Inhomogeneity of asteroid 2008 TC_3 (Almahata Sitta meteorites) revealed through magnetic susceptibility measurements

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Abstract

Magnetic susceptibility measurements were performed on freshly fallen Almahata Sitta meteorites. Most recovered samples are polymict ureilites. Those found in the first four months since impact, before the meteorites were exposed to rain, have a magnetic susceptibility in the narrow range of 4.92 ± 0.08 log 10^{-9} Am^2/kg close to the range of other ureilite falls 4.95 ± 0.14 log 10^{-9} Am^2/kg reported by Rochette et al. (2009). The Almahata Sitta samples collected one year after the fall have similar values (4.90 ± 0.06 log 10^{-9} Am^2/kg), revealing that the effect of one-year of terrestrial weathering was not severe yet. However, our reported values are higher than derived from polymict (brecciated) ureilites 4.38 ± 0.47 log 10^{-9} Am^2/kg (Rochette et al. 2009) containing both falls and finds confirming that these are significantly weathered. Additionally other fresh-looking meteorites of non-ureilitic compositions were collected in the Almahata Sitta strewn field. Magnetic susceptibility measurements proved to be a convenient non-destructive method for identifying non-ureilitic meteorites among those collected in the Almahata Sitta strewn field, even among fully crusted. Three such meteorites, no. 16, 25, and 41, were analyzed and their composition determined as EH6, H5 and EL6 respectively (Zolensky et al., 2010). A high scatter of magnetic susceptibility values among small (< 5 g) samples revealed high inhomogeneity within the 2008 TC_3 material at scales below 1-2 cm.

Keywords

Ureilite, Almahata Sitta, 2008 TC_3, magnetic susceptibility

1. Introduction

On October 6, 2008 a small asteroid called 2008 TC_3 was discovered in space 20 hours prior to impact on Earth (Jenniskens et al. 2009). This was the first Near Earth Asteroid (NEA) that was detected in space before it impacted Earth. The close approach made it bright enough for spectroscopic and lightcurve studies. With 8 hours of warning, the impact point was calculated over northern Sudan in the Nubian Desert.

On December 6-8, 2008, a search expedition led by Dr. Muawia Shaddad of the Physics and Astronomy Department, Faculty of Sciences, University of Khartoum and Dr. Peter Jenniskens of the SETI Institute and NASA Ames Research Center in California was conducted along the projected ground path of the asteroid. In four searches, the expedition recovered over 600 fragments of asteroid 2008 TC_3. The meteorites were named "Almahata Sitta", meaning "The Station 6" in Arabic after a nearby inhabited outpost and the base camp of the expeditions (Jenniskens et al. 2009; Shaddad et al. 2010).

Two aspects of this fall encouraged us to apply magnetic susceptibility measurements to the recovered meteorites. Firstly, it was clear already during the first search that there was a wide variety of materials present among the collected meteorites. Some meteorites where black and scruffy (flaky) looking, while others where light gray and finely grained. Most black and scruffy looking meteorites were since identified as polymict ureilites (Jenniskens et al., 2009). Other meteorites turned out to be of a different type altogether.

Secondly, this was the first time that freshly fallen polymict ureilites were available for study. The Nubian Desert is a dry desert area where any fallen meteorites would be expected to experience very modest terrestrial weathering until the summer rains the next year. Indeed, samples were available from both before and after the summer rains.

Magnetic susceptibility of meteorites have proven useful in rapid scanning of meteorite collections for preliminary classification purposes or identification of mislabeled samples (Kukkonen et al., 1983; Pesonen et al., 1993; Terho et al., 1993; Rochette et al., 2003, 2008, 2009; Kohout et al., 2008). Particularly the meteorite susceptibility review series by Rochette et al. (2009) merges previously published data with new unpublished entries and thus serves as a valuable complex meteorite susceptibility database. Magnetic susceptibility measurements have also proven to be useful during meteorite identification and recovery in the field, due to the fast and easy operation of simple, reliable, and portable instruments (Gattacceca et al., 2004; Folco et al., 2006; Kohout et al., 2008).

In this paper, we studied nature of the Almahata Sitta meteorites through measurements of their magnetic susceptibility and comparison of the results to a meteorite susceptibility database of different meteorite types, incorporating published data by Kukkonen et al. (1983), Pesonen et al. (1993), Terho et al (1993), Rochette et al. (2003, 2008, 2009), Smith et al. (2006), Kohout et al. (2008), and Kohout (2009). First, we selected fresh Almahata Sitta ureilites and calculated their susceptibility mean. We subsequently used this information to test the homogeneity of the Almahata Sitta collection and to distinguish among ureilitic and non-ureilitic lithologies.

2. Instruments and methods

The Almahata Sitta meteorites represent valuable and rare material, discouraging the exchange of large numbers of samples between laboratories. On December 3-15, 2009, during the 2008 TC_3 Workshop at the Department of Physics and Astronomy of the University of Khartoum physical properties of the Almahata Sitta meteorites were measured by non-destructive methods using a mobile laboratory instrumentation of the Department of Physics, University of Helsinki, described in Kohout et al. (2008) and Kohout (2009).

During this exploratory study, measurements focused mainly on magnetic susceptibility and its amplitude and frequency dependence. The samples smaller than 2.5 cm were measured using ZHinstruments SM-100 susceptibility meter operating at 0.5-8 kHz frequency and 10-320 A/m RMS field amplitude. Frequency of 1 kHz and field amplitude of 320 A/m was used for routine measurements. Three samples were tested for frequency and field amplitude dependence using the same instrument. The frequency and field ranges were cross-calibrated using a ferrite standard prior to the measurements. For larger samples, a Hämäläinen TH-1 portable susceptibility meter with large (12 cm) coil was used.

