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Introduction

2008 TC_3: The small asteroid with an impact

The story is now familiar: On October 6, 2008, Richard Kowalski at the Catalina Sky Survey in Arizona spotted a small 3 m sized asteroid, now named 2008 TC_3. It was soon discovered that, 20 h later, this asteroid was to impact Earth. Steve Chesley of NASA/JPL calculated an impact location in the Nubian desert of northern Sudan. In the hours before impact, astronomers measured the light curve of the rare tumbling asteroid and a reflectance spectrum, describing its shape and taxonomic type. This was the first time that an asteroid was studied in space before hitting the Earth.

In the predawn hour of October 7, satellites recorded the fireball west of Station 6, putting the main −20 magnitude detonation at a high 37 km altitude. The impact happened around the time of morning prayer. Thousands along the Nile from Abu Hamed in the south to Wadi Halfa in the north watched the fireball. Some took cellphone images and video of the remaining dust cloud when it was illuminated by the rising Sun. One photo featured later as an Astronomy Picture of the Day (APOD).

And that was not the end of the story. On December 6 that year, students and staff of the Physics department and the Faculty of Science at the University of Khartoum, under the guidance of Peter Jenniskens of the SETI Institute and Muawia Shaddad of the University, searched along the approach trajectory and recovered the first meteorites, now called Almahata Sitta (meaning "Station 6"). Most finds were made south of the calculated trajectory, a topic of ongoing investigation. The recovery of fragments from a frail comet-like fireball exploding this high in the atmosphere was unprecedented. The first meteorites found, and the dominant kind recovered, turned out to be polymict (brecciate) ureilites. This was the first recorded fall of a polymict ureilite, and the first time a meteorite was recovered from a known asteroid.

One year after the fall, on December 6–7, 2009, researchers met at the University of Khartoum to discuss the analysis of the asteroid observations, the conditions during the impact, and the study of the recovered meteorites. The results are reported in this special issue of *Meteoritics & Planetary Science*.

THE IMPACT OF 2008 TC_3 ON *METEORITICS & PLANETARY SCIENCE*

And what an asteroid it was! The research presented here sheds new light on the smelting process recognized in the ureilites. The cooling rates calculated from the quenching of the smelting implied that a protoplanet broke in 10–100 m sized fragments following a giant collision. Those fragments were later ground down into the tiny pieces found in 2008 TC_3, presumably in subsequent collisions. The final fragments gathered in loosely welded together assemblages of small millimeter and sub-millimeter sized fragments, with much pore space in between. Other fragments of Almahata Sitta were compact lithologies, rich in olivine or pyroxene. In all, 2008 TC_3 contained material that represented all known oxygen isotope variation known from other ureilite finds, possibly because all originated from one original ureilite parent body protoplanet.

In those later collisions and reassemblies into daughter asteroids, some nonureilite material became mixed in. Of the recovered Almahata Sitta meteorites, 20–30% are not ureilites at all but meteorites that resemble chondrites. So far, this included meteorites akin to H5 and L4 ordinary chondrites, enstatite chondrites of types EH3, EH4/5, EH5, EH6, EL3/4, EL5/6, and EL6, and a kind of carbonaceous chondrites. The impact explosion appears to have separated nonureilite clasts from the ureilite host material. Numerous arguments are developed in the articles in this special issue that demonstrate that these nonureilites originated in 2008 TC_3 and were not present in the desert before the fall.

These are not your ordinary "ordinary" chondrites, because the centimeter-sized fragments became mixed in with the ureilites long ago. The current population of small asteroid fragments hitting Earth have cosmic ray exposure ages < 100 Myr.Hence, the current population of chondrites originated likely from other sources than the chondrites that were trapped in 2008 TC_3. Instead, those nonureilites may represent material from the impactors that decimated the original ureilite parent body fragments.

Fig. 1. Impressions from the December 5–15, 2009, "2008 TC_3 Workshop" at the University of Khartoum (Khartoum, Sudan) and the associated field expedition to the strewn field of Almahata Sitta. From top to bottom: The Local Organizing Committee with the foreign participants of the 2008 TC_3 Workshop; Local music and coffee ceremony, with Amy Morrow (Stanford University, USA) and Jacob Kuiper (Royal Dutch Meteorological Institute, the Netherlands) sampling the food, during dinner at Dean Sumaia Abu Kashawa's home. The audio-visual facilities were excellent and the workshop attracted much attention. Muawia Shaddad was presented the cover of the issue of Nature that featured the recovery report. Lunch was served in a tent erected in the courtyard of the University. Klaas Jobse (Dutch Meteor Society, the Netherlands) explained his poster to students of the University. During the workshop and field survey, we met many students and staff members, from left to right: Rua Muawia, Mohamed Salah, Deena Abdegafar, Alshfei Hashim, Rana Farouq, and Abdelrahman Abdelgadir. Three busses and five cars brought participants to Station 6 in the Nubian desert. Searching for meteorites was done in the form of coordinated grid searches. In other photos: Peter Jenniskens photographing one of the recovered meteorites in situ; Uwe Keller (Max Planck Institute for Aeronomie, Katlenburg-Lindau, Germany) and Lucy McFadden (NASA Goddard Space Flight Center, Maryland, USA) posing with their finds; and Tomas Kohout (University of Helskinki, Finland) and Jakub Haloda (Czech Geological Survey, Czech Republic) measuring magnetic susceptibility of the recovered samples shortly after their recovery. Archeological sites visited on the return journey included Jebel Barak, the Dafoofa at Kermah, and the pyramids at Nuri. Finally, upon return to Khartoum tea was served on a river boat for a relaxing cruise on the Blue Nile. Muawia Shaddad and Deena Abdelgafar of the local organizing committee. The density of meteorites was measured in the laboratory back at the Physics Department (from left to right: Ayman Kudoda, Sarah Salah, and Diyaa Numan). From photos by: Lucie McFadden, Jakub Haloda, Mark Hammergren, Casper R. ter Kuile, Peter Scheirich, Francois Colas, Fréderic Vachier, Matthew Huntley, and Peter Jenniskens.

