MAGNETISM AND MINERALOGY OF ALMAHATA SITTA. V.H. Hoffmann[1,2], R. Hochleitner[3], M. Torii[4], M. Funaki[5], T. Mikouchi[6] and Almahata Sitta Consortium, [1]Inst. for Geosciences and ZAG, University of Tuebingen, Sigwartstrasse 10, 72076 Tuebingen, [2]Dep. of Geo-and Environmental Sciences, University of Muenchen, Germany, viktor.hoffmann@uni-tuebingen.de; [3]Bavarian Mineral State Collection, Muenchen/Germany; [4]Dep. Geosphere-Biosphere System Science, Okayama University of Science, Okayama/Japan; [5]National Institute of Polar Research, Tachikawa/Tokyo, Japan; [6]Dep. Earth and Planetary Sciences, University of Tokyo, Japan.

Introduction: A small asteroid called 2008 TC3 was discovered by the automated Catalina Sky Survey at Mt. Lemmon, Tucson, Arizona/USA, on October 6 2008 on a collision course with Earth [1]. After entry to Earth atmosphere on October 7, 2008, the small asteroid exploded at about 37 km altitude over the Nubian Desert. Meteorite search campaigns led by J. Jenniskens (SETI) and M. Shaddad (Univ. Khartoum) recovered numerous fragments of the asteroid in the North Sudan desert [2]. The meteorite was named Almahata Sitta and classified as an anomalous polymict ureilite [2,3].

The aims of our investigations are unrevealing Almahata Sitta's (AS) magnetic signature, phase composition and mineralogy (main focus on the opaques) and getting new insights to the ureilite parent body magnetism (2008TC3 belongs to F-type asteroids [2]).

Samples: Two chips of the AS meteorite have been provided for our pilot studies by P. Jenniskens (SETI), "4" (0.38gr, interior) and "39", 1.44gr, individual without fusion crust, both black lithology, in addition a PTS of chip "3-1" was available. For comparison, a sample of the NWA1241 monomict ureilite (0.31gr) was included in our investigations [4].

Fig. 1a: AS chip "39", size is around 15mm. Large-sized Kamacite sheets are seen. b: Some rustiness can be recognized on the (Fe,Ni) metal (effect of terrestrial oxidation, arrow).

Magnetic signature and phases: First results have been presented during the 2008 TC3 workshop in Khartoum in 2009 [5] and are summarized here:

- Natural Magnetic Remanence (NRM) of the two AS samples are 15.4 and 2.99 10^{-3} Am^2/kg, IRMs are 1.67 and 1.57 10^{-1} Am^2/kg, respectively. Log Mrs values (in $10^{-3} Am^2/kg$) are in the range of the other ureilite falls (Novo Urei and Havero) [6]. NRM resembles a typical Kamacite based NRM, demagnetized at low fields, but directionally stable, as known from the few earlier ureilite studies [7].

- Magnetic susceptibility values (logχ in 10^{-9} kg/m^3) of AS are 4.84 and 4.93, of NWA1241 it is 4.68. The mean value of the 3 ureilite falls was found to be 4.95 [6], of all investigated ureilites 4.39 [6]. The lower values of the finds most likely are a result of terrestrial alteration. Anisotropy of magnetic susceptibility (AMS) is an indicator of the degree of shock but is also influenced for example by grain shapes. P values of 1.315 and 1.531 are significantly higher as in case of HED or SNC meteorites (no ureilite data known) [8]. Most probably the magnetic fabric is impact related.

- Our hysteresis data provided complex magnetization behavior, indicating strong magnetic interactions. M_s and M_{rs} values of AS and NWA1241 are comparable; H_c and H_{cr}, however, are significantly higher in case of NWA1241 (16.5 and 24.1 mT for the latter) which points to differences in phase composition and acting particle sizes (NWA1241 contains only Suessite).

- IRM experiments and statistical unmixing suggests three magnetic components with H_{cr} values of ~5/6 mT, ~50 and 65mT, and ~3300 and 7700mT.

- Low field (magnetic susceptibility) and high field (magnetization, H_{ext} = 0.4T) thermomagnetic runs in air and Ar allowed to identify the following magnetic phases in Almahata Sitta: (a) Kamacite (low Ni), two distinct phases with Curie temperatures (T_c) of 750-770°, (b) Suessite with T_c of 550-600°C, (c) probably Schreibersite with a $T_{c,t}$ around 350-450°C, and (d) ~ 80-100°C a likely Fe-oxy-hydroxide as a terrestrial alteration product. In NWA1241 two distinct Suessite phases (T_c ~ 550-580°C) and Scheibersite could be detected, but no Kamacite.

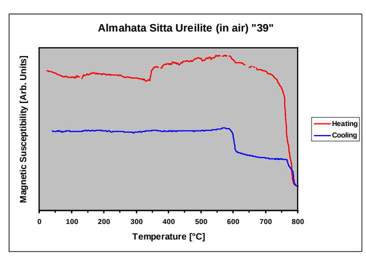

Fig. 2: Thermomagnetic experiment on AS "39", for details see text.

Taking into account space conditions, one needs to include the low temperature regime of the magnetic properties in order to fully control the magnetic signature and record. In this case it concerns phases such as Fe-bearing silicates (both Olivines and Pyroxenes) and specifically Fe-Cr-(Ti) sulfides such as the daubreelite-Heideite series. Therefore we performed a series of low temperature experiments of IRM (zero-field cooling and field cooling of a 1T IRM at 5K). Minor transitions ~ 150K and ~ 70-80K point to Daubreelite-Heideite like phases [9].