The susceptibility was normalized by mass which was determined using a digital OHAUS Navigator balance with 0.1 g resolution. The balance was always calibrated prior to the measurement using internal calibration mass standards. The smaller masses (< 3 g) were re-measured with a University of Khartoum analytical laboratory balance (0.001 g resolution, but around 0.01 g precision). Susceptibility of the samples was measured three times and the average of the measurements was calculated. Additionally, large samples were measured three times among three perpendicular directions using the TH-1 instrument and an average was calculated. Subsequently, a logarithm of the apparent magnetic susceptibility (in 10^{-9} Am^2/kg) was calculated as introduced in Rochette et al. (2003). Relative error in the determination of the magnetic susceptibility logarithm is below 3%. Susceptibility was not shape-corrected due to the lack of the meteorite volume information. But for our samples, the lack of a shape correction of the apparent susceptibility resulted in systematic error in the susceptibility logarithm of only around 1%. Note that the logarithm expresses order of magnitude variations (as observed among various meteorite types).

For remanence measurements a 2G Model 755 superconducting rock magnetometer (SRM) was used. The hysteresis parameters were measured on a Princeton Measurements Model 3900 VSM (Vibrating Sample Magnetometer). Temperature dependence of magnetic susceptibility was measured using an Agico KLY-3S kappa-bridge (operating at 875 Hz and 300 A/m RMS field intensity) equipped with CS-3 and

CS-L temperature control units. Isothermal remanent magnetization (IRM) acquisition was done on a Princeton Measurements Model 7500 VSM. Alternating field demagnetization (AFD) was done using a 2G Model 600 demagnetizer.

3. Rock magnetic and paleomagnetic characterization of Almahata Sitta meteorites

Ten small chips (~ 0.01-0.1 g) of Almahata Sitta ureilite meteorites no. 22 and 27 were provided for brief rock magnetic and paleomagnetic characterization in the Solid Earth Geophysics Laboratory at the Department of Physics, University of Helsinki. All chips from meteorite interior show following consistent behavior. Low-temperature thermomagnetic curve (-180°C to room temperature) of magnetic susceptibility is featureless. In contrast to Hofman et al. 2010 no signature of daubreelite was detected in our samples. The high-temperature thermomagnetic curve (Fig. 1, room temperature to 800°C) measured in argon atmosphere reveals kamacite to be dominant magnetic mineral. This is consistent with mineralogical observations by Bischoff et al. 2010 and Zolensky et al. 2010).There is a indication of multiple Curie points on the heating curve in the range between 700°C and 800°C which is interpreted as presence of multiple populations of kamacite with various Ni contents in agreement with Hoffman et al. 2010. The thermomagnetic curve has also partly reversible kamacite-taenite-kamacite transition between 700°C and 800°C which may be explained by presence of minor fraction of Ni free metal (Kohout et al. 2010). Additionally small peak around 200°C on both heating and cooling curve may indicate minor presence of cohenite $(Fe,Ni,Co)_3C$. The hysteresis loop (Fig. 1) reveal low coercivity (below 2 mT) typical for large multidomain kamacite grains. This is further supported by fast saturation of the isothermal remanent magnetization (Fig. 1, IRM saturates below 400 mT) and alternating field demagnetization (AFD) of the saturation isothermal remanent magnetization (SIRM) resulting in extremely low (3 mT) medium destructive field (MDF, alternating field resulting in 50% loss of remanence). FORC (First Order Reversal Curves) have been also done revealing low coercivity distributions below 15 mT.

The natural remanent magnetization (NRM) seems to be scattered among neighboring samples and is extremely unstable (MDF ~ 1 mT, 90% loss at 4 mT) and thus not suitable for further paleomagnetic investigations.

One chip (from meteorite no. 22) consisting mostly of fusion crust was studied and showed slightly higher coercivities (6 mT) during hysteresis measurements and higher SIRM MDF (14 mT). However the MDF and stability of the NRM was comparable to interior samples.

The frequency and field amplitude dependence of magnetic susceptibility was measured for three larger ureilite samples (no. 99, S127 and S129) and is low (< 1% and < 3% respectively), which is in agreement with previous data on ureilites (Smith et al., 2006).

4. Magnetic susceptibility of Almahata Sitta meteorites

The measured samples consisted of three distinct groups. The first group (Table 1) contained 15 large (more than 10 g) Almahata Sitta samples collected before the summer rains during the first, second and third search in December 2008, February 2009 and March 2009 respectively. These meteorites were collected within half a year since their fall and never experienced rain. They were kept in dry storage throughout the year. They are fresh-looking and are expected to have low levels of terrestrial weathering. The presence of fusion crust on these samples does not affect the susceptibility measurement as the fusion crust is thin (< 1 mm) and its volume compared to the volume of these samples (in general larger than 2 cm^3) is negligible.

In data processing we used the approach introduced by Rochette et al. (2003, 2008, 2009) in order to be consistent with the most complex meteorite susceptibility database up to date. The (arithmetical) mean of the apparent magnetic susceptibility logarithm (log 10^{-9} Am^2/kg) for these fresh Almahata Sitta meteorites with ureilite appearance was determined to be 4.92 with standard deviation (s. d.) of 0.08. (Table 1, Fig. 2 and 3). This value is identical to the 4.95 ± 0.14 log 10^{-9} Am^2/kg range of other ureilite falls reported in Rochette et al. (2009), but more than half an order of magnitude higher than the range of all (both falls and finds) unbrecciated ureilites 4.39 ± 0.29 and brecciated ureilites 4.38 ± 0.47 (Fig. 2).

As this group contains the freshest samples, we use the value 4.92 ± 0.08 log 10^{-9} Am^2/kg as the most reliable base for distinguishing samples with anomalous susceptibility among all three groups. The distinguishing criterion for an anomalous magnetic susceptibility is more than three standard deviations difference from the ureilite mean, similarly to that applied by Rochette et al. (2009).

