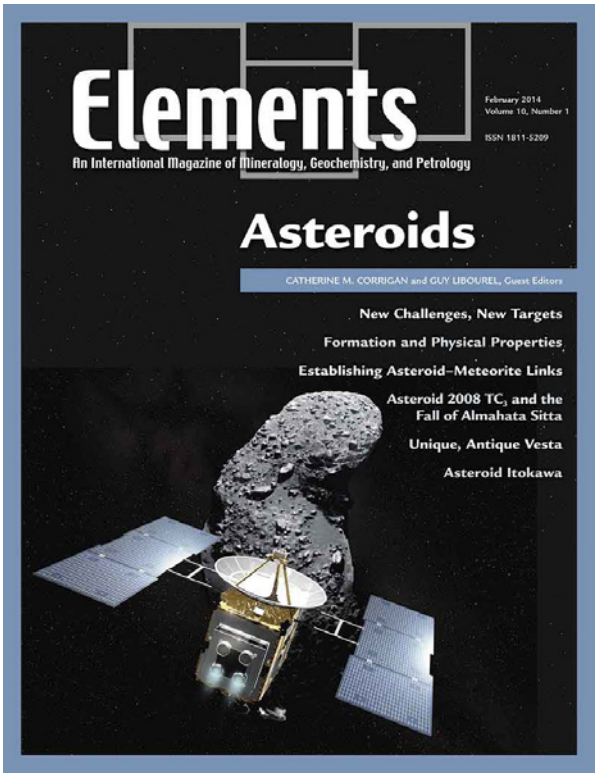
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Asteroid 2008 TC_3 and the Fall of Almahata Sitta, a Unique Meteorite Breccia

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Sample of the Almahata Sitta meteorite (UOK #1013) in the desert of northern Sudan where it was found in 2009. The sample is about 2 cm in diameter. IMAGE COURTESY OF THE FINDER, DR. PETR SCHEIRICH (ASTRONOMICAL INSTITUTE, ACADEMY OF SCIENCES, CZECH REPUBLIC)

On October 6, 2008, the small (~4 m) asteroid 2008 TC_3 was discovered and predicted to hit Earth within ~19 hours. Photometric data and a reflectance spectrum were obtained. The asteroid fragmented at ~37 km altitude above Sudan. Approximately 700 centimeter-sized fragments were recovered and constitute the meteorite Almahata Sitta. It is a unique meteorite breccia, consisting of ~50–70% ureilitic materials, plus samples of nearly every major chondrite group. The reflectance spectrum of 2008 TC_3 is closest to that of F-class asteroids, not previously associated with any meteorite type. 2008 TC_3/Almahata Sitta records a complex history of fragmentation, migration, and reaccretion of materials in the Solar System.

KEYWORDS: asteroids, meteorites, 2008 TC_3, Almahata Sitta, ureilites, reflectance spectra, chondrites

THE DISCOVERY OF ASTEROID 2008 TC_3

On October 6, 2008, the small asteroid that was subsequently named 2008 TC_3 was discovered by Richard Kowalski of the Catalina Sky Survey at Mt. Lemmon Observatory in Tucson, Arizona, USA. The discovery was reported to the Minor Planet Center in Cambridge, Massachusetts, where it was soon realized that this asteroid was on a trajectory to hit the Earth. The news spread quickly around the world, and both professional and amateur astronomers began to track and study this soon-to-be meteoroid. Steve Chesley of the Jet Propulsion Lab in Pasadena, California, calculated the asteroid's orbit and predicted that it would impact the Earth over northern Sudan about 19 hours after the time of its discovery. In the ensuing hours before impact, its orbit was determined very precisely, photometric data (measuring its brightness) were collected, and a reflectance spectrum of the asteroid was obtained.

Early in the morning on October 7, 2008, eyewitnesses along the Nile River near Wadi Halfa and at Train Station 6 in the Nubian Desert of Sudan saw the fireball that resulted when 2008 TC_3 hit the Earth's atmosphere. The US government's weather satellite Meteosat 8 first detected the bolide (a term for an especially bright fireball) at an altitude of ~65 km. A few seconds later, at ~37 km above the Earth, the atmosphere created pressures of up to 1 MPa on the rock, causing it to shatter into fragments in a series of explosions. Meteosat 8 observations in mid-infrared channels detected two dust clouds in the atmosphere (FIG. 1A) resulting from the explosions (Borovička and Charvát 2009). No significant dust deposition was observed below about 33 km, and no meteorites were expected to survive (Jenniskens et al. 2009).