Mineralogy of the opaques phases in Almahata Sitta: SEM/EDX and EMPA analyses were performed systematically on a large number of particles in AS "39" PS. The main silicate phases are olivine and pyroxene with compositions as reported by [2, 3]. Our main interest is on the clarification of the opaque phase's mineralogical composition, part of them representing the major magnetic recorders.

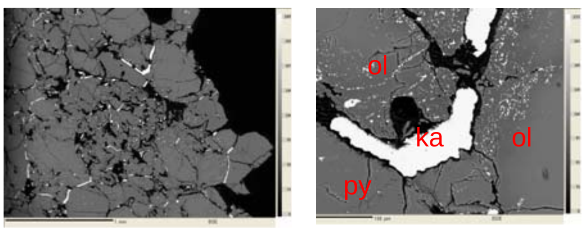

Fig. 3a: AS "39" in backscattered SEM. Large Kamacite (ka) laths or sheets can be seen in the graphite rich veins, and (b) many (sub-)micron particles in the adjacent olivines (ol, few only in the pyroxenes, py) with rim thicknesses of the reduced olivines ~ 20 to 50µm.

Two distinct Kamacite phases with slightly different contents of Fe (92.41 and 95.24 wt %) and Ni (4.52 and 1.28 wt %) were found, whereby Si (2.25, 2.28 wt %), Cr (0.14, 0.16 wt %), P (0.21, 0.31 wt %) show similar values. The two different Curie points above 700°C can be attributed to these distinct Kamacites. A Fe-Cr sulfide phase with Fe (25.8 wt %), Cr (39.1 wt %), S (35.3 wt %), Mn (3.0 wt %), Si (0.39 wt %), Ti (0.14 wt %) and V (0.51 wt %) belongs to the Daubreelite-Heideite series, eventually intergrown with Troilite. Schreibersite or other phases could not be identified by EMPA, most likely due to their small particle sizes.

Putting together the mineralogical data, as there is a high graphite content (graphite/metal certainly >10 Vol.%), rim thicknesses of the reduced olivine of ~20-50µm, low degree of hardness (soft and brittle) and the presence of diamonds [10], the AS polymict ureilite does not fit into the proposed ureilite scheme which is based on the reduction characteristics (R1-R4/5).

Summary and conclusions: In Alamahata Sitta we found a variety of magnetic phases comprising Kamacite(s) (low-Ni), Suessite, Schreibersite and Troilite; in addition a Daubreelite-Heideite like phase was detected for the first time in ureilites. The latter finding is not a surprise as clasts of ord. chondritic or E-chondritic mineralogical signature have been described in ureilites [11]. The magnetic record is dominated by Kamacite (two distinct Kamacite phases with slight variations in Fe/Ni) in micron sized particle sizes. The role of Suessite, Schreibersite or respective intergrowths (see hysteresis curve, indicating significant magnetic interactions) needs to be further investigated. In case of NWA1241, Suessite is the only and dominating magnetic recorder. However, the knowledge concerning the Fe-Si phases magnetic signature and record is very poor presently. In the past, Suessite magnetic properties, e.g. Curie-temperatures around 570-600°C have been misinterpreted as due to magnetite [12].

Indigenous or impact formation are discussed as possible formation processes for the ureilite vein metal. A recent investigation proposed that a Ni-poor Iron meteorite (IIAB or Bellsbank group type) could be the source of the vein metal [13,14]. The (paleo)magnetic signature of Almahata Sitta is extraterrestrial without doubt and most probably represents an ureilite parent body magnetic record. A more detailed interpretation of the magnetic record and signature of Almahata Sitta and moreover, of the ureilites in general, is quite complex and requires a better understanding in terms of the formation and origin of the magnetic recorders, the opaque phases.

References: [1] Boattini A., et al., 2009. The discovery of 2008TC3 at the Catalina Sky Survey. DPS conference abstract. [2] Jenniskens P., et al., 2009. Nature 458: 485-488. [3] Zolensky M.E., et al., 2009. Mineralogy of the Almahata Sitta Ureilite. 72nd Meteoritical Society Meeting, #5183. [4] Ikeda Y., 2007. Polar Science 1: 45-53. [5] Hoffmann V., et al. 2009. Abstract/Poster Workshop Asteroid 2008TC3. [6] Rochette P., et al. 2009. Meteoritics Planet. Science, 44: 405-427. [7] Sugiura N., Strangway D.W., 1988. In: Kerridge J.F., Matthews M.S., Meteorites and the early Solar System. Univ. Arizona Press, Tucson, 595-615. [8] Gattacceca J., et al., 2008. Earth Planet. Sci. Lett. 270: 280-289. [9] Kohout T., et al., 2007. Earth Planet. Science Lett.: 261: 143-151. [10] Steele A., et al., 2009. Characterisation of Diamond in the Almahata Sitta meteorite. DPS conference abstract. [11] Goodrich C.A., 1992. Meteoritics 27: 327-352. [12] Rowe M.W., et al., 1976. NASA Report CR-1411-43, N75-146. [13] Gabriel A.D., Pack A., 2009. 40th Lunar Planetary Science Conference, # 2462. [14] Goodrich C.A., 2009. 40th Lunar Planetary Science Conference, # 1132.