Strikingly, some samples show significantly higher susceptibility values (more than 3 times s. d.) compared to this Almahata Sitta ureilite mean (Table 2, Fig. 3). Visual inspection of those samples showed that they have also mostly non-ureilitic visual appearance (different texture, color, or different fusion crust pattern). These samples were thus not included in the Almahata Sitta ureilite susceptibility mean calculations and will be discussed individually in the following chapter. Sample numbers refer to those listed in Shaddad et al. (2010).

The measurements of the second sample group were made in the field on 13 relatively large samples that were collected during the fourth search, immediately following the 2008 TC_3 Workshop in December 2009 (Table 2). These meteorites were collected more than one year after the fall and thus experienced some showers during the summer wet season. Samples which were not fully crusted were found to have a few rusty spots. The mean calculation of the magnetic susceptibility logarithm again excludes samples with difference from the ureilite mean of the first group more than three standard deviations or with non-ureilitic appearance. The mean of those samples with ureilite appearance is 4.90 (log 10^{-9} Am^2/kg) with s. d. of 0.06 (Table 1, Fig. 2). This is slightly lower compared to the samples from the first group, but still within a difference of one s. d., revealing that the weathering effects in this group are still minor. This group also contains samples with non-ureilitic visual appearance and higher susceptibility (Table 2, Fig. 3) and, similarly to those from the first group, they were excluded from the ureilite mean calculation and will be discussed individually in the following chapter.

The third group of samples included all small meteorites collected in the tail of the strewn field where ~ 1 gram masses were expected to have fallen (Fig. 4). These samples were collected in December 2009 (Shaddad et al., 2010) and thus have the same terrestrial residence age as samples in the second group. These samples are below 5 g and many are almost completely covered by fusion crust. The mean of the magnetic susceptibility logarithm calculated from all samples within this group is 4.97 (log 10^{-9} Am^2/kg) with s. d. of 0.34 while the mean calculated from the samples excluding the anomalous ones (based on group 1 mean and 3 s. d. criterion) is 4.89 ± 0.20 (Table 1, Fig. 2).

The standard deviation in both cases is three times higher. As discussed in more detail in the next section, such a high scatter in this group (Table 2, Fig. 5) may be attributed partially to terrestrial weathering, partially to the fact that inhomogeneities (variation in metallic fraction) in the 2008 TC_3 material are not averaged-out at this scale, or to the presence of a significant fraction of non-ureilitic material within the 2008 TC_3 body. The presence of fusion crust in extremely small samples (below 0.5 g) may add a few percent error in logarithm of susceptibility. However this error is still about the symbol size in Fig. 5 and can not itself explain the observed wide scatter.

The portable Geofyzika KT-6 and ZHinstruments SM-100 susceptibility meters were also used in the field to recognize terrestrial rocks from meteorites. Over ten additional dark crust-coated samples collected and measured during the 4th field search campaign were identified by more than two orders of magnitude lower susceptibility as ordinary rocks and were subsequently discarded.

5. Discussion

The magnetic susceptibility of most of the larger Almahata Sitta samples occupies a distinct range, with values similar to previously reported ureilite data. From ureilitic samples in our data set only sample S138 was mineralogical characterized by Zolensky et al. (2010) to be an olivine rich ureilite, which is in agreement with its susceptibility value. From the samples identified to have anomalously high magnetic susceptibility values as well as non-ureilitic visual appearance only samples no. 16, 25, and 41 have been analyzed so far and classified as EH6, H5 and EL6 chondrites (Zolensky et al. 2010). Indeed, their susceptibility values fall in the range of other freshly fallen enstatite and ordinary chondrites (Rochette et al., 2003, 2008), as shown in Fig. 2.

An interesting question remains whether these chondritic samples were part of the 2008 TC_3 body or whether they originate from unrelated meteorite falls. The average density of meteorites in unexplored deserts is about 0.2-10 km^{-2} (Gattacceca et al. 2009), from which we expect about 10-500 non-related finds for the Almahata Sitta strewn field area of 50 km^2. However, all recovered meteorites were biased towards fresh-looking (black) meteorites, as more weathered stones were hard to recognize among the surface gravel.

Our measurements confirm the visual appearance of the non-ureilitic meteorites, in that they too are fresh falls. Terrestrial weathering results in metal oxidation and a decrease of susceptibility values and thus finds tend to have susceptibility values below the range of fresh falls of the same class (Rochette et al., 2003). In contrast susceptibility of recovered Almahata Sitta ureilites as well as chondrites (Fig. 2) fall into the narrow range identified by

Rochette et al. (2003, 2008) for fresh falls. This confirms their young terrestrial residence age (less than a few years) and supports their common origin from the 2008 TC_3 fall. Due to the young terrestrial age of recovered ureilitic as well as non-ureilitic lithologies in all three groups, and because fragments of similar size were grouped together, we think that (nearly) all were part of the 2008 TC_3 parent body (Shaddad et al., 2010).

This is further supported in study of another set of the Almahata Sitta material by Bischoff et al. (2010) and Horstmann et al. (2010). Among their independently collected sample set similar enstatite and ordinary chondrite compositions were reported. Furthermore, similarly increased abundance of short-lived cosmogenic radioisotopes in one chondritic as well as one ureilite sample (Bischoff et al. 2010) further support short terrestrial residence age and common impact origin of these samples.

An exceptional appearance and susceptibility is that of fragment no. 33. It has a mass slightly below 10 g (9.2 g), shiny metallic appearance and far the highest susceptibility of 5.7 $\log10^{-9}$ Am^2/kg. Zolensky et al. (2010) described this sample as an ureilite with shock melting produced kamacite-troilite dendrites. This sample seems to be also similar to samples MS-158 and MS-166 in study by Bischoff et al. (2010)

Other samples with anomalously high magnetic susceptibility values as well as non-ureilitic visual appearance have not been analyzed and classified so far and thus we present just their brief description here.