THE SEARCH FOR METEORITES

Nevertheless, based on the asteroid's trajectory and predicted geographic coordinates of its impact with the atmosphere, it was possible to outline a footprint for any potential rock fragments reaching the ground (Borovička and Charvát 2009). However, initial searches for meteorites in this area were not successful. Possibly the main reason that this initial prediction of the fall area was off-target is that the asteroid shattered much higher in the atmosphere than expected based on fireballs associated with ordinary chondrites, making the predicted geographic coordinates of its impact incorrect. In December 2008, Peter Jenniskens of the SETI Institute (Mountain View, California) and Muawia Shaddad of the University of Khartoum, Sudan, teamed up to try again. Based on eyewitness accounts, dust-train observations, atmospheric factors (winds), and the new geographic coordinates of the asteroid's impact with the atmosphere, they refined the predicted fall area and led a team of 45 students and staff from the University of Khartoum on an organized search (FIG. 1B). The first meteorite was found a few hours after the search began. Three more organized search campaigns were carried out in 2008 and 2009, involving international astronomers and meteoriticists in addition to the students and staff of the University of Khartoum. More than 600 individual meteorite fragments were collected during these searches, over an area of about 7 × 30 km. Further search activities recovered additional samples, 80 of which were classified at the University of Münster (Bischoff et al. 2010a, b, 2012, 2013; Horstmann et al. 2012). All these fragments were small, ranging from ~0.2 to 400 g in mass. Collectively they are considered to be a single meteorite named Almahata Sitta, which means "Station 6" in Arabic (FIG. 1C). Almahata Sitta is the first meteorite derived from a known asteroid, that is, an asteroid that was tracked and studied by astronomical methods before it hit the Earth. In particular, it is the first meteorite observed to originate from a spectrally classified asteroid. The importance of this meteorite for linking asteroid classes with meteorite classes (see Cloutis 2014 this issue) was immediately recognized by planetary scientists.

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Figure 1 (**A**) Just before dawn on October 7, 2008, this luminous train resulting from the impact of asteroid 2008 TC_3 with Earth's atmosphere was visible over the Nubian Desert of northern Sudan. Photo by Mohamed Elhassan Abdelatif Mahir (Noub NGO), courtesy of Dr. Muawia H. Shaddad (University of Karthoum) and Dr. Peter Jenniskens (SETI/NASA Ames). (**B**) Students and staff of the University of Khartoum, under the leadership of Dr. Muawia Shaddad and Dr. Peter Jenniskens, search the Nubian Desert of northern Sudan in December 2008 for meteorites derived from the impact of asteroid 2008 TC_3. The Nubian Desert has rocky plains interspersed with hills, rocky outcrops, and sandy river valleys. The terrain demanded a foot search at relatively close distance between the searchers. (**C**) The meteorite Almahata Sitta was named after Train Station 6 (*Almahata Sitta*, in Arabic) along the railroad between Wadi Halfa and Abu Hamad in northern Sudan. Images B and C courtesy of Dr. Peter Jenniskens

ALMAHATA SITTA: THE SAMPLES

Based on their physical, chemical, and mineralogical properties, the samples collected from the Almahata Sitta meteorite strewn field are remarkably heterogeneous (Fig. 2). The first sample studied petrologically and chemically (sample #7, which had a mass of 1.5 grams) was identified as a ureilite (see Box 1) on the basis of its oxygen isotopes (Fig. 3) and carbon-rich composition, as well as several other distinguishing mineral and bulk-chemical features (Jenniskens et al. 2009). It was also recognized to be a polymict ureilite (a relatively rare type) because it consisted of welded-together clasts of a variety of ureilite types. In addition, it was atypical even for a polymict ureilite because it was unusually porous. About 10–25% of this sample consists of pores (Fig. 2a) lined with euhedral to subhedral crystals of olivine that may have been deposited from vapors (Jenniskens et al. 2009; Zolensky et al. 2010). This feature had not previously been seen in a ureilite. On the basis of studies of this one sample, Almahata Sitta was classified as an anomalous polymict ureilite (Jenniskens et al. 2009).

As additional samples of Almahata Sitta were studied, it became apparent that many of the pieces of rock collected from this meteorite were not like sample #7, but rather were fragments of typical main-group ureilites with different mineral and oxygen isotope compositions (Bischoff et al. 2010b; Rumble et al. 2010; Zolensky et al. 2010). In addition, the Almahata Sitta samples included a variety of chondritic lithologies (Bischoff et al. 2010a, b, 2012; Zolensky et al. 2010; Horstmann et al. 2010, 2012; Rumble et al. 2010; Kohout et al. 2010). These samples were identified as chondrites on the basis of their mineralogy and oxygen isotope compositions (Fig. 3), which are quite distinct from those of ureilites. The first analyses of short-lived cosmogenic radionuclides of two of these chondritic samples demonstrated that they were part of the Almahata Sitta meteorite shower (Bischoff et al. 2010a). Based on analysis of the magnetic susceptibility of 60 samples from the strewn field, Kohout et al. (2010) estimated that half of their studied samples could be non-ureilitic. Thirty chondrites (~40%) were found among the 80 samples examined at the University of Münster (Bischoff et al. 2010a, b; Horstmann et al. 2010, 2012). In addition,

Box 1

Chondrites and Achondrites – Meteorites are divided into two major categories based on their bulk-chemical compositions and textures: differentiated and undifferentiated. Chondrites, which constitute more than 80% of the current meteorite flux, are undifferentiated. They have bulk compositions that closely match the composition of the Sun, with the exception of a few highly volatile elements. They are interpreted to represent the most primitive Solar System materials available. Achondrites are silicate-rich (in contrast to iron and stony-iron meteorites) differentiated meteorites. They are rocks that experienced igneous processing on their parent asteroids. Unlike chondrites, some achondrites resemble terrestrial igneous rock types.