One consequence of this collisional evolution, outlined in several articles in this issue, is that volatiles in 2008 TC_3 ended up contaminating all parts of the daughter asteroids. This is a new aspect of asteroid evolution not previously demonstrated. A most striking result of the mobility of volatiles is that the pores between mineral clasts contained vapor-deposited olivine crystals. Also, the nonureilites were contaminated by organic compounds that originated in the ureilites. The ureilites were found to have a distinct polyaromatic hydrocarbon fingerprint unlike that of carbonaceous or ordinary chondrites, and that same fingerprint was found in an H5 and an EH6 Almahata Sitta meteorite (but not in a not-so-porous EL6 chondrite). Finally, it was found that the contamination went both ways. Amino acids were detected in the ureilites, but those molecules should have been lost when organic matter was heated in the parent protoplanet to the point of turning into graphite. Possibly, those amino acids were a later form of contamination, formed from compounds in the trapped carbonaceous chondrites instead.

THE IMPACT OF 2008 TC_3 ON NEO SEARCHES

2008 TC_3 is also having an impact on the field of near-Earth object searches.While small <5 m asteroids are no danger in the big picture of the asteroid impact hazard threat, they have proven to be a valuable alternative to sample return missions in studying the material properties of the dangerous larger asteroids. It is clear now that, given sufficient warning time, these small asteroids can be studied in much detail before impact. Although it is likely that the next impact will be over the ocean, the fireball alone may provide much insight into the asteroid's elemental composition and internal structure. To increase the probability of future pre-impact discoveries of small asteroids, new observing strategies are needed.

THE IMPACT OF 2008 TC_3 ON FUTURE METEORITE RECOVERIES

We now know that material can be recovered from frail bodies, under certain circumstances, if the asteroid is large enough. We also now know that one recovered fragment may not be representative of all materials in an impacting asteroid.

The diversity of Almahata Sitta has raised a unique problem. Because Almahata Sitta contained so many different meteorite types, it is necessary to establish clear provenance to keep assured that a given meteorite did really originate from this fall. Also, the shattering of material during the explosion may have left an imprint of the original association of materials in the asteroid by association of fragments in the strewn field, making the Almahata Sitta strewn field much akin to an archeological site.

For that reason, all approximately 600 meteorites collected by the University of Khartoum research team to date are cataloged and their find locations made public in this special issue. In this way, the different materials can be studied in context.

Material from this fall was made available to the international community through a formal collaboration of the Physics (and Astronomy) Department of the University of Khartoum and the SETI Institute in California. An international consortium of interested parties, called the Almahata Sitta Consortium, was formed to coordinate the analysis of the available samples. Members of the consortium and their focus of study are given at the websitehttp://asima.seti.org/


Workshop on Asteroid 2008 TC3
(Almahata Sitta Meteorite)
nature

2008TC3/. The product of that work to date is presented in this special issue.

In addition, samples were taken from the strewn field by a party that joined in the third survey, but later operated outside of the University of Khartoum organized field surveys. A total of 40 meteorites were shipped abroad and have been sold commercially. Some of those samples are described in the works by Bischoff and Horstmann in this special issue. It is our hope that the find locations of these samples will be added to the detailed site information at some point in the future, so that the scientific record is complete. For now, we consider these samples undocumented and of uncertain provenance, with different catalog numbers being used by the meteorite dealer and the researchers. The problem of undocumented fragments is also put in sharper light by a warning that atypical weathered meteorites labeled as "Almahata Sitta" have appeared on the market.

THE ASTEROID'S IMPACT ON RESEARCH IN SUDAN

For the Physics Department of the University of Khartoum, the research of the Almahata Sitta strewn field has been very important. Four field surveys have been organized, one of which was documented by a TV6 film crew and made into a National Geographic's documentary. In total, about 150 students, staff, and guests participated in the field work. The ongoing study of the meteorites continues to offer opportunities for international collaborations and advancement of the research conducted at the Department.

In December 2009, the Department hosted the 2-day "2008 TC_3 Workshop" (see Fig. 1). We thank all participants who contributed to this special issue of *Meteoritics & Planetary Science*. The workshop was the topic of conversation in the local media on four consecutive days. All foreign participants to the workshop subsequently had an opportunity to visit Station 6 and take part in the fourth field survey. We were very pleased to learn that each participant collected at least one fragment of 2008 TC_3, further increasing the diversity of recovered materials.

Acknowledgments—We are grateful to the many communities in Sudan and abroad that made the research described in this volume possible. We thank all the local communities in Almahata Sitta and from Wadi Halfa up stream the Nile to Abu Hamad for their hospitalities, support, interest and kindness to the research teams. We also thank the University of Khartoum, the "2008 TC_3 Workshop" Local Organizing Committee, and the many student volunteers. And we express our thanks to the NASA-sponsored programs that enabled the discovery of the asteroid and facilitated the recovery.

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