The magnetic susceptibility of the sample 14 (5.2 $\log10^{-8}$ Am^2/kg; 152.6 g) is somewhere in-between ureilites and H chondrites. Sample S194 with its mass of 82.4 g has susceptibility in the range of the H or E chondrites. Another sample with high susceptibility is no. 87 (10.3 g) but is fully coated with fusion crust so no conclusion on its internal appearance and composition can be made. Sample 82 has susceptibility within the Almahata Sitta ureilite range but it has a brighter appearance compared to other ureilites and it seems also to have a high porosity. Because of this, it was excluded from ureilite susceptibility mean calculation. Samples 1001, 1005, 1007, 1008, 1009 and 1011 (Fig. 6) are members of the second group and were collected and measured in the field during the fourth search campaign. Their more detailed examination and characterization should be a subject of future work. Based on their visual appearance samples 1001 and 1011 resemble sample 33 and thus may be of similar composition.

It is interesting to point out that all three meteorites with high magnetic susceptibility and confirmed chondritic lithology (16, 25, and 41) are large masses. In contrast, ureilites and sample 33 (a kamacite-troilite-ureilite assemblage) are samples with considerably lower mass, below 50 g. This may be due to the fact that ureilites are of lower mechanical strength compared to these chondrites and thus broke down to smaller fragments during atmospheric entry. Sample S194 with anomalously high magnetic susceptibility has a mass of 82.4 g, similar to other recovered chondrites, and thus may also be a chondrite. To make such identifications is uncertain, however, and this sample should be analyzed in the future. In a more general sense, we can say that non-ureilite masses comparable to those of the recovered ureilites appear to exist within all three groups (Shaddad et al., 2010).

It is very interesting to find a wide scatter in susceptibility among the very small (< 5 g) samples from the third group. It is very unlikely that any of these fresh-looking tiny samples originated from unrelated meteorite falls in the area. The scatter of susceptibility values in this group is independent on sample mass and, as it is more symmetric towards low and high values, we interpret this scatter to be predominantly due to an inhomogeneity in the 2008 TC_3 material (mainly in terms of metal distribution) on a spatial scale corresponding to the size of these fragments (1-2 cm, less than 5 g).

Although terrestrial weathering may partly explain the low susceptibilities observed in some samples of group 3, the different visual appearance of some of these tiny meteorites suggests that the scatter in susceptibility is at least partly related to the presence of non-ureilitic materials being found among ureilites. No mineralogical data exists on these meteorites so far.

The variety of different lithologies within recovered Almahata Sitta material, all represented by fresh meteorites, is exceptional. However, there are known breccias among other meteorites containing various chondritic and achondritic clasts. Clasts of material resembling or being derived from chondritic materials including enstatite chondrites, aubrites and angrites have been reported in other polymict ureilites (Goodrich 1992). A single meteorite fragment composed of both ureilitic and chondritic clasts have not been reported yet among analyzed Almahata Sitta meteorites. But there is evidence mentioned above that these lithologies were incorporated together in the 2008 TC_3 asteroid. Thus 2008 TC_3 may represent a body which originated after a catastrophic collision among ureilitic and chondritic bodies and may be similar to Kaidun breccia as discussed in Bischoff et al. 2010. So far only a minor fraction of recovered Almahata Sitta meteorites have been examined in detail and mineralogically classified and future research should focus on the possible identification of such a sample. If these lithologies were both incorporated together in the 2008 TC_3 asteroid, then the lack of meteorites composed of multiple lithologies suggests these were loosely packed.

6. Conclusions

The magnetic susceptibility of most Almahata Sitta ureilites occupies a narrow range consistent with previous measurements of laboratory ureilite samples. The specific susceptibility range of Almahata Sitta ureilites allowed us to identify samples of non-ureilitic compositions among the meteorites collected in the Almahata Sitta strewn field, as well as separate terrestrial rocks misidentified as meteorites. During our measurements a significant number of meteorites (about half of the samples measured) were found to have anomalously high susceptibility. However, most do not yet have information about their composition. Only four of these samples, no. 16, 25 and 41 and 33, have been analyzed so far and identified as EH6, H5, EL6 chondrites and a kamacite-sulfide rich fragment derived from ureilitic lithology. These meteorites have not their susceptibilities and mineralogy significantly altered by terrestrial weathering. The fresh appearance of all different meteorite types recovered in a common area is further evidence that the non-ureilitic meteorites were deposited together with the ureilites during the breakup of 2008 TC_3.

Among the smaller (< 5 g) Almahata Sitta samples found in the tail of the strewn field, we found considerably variation in their susceptibility predominantly due to inhomogeneity within Almahata Sitta ureilites below the 1-2 cm scale, but also in part due to slight terrestrial weathering or presence of non-ureilitic compositions.

This study showed that the non-destructive technique of magnetic susceptibility measurements is very useful in identifying and classifying non-ureilitic meteorites among the Almahata Sitta meteorites and in probing the level of inhomogeneity of the asteroid 2008 TC_3's material. The measurements are easy, fast and can also be used to identify samples in the field. As magnetic susceptibility is a penetrative (but non-destructive) type of measurement, it can successfully characterize also samples fully coated by fusion crust.

In the future we hope to further characterize the non-ureilitic compositions of meteorites identified by high and low magnetic susceptibility using mineralogical analysis. We also hope to measure the magnetic susceptibility of the whole Almahata Sitta collection in order to more precisely determine the distribution of various meteorite types within the strewn field.

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Table 1: Arithmetical mean of the magnetic susceptibility logarithm (log 10^{-9} Am^2/kg) of the three groups of Almahata Sitta ureilites. Calculations exclude anomalous samples as defined in the text (with the exception of the last entry which includes all samples in the third group). The number of samples used to calculate the mean is in the last column.