Ureilites – These are the second-largest group of achondrites (Mittlefehldt et al. 1998). They are coarse-grained ultramafic rocks, consisting mainly of the minerals olivine and pyroxene, and are thought to represent the residual mantle of a partially melted asteroid. One of the distinguishing characteristics of ureilites is their high abundance of carbon. The carbon is mostly in the form of graphite, but diamonds occur as well. Ureilites are also characterized by their oxygen isotope compositions, which set them apart from any other group of achondrites. Mineral and oxygen isotope compositions are very homogeneous within each ureilite, but vary greatly among samples. Ureilites are divided into different types, or lithologies, based on these differences. About 5% of known ureilites are polymict breccias, thought to be samples of regolith formed on a ureilitic asteroid (Goodrich et al. 2004).

Breccias – A breccia is a rock consisting of fragments derived from an earlier generation of rock(s) and consolidated into a new clastic rock, typically (in the case of meteoritic breccias) by shock metamorphism. The most common types of meteorite breccias include monomict, polymict, and regolith breccias (Bischoff et al. 2006). In **monomict** breccias, both matrix and clasts are derived from the same primary rock type, whereas in **polymict** breccias, lithified fragments of various types, origins, and/or compositions coexist. **Regolith** breccias derive from the upper surface of a parent body (and therefore contain solar wind–implanted gases).

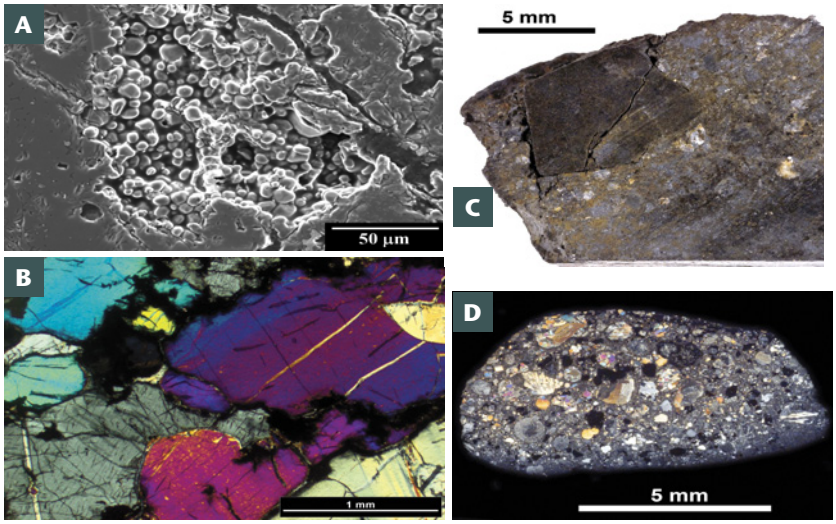


Figure 2 Variety of lithologies among samples of the Almahata Sitta meteorite. (**A**) Scanning electron microscope image of a porous area of ureilitic sample #7. The pores contain crystals of FeO-rich olivine and pyroxene, along with metal spherules and botryoidal troilite. Courtesy of Mike Zolensky (NASA JSC). (**B**) Light microscope (crossed polars) image of coarse-grained, pyroxene-rich sample MS-MU-005, which resembles many main-group ureilites. (**C**) Cut surface of the EL chondritic breccia MS-179, which contains different types of EL chondrite lithologies embedded in a fine-grained matrix of EL chondritic material. (**D**) Unique sample MS-CH (Horstmann et al. 2010), which is similar to R chondrites but with unusual properties.

based on hand-specimen properties, Shaddad et al. (2010) estimated that about 20–30% by mass of the samples in the University of Khartoum collection are non-ureilitic. Never before had pieces of several different meteorite types been collected from the same fall. Approximately 100 samples have so far been classified on the basis of mineralogical, chemical, and oxygen isotope properties. However, since this represents only ~15% of all samples collected, there is no guarantee that the studied samples give a representative picture. It is possible that additional new lithologies will be found among the petrologically unstudied samples.

