DISCUSSION

The impact origin of the Luizi structure proposed by Dumont (1990) is confirmed by the presence of (1) shatter cones, (2) multiple sets of PDFs in quartz grains, (3) rare shocked feldspars, (4) the occurrence of monomict lithic impact breccia dikes, and (5) the morphology of the structure. Of perhaps greater interest to the community is the fact that the overall morphology of the structure appears to be relatively well preserved based on comparisons with other similar-sized impact craters (e.g., Haughton impact structure, Canada; Osinski and Spray, 2005); however, the absence of crater-filling impact breccias within the structure suggests that at least 200–300 m of material was removed by erosion.

The Luizi structure displays characteristic of complex impact craters on other planetary surfaces, i.e., an elevated structural rim, an annular depression, and a central uplifted zone. On the Moon, even though the target rocks and the scaling are quite different, central uplifts typically show a progression from central peak to peak ring basin morphology with increasing crater size. (Note also that this represents the pristine morphology with the peak or peak ring protruding through the coherent impact melt sheets that typically line these large complex craters.) The original morphology of Luizi is unclear; however, it displays several intricate structural features, i.e., an intermediate ring and an ~2-km-wide circular central ring around a central depression (Fig. 1). The occurrence of such types of intermediate inner rings is particularly rare on Earth, and they are generally interpreted, as in the case of the Haughton (Canada) and Serra da Cangalha (Brazil) structures, to represent the differentially eroded remnants of central uplifts formed in layered sequences of target rocks (Osinski and Spray, 2005; Reimold et al., 2006). We note that formation of these ring features should not be confused with the peak ring basin morphology of pristine impact craters, although the formation processes may actually be similar, as discussed in the following.

A comparison with the well-exposed and well-documented Haughton structure is particularly interesting, as Haughton has a rim diameter of 16 km (Osinski and Spray, 2005). Most notably, both Luizi and Haughton lack a central topographic peak that is characteristic of craters of this size developed in crystalline rocks on Earth and other planetary bodies (Melosh, 1989; Grieve and Therriault, 2004). Instead, both structures comprise a central ~2-km-diameter depression surrounded by a series of structural rings, which are also manifest topographically, likely due to differential erosion. Based on detailed structural mapping of Haughton, these observations were explained as being due to the partial collapse of an unstable central peak due to the sedimentary target lithologies (Osinski and Spray, 2005). Therefore, our observations at Luizi suggest that this may be a typical feature for mid-size craters developed in layered target rocks. We can thus propose that the interaction of two flow regimes, namely, the inwardly collapsing crater rim and the outwardly collapsing central peak involved in peak ring basin formation, as modeled numerically (e.g., Collins et al., 2002), is enhanced in the case of layered sedimentary rocks, as they are much less resistant to horizontal movement than crystalline rocks. This may provide an explanation to the long-standing observation (Grieve and Therriault, 2004) that mid-size complex impact craters (~15–30 km in diameter) formed in sedimentary rocks (e.g., Haughton, Ries, or Zhamanshin) do not appear to form central topographic peaks that are characteristic of craters formed in crystalline targets in the similar size range (e.g., Boltysh) and that would be predicted from observations of lunar craters. Further work is required in order to determine whether the observed topographic features at Luizi are completely structurally controlled, linked to the collapse of the central uplift and transient cavity walls, or if they are purely artifacts of differential erosion. Nonetheless, Luizi provides a new source of information for furthering our understanding on how central peaks form and collapse within sedimentary target lithologies. The discovery and confirmation of the impact origin of the Luizi structure also fills a gap in the terrestrial cratering record since impact structures of this size in sedimentary lithologies are underrepresented on Earth.

ACKNOWLEDGMENTS

This paper is dedicated to the memory of E. Grosse. The field campaign was supported by the National Geographic Society/Waitt Grants Program (grant 69-09). Ferrière was supported by the Department of Foreign Affairs and International Trade, Government of Canada. Osinski is supported by an Industrial Research Chair sponsored by the Natural Sciences and Engineering Council of Canada, MDA (MacDonald, Dettwiler and Associates Ltd.) Space Missions, the Canadian Space Agency, and the Ontario Ministry of Innovation Early Researcher Award fund. The two anonymous reviewers and W.J. Collins are thanked for their valuable comments and suggestions to improve the quality of the manuscript.

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Manuscript received 11 December 2010
Revised manuscript received 12 April 2011
Manuscript accepted 13 April 2011

Printed in USA