Group	Arithmetical mean (log χ in 10^{-9} Am^2/kg)	Standard deviation	No. of samples
1	4.92	0.08	7
2	4.90	0.06	7
3	4.89	0.20	22
3 (all)	4.97	0.34	34

Table 2: List of all measured meteorites with their logarithm of magnetic susceptibility and mass. The three different meteorite groups are described in the text. Anomalous (most likely non-ureilitic) samples are distinguished by difference with the ureilite mean of group 1 (i.e., exceeding three standard deviations) or by their anomalous appearance.

Meteorite	log χ (in 10^{-9} Am^2/kg)	Mass (g)	Group	Anomalous susceptibility	Note
14	5.21	152.58	1	X	
16	5.38	171.08	1	X	Fine-grained, EH6 chondrite
25	5.30	190.7	1	X	H5 chondrite
33	5.69	9.2	1	X	Dark shiny metallic appearance
41	5.47	49.1	1	X	Fine-grained, EL6 chondrite
82	5.02	10.3	1		Distinct bright appearance, susceptibility within range
87	5.55	10.3	1	X	Fully coated by fusion crust
99	4.93	7.8	1		
S127	4.90	20.6	1		
S129	5.08	9.3	1		
S138	4.79	35	1		
S164	4.95	28.8	1		
S194	5.43	82.4	1	X	Compact
S195	4.91	28.9	1		
S195A	4.92	24.9	1		
603	4.94	17.3	2		
607	4.97	20.9	2		
1001	5.65	48.5	2	X	Similar to 33
1003	4.84	10.8	2		
1004	4.81	13.5	2		
1005	5.39	21.3	2	X	
1006	4.87	12.3	2		
1007	5.32	23.5	2	X	
1008	5.55	23.6	2	X	
1009	5.67	13.8	2	X	
1010	4.94	23.7	2		

1011	5.66	22	2	X	Similar to 33
1012	4.94	28.7	2		
716	4.94	0.89	3		
717	4.68	1.05	3		
720	5.44	0.36	3	X	
721	5.13	0.78	3		
722	4.60	0.99	3		
723	4.98	2.51	3		
724	5.39	2.59	3	X	
725	5.37	0.30	3	X	
726	5.19	0.39	3		
727	4.93	0.30	3		
1104	4.47	1.07	3	X	
1105	5.35	0.43	3	X	
1106	5.37	0.30	3	X	
1107	5.50	1.82	3	X	
1109	4.39	1.82	3	X	
1110A	4.45	6.88	3	X	
1110B	4.40	0.73	3	X	
1111	5.57	0.46	3	X	
1112	4.69	2.38	3		
1113	4.74	3.74	3		
1114	5.02	0.38	3		
1115	4.88	1.37	3		
1116	4.63	1.79	3		
1118	4.76	0.92	3		
1119	5.30	0.82	3		
1120	5.17	1.11	3		
1213	5.14	0.77	3		
1214	4.82	0.87	3		
1215	5.51	0.44	3	X	
1216	4.83	0.70	3		
1217	4.87	2.39	3		
1219	4.84	1.88	3		
1220	4.88	1.57	3		
1221	4.61	2.17	3		

Figure 1: Rock magnetic investigations of the small chip from sample no. 27 (ureilite) reveal multidomain low Ni kamacite as a main magnetic mineral with a minor fraction of iron and additional presence of cohenite. The measurements consist of thermomagnetic curve of magnetic susceptibility measured in argon atmosphere (up), hysteresis loop (middle) and isothermal remanent magnetization acquisition curve (down).