Based on the main data sets currently available (Zolensky et al. 2010; Bischoff et al. 2010b; Horstmann et al. 2012), the most abundant Almahata Sitta samples are compact (dense, not porous), main-group ureilitic lithologies with various olivine/pyroxene ratios, mineral compositions, and grain sizes (Fig. 2B). Coarse-grained (up to several millimeters), olivine-rich ureilitic fragments are dominant. There are also many coarse-grained, pyroxene-rich ureilitic fragments, typically with grain sizes significantly less than 1 mm (Fig. 2B). The second most abundant lithology can be described as a fine-grained, porous ureilitic type, mainly composed of 10–30 µm sized olivine and pyroxene grains in a granoblastic mosaic texture, with abundant opaque phases, such as metal, sulfides, and carbon polymorphs. This texture is similar to what is seen in some shock-melted main-group ureilites (e.g. Warren and Rubin 2010). These fine-grained fragments are often quite dark or have dark areas due to the high abundances of metals, sulfides, and carbon phases. The grain sizes of olivine and pyroxene are not always homogeneous throughout these fragments; some (such as sample #7) contain areas with larger crystal sizes. Surprisingly, in some Almahata Sitta samples, sulfide and metal are the dominant constituents, which is not the case in any previously known ureilite. These samples have been described as "metal-sulfide assemblages with enclosed ureilitic portions" (Bischoff et al. 2010b), indicating their affinity to the ureilitic lithologies. One sample with ureilitic oxygen isotope characteristics is an andesite, possibly derived from the crust of the ureilite parent body (Bischoff et al. 2013). So far, no achondritic lithologies other than ureilites have been found among Almahata Sitta samples.

Among the chondritic Almahata Sitta samples, enstatite (E) chondrites are the most abundant (see Box 2). They are similar in overall abundance to the fine-grained, porous ureilites. Samples of both E chondrite subgroups (EL and EH) have been encountered, with the EL subgroup being dominant. For both subgroups, individual samples of various petrologic types (e.g. EL3, EL4, EL5, EL6) occur, and these are indistinguishable from previously known E chondrites. Some of the E chondrites are heavily brecciated and shock-darkened, and may contain shock(?)-melted metal–enstatite assemblages. The complex EL chondritic breccia MS-179 (Fig. 2C) contains clasts of different types of EL chondritic lithologies (EL3–5) embedded in a fine-grained, clastic matrix that is only loosely cemented (Horstmann et al. 2012).

Box 2 Chondrites

There are 4 major chondrite classes defined on the basis of mineralogical, textural, and isotopic properties. **Ordinary chondrites** are the most abundant group and are subdivided based on their Fe concentration and metal abundance into three subgroups (H = high-iron; L = low-iron; LL = low-Fe, low-metal). **Enstatite (E) chondrites** contain minerals that formed under highly reducing conditions (e.g. Si-bearing metals, graphite, sinoite [Si_2N_2O], enstatite with very low FeO). Based on their bulk-compositional Fe/Si ratios, they are subdivided into the EL (low-Fe) and EH (high-Fe) subgroups. **Carbonaceous chondrites** are subdivided into 8 major subgroups (CI, CM, CO, CV, CK, CR, CH, CB) based on their mineralogy, texture, and chemical/isotopic composition. Typically, they have higher abundances of fine-grained matrix than the other chondrite groups, leading to a darker appearance in hand specimen and thin section. **Rumuruti (R) chondrites** are olivine-rich rocks (commonly breccias) with distinct oxygen isotope compositions. Their olivine has mostly high FeO contents ($Fa_{38\text{-}40}$), indicating formation under highly oxidizing conditions.

Petrologic Type – Although chondrites and their constituents are considered to be "relatively pristine" Solar System materials, their parent bodies have experienced some secondary processes, such as hydrothermal alteration and metamorphism. Annealing has modified different components of chondrites to different degrees. This effect is described by the petrologic types 3–6: Type 6 chondrites have undergone a high degree of thermal metamorphism, whereas type 3 chondrites show no or only minor modification. If pristine Solar System material reacted with water, distinct minerals may have formed (e.g. phyllosilicates, magnetite, carbonates). The degree of aqueous alteration is defined by petrologic types 1 and 2, with the type 1 chondrites showing the highest degree of aqueous alteration.

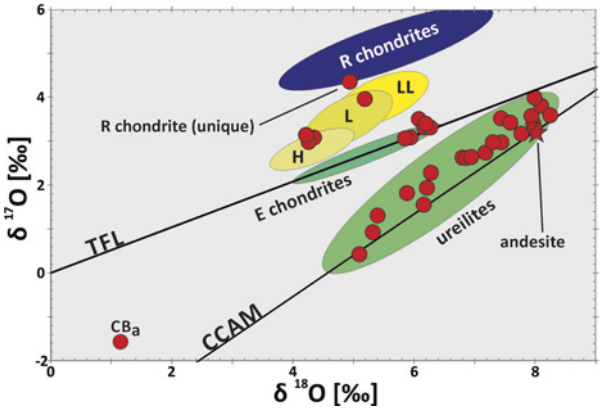


Figure 3 Oxygen isotope compositions of 34 Almahata Sitta samples (red symbols) compared with the compositional fields of ureilites, E chondrites, ordinary chondrites (H, L, LL), and R chondrites. Data are from Jenniskens et al. (2009), Bischoff et al. (2010b, 2012, 2013), Rumble et al. (2010), and Horstmann et al. (2010, 2012). In cases of multiple analyses from one sample, the average was calculated. CCAM = carbonaceous chondrite anhydrous mineral mixing line. TFL = terrestrial fractionation line; all Earth rocks plot on this line.