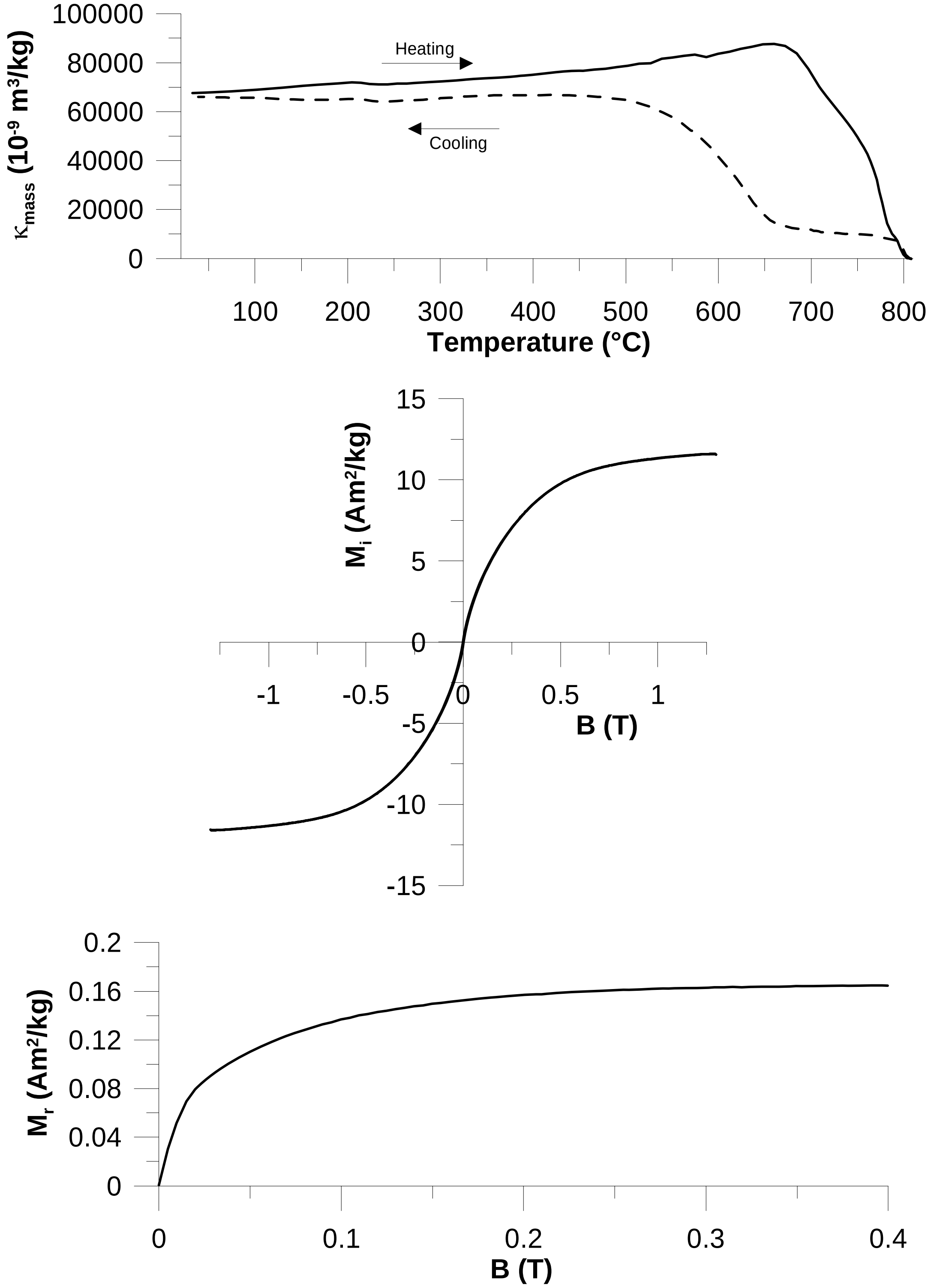

Figure 2: Arithmetical means and standard deviations of the magnetic susceptibility logarithm (log 10^{-9} m^3/kg) of the ureilites from three groups of Almahata Sitta meteorites compared to values of other meteorites by Rochette et al. (2003, 2008, 2009). Calculations exclude the non-ureilitic samples as defined in the text (with exception of the group 3 where the calculation for all samples is also presented).

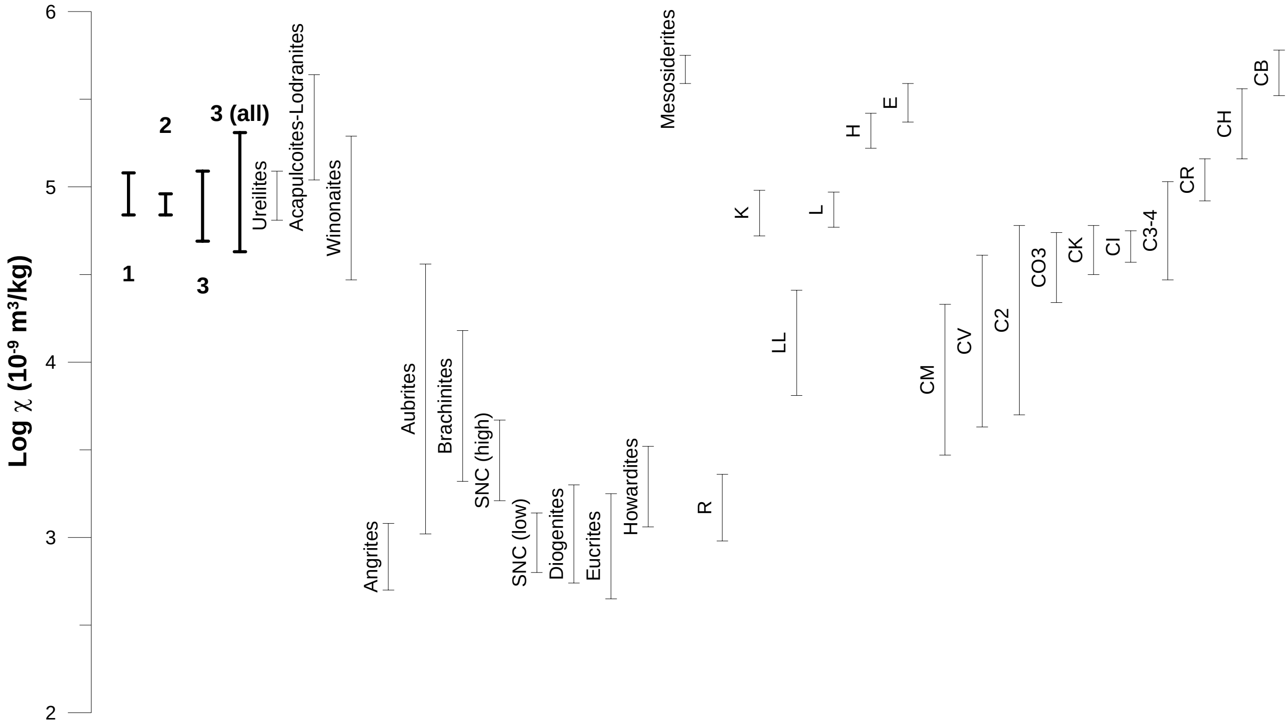

Figure 3: Magnetic susceptibility logarithm (log 10^{-9} m^3/kg) of meteorites from the first group (solid symbols) and the second group (open symbols). Samples are sorted by increasing mass (from 7.8 to 190.7 g in group 1 and 10.8 to 48.5 g in group 2). Gray area indicates mean and standard deviation of values from the first group (excluding non-ureilitic samples). Dashed lines indicate the three standard deviations margins used to identify non-ureilitic samples. The error in the susceptibility logarithm is smaller than the data points shown. Values for different chondrite types are from Rochette et al. (2003).