Samples of other chondrite types (ordinary, carbonaceous, and R chondrite–like) also occur among the Almahata Sitta samples but are less abundant than E chondrites. So far, several L- and H-group ordinary chondrites have been analyzed, as well as one CB_a carbonaceous and one Rumuruti (R)–like chondrite (e.g. Bischoff et al. 2010a, b, 2012; Zolensky et al. 2010; Horstmann et al. 2010, 2012). The juxtaposition of all these different chondrite types within a single asteroid is remarkable, because they represent a large range of chemical and oxygen isotope (Fig. 3) environments in the early Solar System. While the components of the enstatite chondrites and the metal-rich CB chondrites formed under reducing conditions, the opposite is the case for the R chondrites. These chondrites are characterized by a lack of metal and high FeO concentrations in their silicates, indicating formation under oxidizing conditions. The Almahata Sitta R-like chondrite sample (Fig. 2d) is unique. It shows many characteristics typical of R chondrites but has higher abundances of metal compared with typical R chondrites (Bischoff et al. 2011).

THE STRUCTURE OF 2008 TC_3

What held all these different pieces of rock together in the asteroid 2008 TC_3? To understand this, we need to know the density of the asteroid compared to the densities of the collected samples, which requires that we first know its pre-atmospheric size. Based on observations of the brightness of 2008 TC_3 prior to its entry into the atmosphere (Fig. 4), combined with the measured albedo (a measure of the reflectivity of the surface of a body) of other known F-class asteroids (see next section), a pre-atmospheric volume of approximately 25 ± 10 m^3 was estimated (Scheirich et al. 2010). This corresponds to a mean radius of 1.8 ± 0.2 m, although substantial brightness variations were observed, indicating that the body was quite elongated.

The density of the asteroid can then be determined by combining its size with measured abundances of the cosmogenic nuclides ^{10}Be, ^{26}Al, and ^{36}Cl in the meteorite samples. Cosmogenic nuclides are isotopes of certain elements that are produced on the surface and near-surface of rocky bodies by interaction of cosmic rays with atoms in the rock. The concentrations of cosmogenic nuclides in rocks from a small asteroid are dependent on both the depth in the asteroid and the density of the overlying material through which the cosmic rays had to pass. Using this technique, Welten et al. (2010) determined the average density of asteroid 2008 TC_3 to be approximately 1.7 g cm^{-3}. This density is much lower than the densities of many of the Almahata Sitta meteorite samples. For example, the compact, main-group ureilite samples have densities of 3.0–3.3 g cm^{-3} (Welten et al. 2010; Shaddad et al. 2010). Therefore, the asteroid on the whole must have had an average porosity of ~50%. Such high porosity suggests that the asteroid was very weak (low tensile strength), which would explain why it exploded at such a high altitude in the atmosphere (Borovička and Charvát 2009). In other words, 2008 TC_3 was far from being a solid rock. Instead, it consisted mostly of fine-grained, highly porous matrix material, weakly cementing a small fraction of isolated, centimeter-sized fragments of denser rocks that became the fallen meteorites.

These data also tell us that the vast majority of the material in 2008 TC_3 was lost, probably as fine dust dispersed in the Earth's atmosphere. Assuming that the asteroid was a sphere 1.8 m in radius, with an average density of 1.7 g cm^{-3}, it would have had a total mass of ~41 tons. For comparison, the total mass of fallen material was estimated to be ~39 ± 6 kg, based on the areal density of recovered meteorite mass (Shaddad et al. 2010). This implies that ~99% of the asteroid's mass was not recovered. Most of this material was probably the fine-grained matrix material in which the more coherent rock fragments were embedded. What did this lost material consist of? We turn to the reflectance spectrum of 2008 TC_3 to address this question.

THE REFLECTANCE SPECTRUM OF 2008 TC_3 AND ASTEROID–METEORITE CONNECTIONS

The reflectance spectrum of 2008 TC_3 (Fig. 5) is most closely matched by the spectra of F-class asteroids (Jenniskens et al. 2009) in the Tholen asteroid taxonomy (Tholen and Barucci 1989). F-class asteroids are rare, comprising only about 1% of all bodies in the main asteroid belt. Along with the C, B, and G classes, they fall in the broader C group of asteroids, which are thought to be related to carbonaceous chondrites. F-class asteroids are similar in spectrum to B-class asteroids such as 1999 RQ36, the target of the OSIRIS-REx mission. The two are not always easy to distinguish from one another, but often appear as distinct groups in photometric color plots (i.e. plots of U-B vs. B-V, where U, B, and V are the brightnesses in different filters). Until the discovery and impact of 2008 TC_3, F-type asteroids were not suggested as the source of any known meteorite types. Thus, it was particularly surprising when the first sample of the Almahata Sitta meteorite turned out to be a ureilite, since ureilites had previously been suggested to come from S-type asteroids (Gaffey et al. 1993). However, considering the great lithological diversity and the loosely consolidated structure of the asteroid, the meaning of the asteroid's reflectance spectrum must be considered carefully. It seems clear that this spectrum does not represent a single, coherent rock, and it may be very different from the reflectance spectrum of the original ureilite parent body.