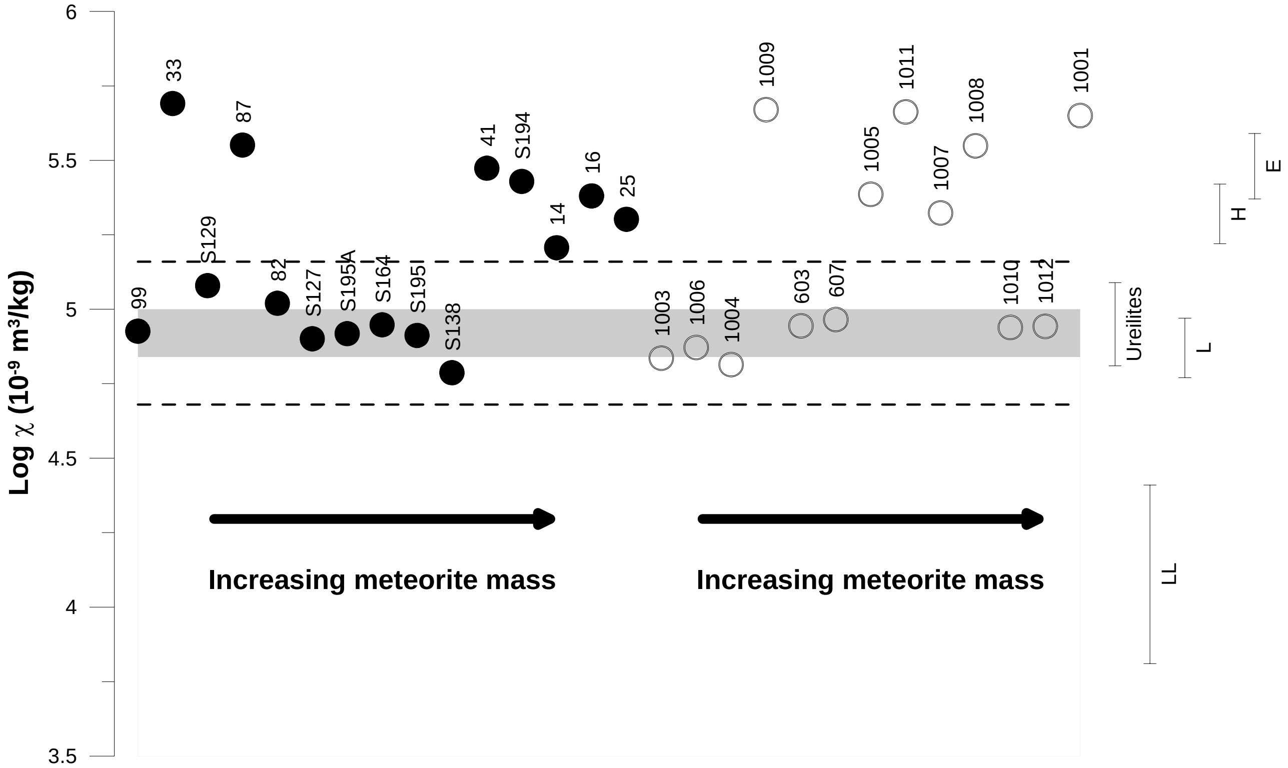

Figure 4: Locations (indicated by arrows and dots) of the finds in the third group, at the location where ~ 1 gram masses were expected to have fallen (after Shaddad et al., 2010). Two examples with different texture are shown.