The reflectance spectrum of 2008 TC_3 can be compared to laboratory-obtained spectra of Almahata Sitta rock samples in the same spectral range in order to shed light on what the asteroid spectrum represents. One such study was carried out on rock chips and powders of 11 Almahata Sitta samples, of which 10 were ureilitic and one was an ordinary chondrite (Hiroi et al. 2010). The spectra of the ureilite samples were consistent with those of previously studied ureilites (Cloutis et al. 2010), with low reflectance due to high carbon and metal contents

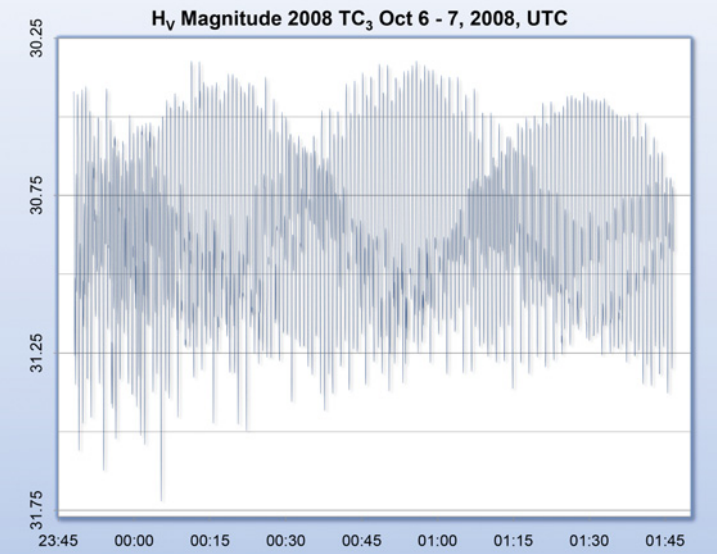


Figure 4 Filtered light curve (absolute magnitude on y-axis) of the Earth-impacting asteroid 2008 TC_3 over a period of about 2 hours on October 6 and 7, 2008 (time UTC on the x-axis). The asteroid was imaged using the 25", f/9.6 telescope at the Clay Center Observatory in Brookline, Massachusetts (Kozubal et al. 2011). The light curve allowed the size and shape of the asteroid to be determined. Figure courtesy of Marek Kozubal (Clay Center Observatory)

and spectral features indicating various olivine/pyroxene ratios. The spectrum obtained for the ordinary chondrite sample was distinct from the spectra of the ureilites and similar to those of H chondrites. Various combinations of these sample spectra were then compared to the spectrum of the asteroid. This comparison indicated that mixtures dominated by ureilite rock chips could reproduce the main features of the asteroid spectrum, namely, the relatively flat visible-light spectrum and the weak near-ultraviolet and 1 µm band absorptions (Fig. 5). This is consistent with ureilitic material dominating the surface of the asteroid, but seems to suggest that little of this material was in the form of fine-grained regolith (Hiroi et al. 2010). The latter is surprising, given the inference that the asteroid consisted of ~99% fine-grained material. On the other hand, only a few combinations of Almahata Sitta sample spectra have been examined, and these include only two of the many different meteorite types that are present. The degree to which these other types—in particular, the E chondrites, which constitute a significant fraction of the collection—are reflected in the asteroid spectrum is unknown. Thus, it is not yet possible to draw any firm conclusions about the nature of the ~99% of unsampled material in 2008 TC_3.

Comparing the spectrum of 2008 TC_3 and Almahata Sitta samples with that of main belt asteroids suggests the Nysa-Polana asteroid family as a possible source of 2008 TC_3 (Jenniskens et al. 2010; Gayon-Markt et al. 2012). This family is located at low inclination next to the 3:1 resonance with Jupiter, a powerful route for delivering material to near-Earth space. Furthermore, it is a complex family, consisting of various subgroups and asteroids of different spectral types. The Polana group is primarily F-class, the asteroid Nysa itself is E-type, and most of the rest of the Nysa group is S-type (these S-types are sometimes referred to as the Mildred family). This diversity of material in a small dynamical region may be tied to the origin of 2008 TC_3 and Almahata Sitta. The discovery of Almahata Sitta has raised the possiblity that some asteroid spectral types do not correspond to single meteorite types, but rather to complex mixtures of types.

THE IMPACT OF ASTEROID 2008 TC_3 AND THE ALMAHATA SITTA METEORITE

The advent of asteroid 2008 TC_3 was a remarkable event, for many reasons. It demonstrated how effectively scientists around the world can work together to track Earth-approaching asteroids and how quickly they can mobilize resources to study unpredictable arrivals. It led to the rapid deployment of an international team that recovered over 600 fragments of the freshly fallen meteorite. It provided the first "data point" definitely linking an asteroid spectral type with a meteorite type. And it brought us an extraordinary new type of meteorite.

Ureilites are an enigmatic group of achondrites (Mittlefehldt et al. 1998). For this reason, new ureilites bringing potentially new information about their petrogenesis are always welcome. Fresh falls are particularly valuable because the metallic minerals in ureilites are susceptible to terrestrial weathering and can lose the information they hold about their extraterrestrial formation in a very short time on the Earth's surface. The early realization that Almahata Sitta was polymict made it even more important because polymict ureilites can contain rock types from the ureilite parent body that are not represented as individual meteorites in the world's collections. However, compared to previously known polymict ureilites (Goodrich et al. 2004; Downes et al. 2008), Almahata Sitta probably has a much higher ratio of matrix to clasts, is much less coherent, and has a higher proportion of highly shocked material. Furthermore, Almahata Sitta has a much larger component of non-ureilitic material (at least among the clasts), possibly as much as 50%, compared with <1% in previous polymict ureilites. Perhaps Almahata Sitta should not even be classified as a ureilite, but rather as a unique meteoritic breccia.

The closest analog to Almahata Sitta among previously known meteorites is the complex breccia Kaidun (Zolensky and Ivanov 2003). Unlike Almahata Sitta, Kaidun fell (in 1980) as a single, coherent chunk of rock, weighing ~1 kg,

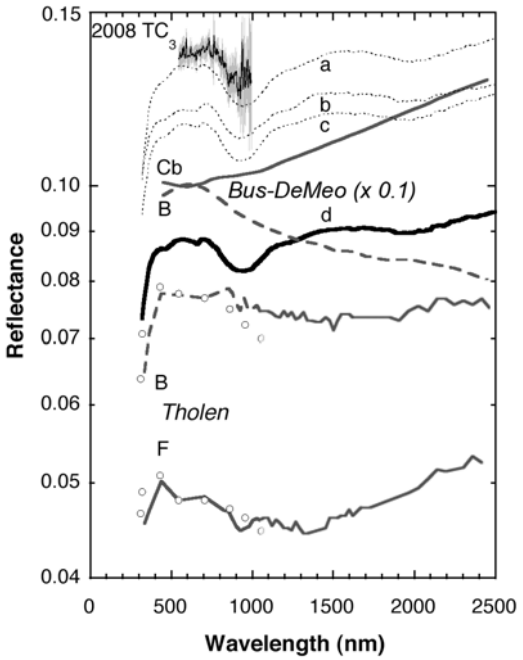


Figure 5 Comparison of the measured reflectance spectrum of 2008 TC_3 (top) with the laboratory reflectance measurements of various combinations of Almahata Sitta samples (lines a-d), spectra of the Bus-Demeo B and Cb asteroid taxonomic classes, and the Tholen B and F classes. Spectra are scaled vertically for easier comparison. Figure modified from Jenniskens et al. (2010)