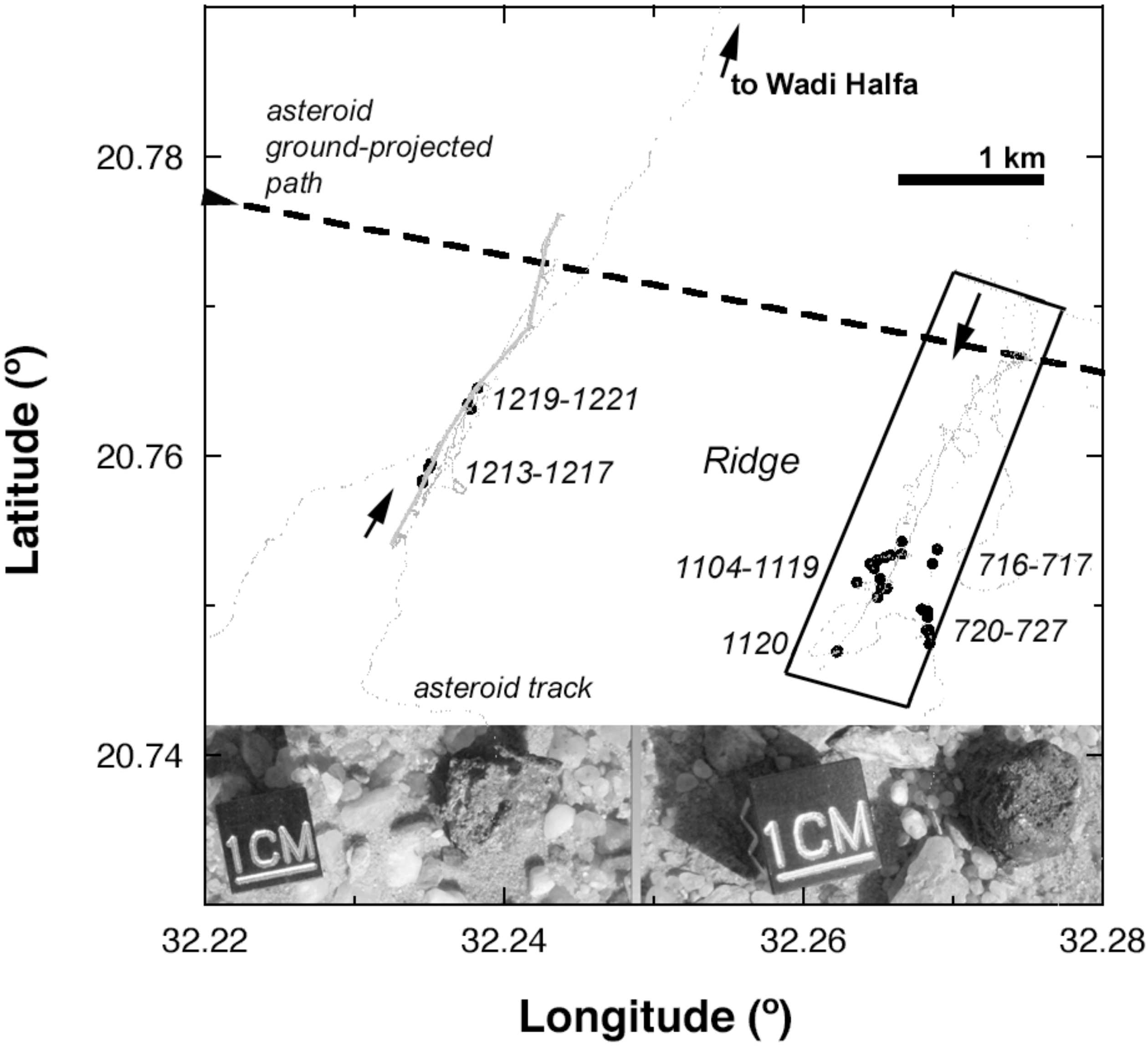

Figure 5: Magnetic susceptibility logarithm (log 10^{-9} m^3/kg) of meteorites from the third group. Samples are sorted by increasing mass (from 0.30 to 6.88 g). Gray area indicates mean and standard deviation of values from the first group (excluding non-ureilitic samples). Dashed lines indicate the three standard deviations margins used to identify non-ureilitic samples. The error in the susceptibility logarithm measurement is smaller than the data point.

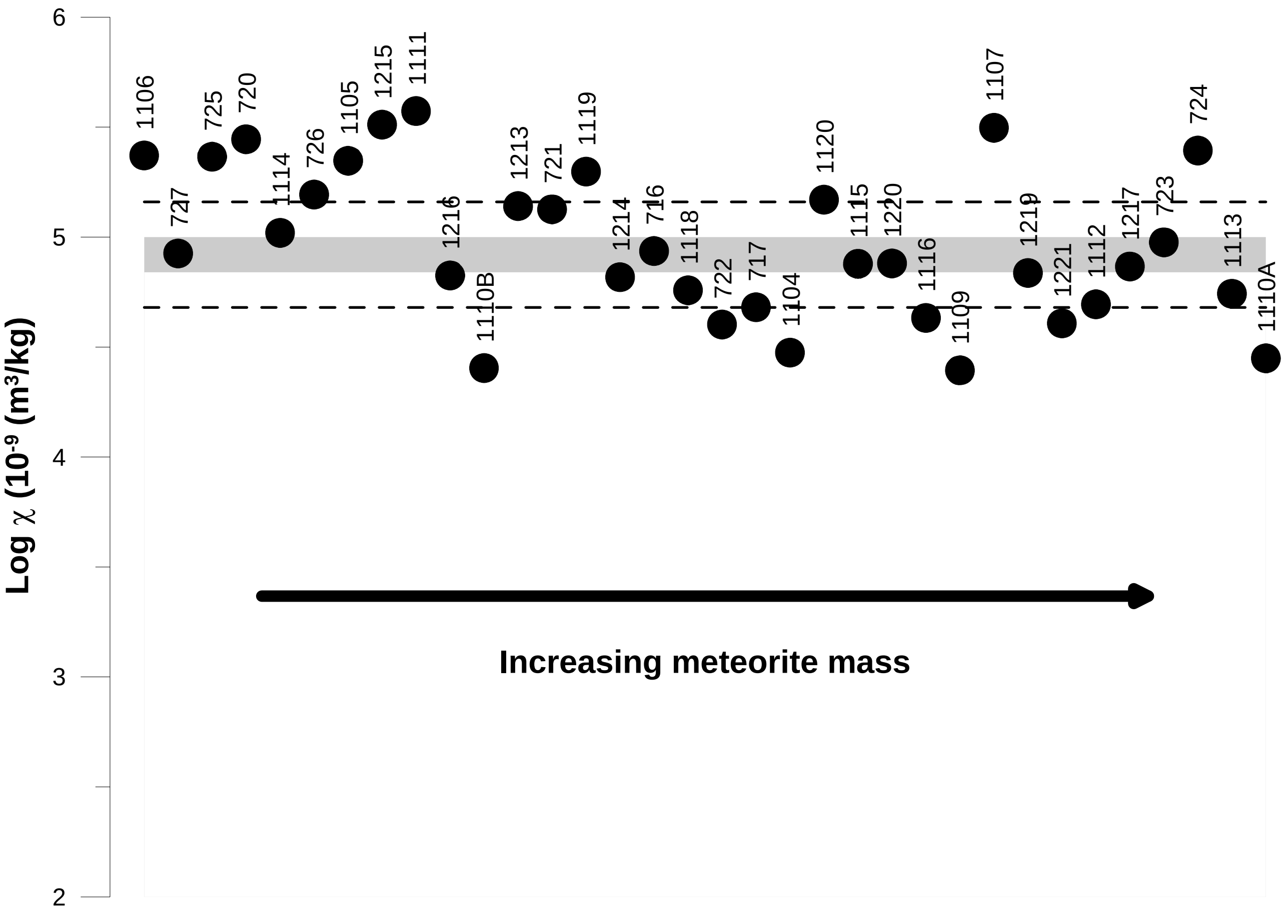

Figure 6: A composite image of the second group of finds recovered in December 2009, demonstrating the variability of the meteorite textures. Meteorite type identifications are based on the magnetic susceptibility measurements and visual appearance.