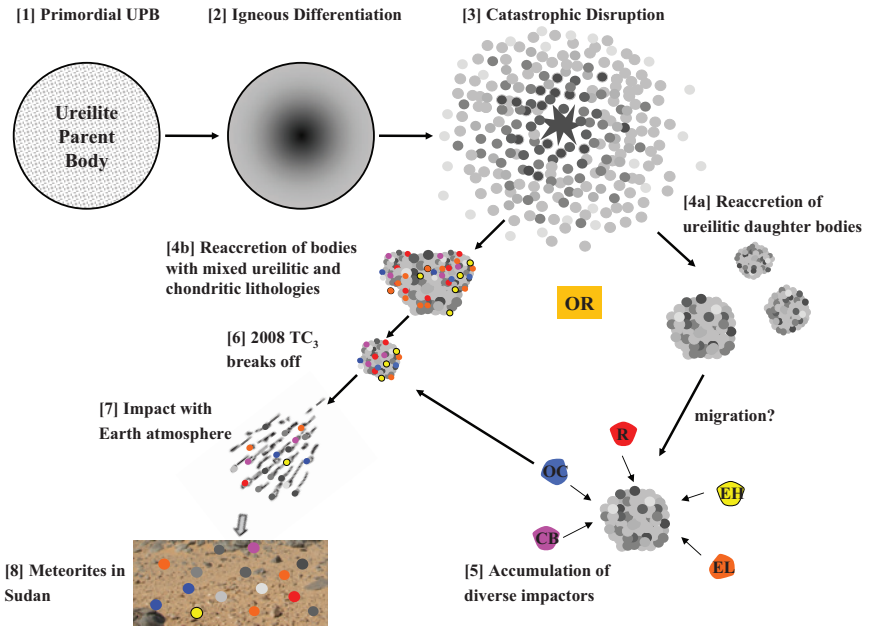


Figure 6 Cartoon showing an evolutionary sequence for ureilitic material and 2008 TC_3/Almahata Sitta, as hypothesized by several groups of researchers (Bischoff et al. 2010b; Herrin et al. 2010; Jenniskens et al. 2010; Hartmann et al. 2011). [1] The ureilite parent body (UPB) accretes within a few million years of formation of the Solar System. Alternatively (not shown), there may have been more than one UPB. The location of accretion (outer asteroid belt? inner asteroid belt? terrestrial planet region?) is not known. [2] The UPB is heated internally to ~1300 °C and is partially melted and differentiated. The resulting compositional structure of the UPB is poorly known. [3] A major impact disrupts the UPB, possibly shattering it completely into fragments. [4a] Subsamples of those fragments reaccrete within a few days to form second-generation (daughter) bodies, followed by [5] migration of one daughter to a new location where a variety of chondritic debris accretes to it. OR [4b] Ureilitic debris reaccrete along with fragments of various chondritic lithologies to form a second-generation mixed body. [6] In recent times, a piece of the resulting polymict asteroid breaks off and becomes asteroid 2008 TC_3. [7] 2008 TC_3 intersects Earth's orbit, impacts with its atmosphere, and shatters into small fragments. [8] The largest of these fragments land on the Earth's surface and are collected as pieces of the meteorite Almahata Sitta. For the meaning of the abbreviations in [5], see Box 2.

but it fell into pieces upon initial transport, demonstrating that it was also a very weak rock. Like Almahata Sitta, Kaidun is a breccia that contains an extraordinary mix of meteorite types. It consists of millimeter-sized clasts, weakly cemented together by only a very small fraction of fine-grained matrix material. The clasts comprise a large variety of carbonaceous and enstatite chondrite types—including some that are unknown as individual meteorites—plus unique achondritic lithologies, a variety of impact-melt products, and many other materials that have not yet been characterized (Zolensky and Ivanov 2003). Although it is common for meteorites to contain "xenoliths"—foreign clasts of meteorite types different from their host—such clasts are usually volumetrically minor (Bischoff et al. 2006). Kaidun appears to represent the opposite extreme, a breccia comprised of so many different meteorite types that it cannot be classified as any one type. Almahata Sitta may be an intermediate example, a breccia still dominated by one main type (ureilite) but containing 20–50% of "foreign" materials.

It appears that asteroid 2008 TC_3 (or its immediate parent) accumulated materials that formed in a wide range of chemical and physical environments in the solar nebula, probably implying a wide range of helicocentric distances as well. As such, it records a complex history of fragmentation, migration, and reaccretion of materials (Fig. 6). A major fragmentation event in ureilite history is not a new idea. All ureilites show mineralogical/petrologic evidence of very rapid cooling (on the order of 10–50 °C/h), accompanied by a sudden drop in pressure (Mittlefehldt et al. 1998). This is interpreted as resulting from excavation by a large impact while the ureilite parent body was still hot, possibly as early as 5–10 million years after the formation of the Solar System. Various lines of evidence suggest that this event involved complete fragmentation of the parent body, followed by gravitational reaccumulation of portions of the fragmented materials to form a family of offspring. It has been postulated that one of these offspring (called a daughter body) became the source of all ureilitic material that was delivered to Earth in modern times (Goodrich et al. 2004; Downes et al. 2008). Almahata Sitta may provide information on the intermediate stages of this history. Several groups of researchers (Bischoff et al. 2010a, b; Herrin et al. 2010; Jenniskens et al. 2010; Hartmann et al. 2011) have hypothesized that a ureilitic daughter body accumulated material from diverse chondritic impactors to become the parent asteroid of 2008 TC_3 (Fig. 6). Where and how the various stages of this evolutionary scenario occurred, and the details of the many processes involved, are actively being explored and will probably be debated for some time to come.

CONCLUDING REMARKS

The discovery of 2008 TC_3 and the fall of Almahata Sitta have given us a unique opportunity to link astronomical observations of an asteroid to fragments of that asteroid (i.e. meteorites) collected on the ground. Thus, it has provided an important data point for mapping asteroid–meteorite connections. However, the connection is not always straightforward. Asteroid 2008 TC_3/Almahata Sitta has heightened our awareness that many near-Earth asteroids could be loosely consolidated breccias on a whole-body scale, and could even be polylithologic (Herrin et al. 2010; Popova et al. 2011). It has also led to speculation that polygenetic objects could be a common vehicle for simultaneous delivery of meteorites of different types to Earth (Herrin et al. 2010; Popova et al. 2011). Perhaps the complex sequence of events that resulted in Almahata Sitta (e.g. Fig. 6) is not commonplace. However, even if that is the case, it is often the anomalies that provide the most useful information, and further studies to understand the history of this unique meteorite will reveal important new clues to Solar System processes.

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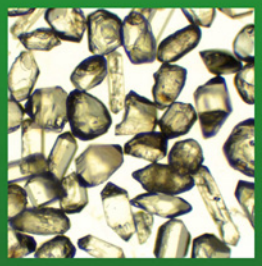
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