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The elemental composition of Almahata Sitta.

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Abstract – We quantified up to 60 elements in four individual fragments (#4, #7, #15, #47) of the meteorites collectively known as Alamhata Sitta, which entered the Earth's atmosphere on 7 October 2008. The Almahata Sitta meteorites are indisputably fragments resulting from portions of asteroid 2008 TC_3 surviving passage through the Earth's atmosphere. Each of the four analyzed fragments has a ureilitic composition based on comparisons with literature data. Fragment #7 contains Rare Earth Element (REE) abundances that are generally elevated (>0.1×CI) when compared to other ureilites, and enrichments in the trace elements Rb, and Cs, which usually correlate with signatures associated with polymict ureilites. Fragments #4, #15, and #47, on the other hand, have overall compositions that, when taken alone, would suggest a monomict ureilite compositional association. None of the fragments displays the classic V-shaped REE pattern that are often found in ureilites. Our results imply that chemically polymict and monomict ureilitic material can co-exist in the same asteroid on the spatial scale of a few meters.

keywords:
Almahata Sitta
ureilite
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INTRODUCTION

The discovery, observation of asteroid 2008 TC_3's approach toward the Earth, and recovery of associated asteroidal fragments in the form of the Almahata Sitta meteorites has provided an unprecedented connection between asteroids and meteorites. Initial petrographic, chemical, and isotopic examination of the resulting meteorites identified them as anomalous polymict ureilites (Jenniskens et al. 2009; Zolensky et al. this issue; Rumble et al., this issue). Ureilites are enigmatic carbon-rich ultramafic achondrites with origins that reflect early high-temperature planetary differentiation processes curiously combined with a complement of characteristics that are trademarks of more primitive (chondritic) materials (for reviews see Goodrich 1992 and Mittlefehldt et al. 1998). Since the various fragments of Almahata Sitta were collected between only 2 to 5 months after their documented fall, the elemental composition is expected to be relatively unaltered by terrestrial weathering processes, which are a concern for the majority (>97%) of ureilites, which are finds collected from cold Antarctic icefields or hot deserts. Initial chemical analysis of Almahata Sitta was performed on a small (~50 mg) sample of single fragment (#7) for trace elements only. In this work, we expand the investigation in terms of both number of fragments investigated and elements analyzed. The augmented compositional results again show that the three additional fragments, along with the original fragment #7 are unquestionably ureilites when compositions are compared to literature values. However, as we will see, only occasionally does Almahata Sitta clearly exhibit the compositional trademarks typically associated with the handful of other known polymict ureilites.

METHODS

Samples

To date, we have studied portions of 4 individual fragments of the Almahata Sitta meteorite. The first sample consisted of 51.5 mg of fragment #7. Trace element results for this fragment were reported in Jenniskens et al. (2009). Following up on this work, we analyzed 35.5 mg of crumbs of fragment #15 and about 200 mg of fragment #47. The latter sample was homogenized by grinding in a clean agate mortar and pestle and analyzed by us in two separate aliquots of 103.2 and 94.1 mg. In addition, we analyzed two larger chips of fragment #4. Each chip was about one quarter of a gram in mass. Both chips were individually homogenized as above and, in total, these pieces yielded five aliquots of 126.6, 110.5, 86.4, 94.9, and 91.2 mg. Each of these aliquots was individually processed for analysis and to minimize the effects of sample inhomogeneity in our compositional reporting, we report the mean of all analytical aliquots processed for each fragment here.

The four samples were derived from meteorites with different macroscopic textures, representing just a few of many faces of Almahata Sitta. Sample #7 was fine grained and inhomogeneous with layers of white pyroxene-rich material, on average a high 20% pyroxene content in the Olivine-Pyroxene composition (Sandford et al., this issue), and macorporosity from partially sintered grains (Jenniskens et al. 2009; Zolensky et al., this issue). Sample #4 was fragile, course grained, and homogeneously dark in appearance, with a flat reflectance spectrum between 0.35 and 2.5 μm (Hiroi et al., this issue). The pyroxene content was low at 7-12% (Sandford et al., this issue). The meteorite density was 2.55 ± 0.08 g/cm^3. Sample #15, too, was course grained, but more cohesive, with ~7% pyroxene, and was taken from a nearly completely fusion crusted meteorite with a density of 3.11 ± 0.02 g/cm^3. Sample #47 was course grained with well mixed large grains of olivine and pyroxene. It contained a weak pyroxene band at 0.9 μm and olivine absorption < 0.5 μm, between 0.9 and 1.6 μm, and around 2 μm (Hiroi et al., this issue). Sample #47 had broken early in small fragments and was slightly weathered, with spots of brown limonite forming on metal fractions. Its density was measured at 2.96 ± 0.05 g/cm^3.

Analytical Methods

We determined the bulk composition of fragments of the Almahata Sitta meteorite by analyzing solutions derived from acid-dissolution of homogenized powders using quadrupole-based inductively coupled plasma mass spectrometry (ICPMS). Concentrations of trace elements were determined using methodology described in Friedrich et al. (2003) using a Thermo Electron X Series II ICPMS. In addition, major and minor elements Na, Mg, Al, P, K, Ca, Cr, Fe and Ni were determined on diluted aliquots of dissolved meteorite using methodology and instrumentation described in Wolf et al. (2005). The highly volatile trace elements Cd, In, Tl and Bi were also determined using methodology and instrumentation described in Wolf et al. (2005).

Acid dissolution procedures involved a HF-HNO_3 microwave digestion step followed by heating to incipient dryness at temperatures no greater than 70ºC. The subsequent addition of perchloric acid followed by heating at the same temperature as the previous step was then used to achieve nearly complete dissolution. Nevertheless, some carbonaceous residue remained in the case of our samples of fragments #4, #15, and #47. Our sample of fragment #7 did not appear to contain noticeable amounts of this perchloric-insoluble carbonaceous residue. Such carbonaceous matter is known to be present in ureilites in the form of graphite and diamond (Rai et al. 2002) and the lack of carbonaceous matter points to an inhomogeneous sampling of our sample of fragment #7 (see Results section). The relative density of the residue was clearly lower than that of chromite, another mineral that can be resistant to repeated harsh acid digestion procedures. Chromite is a phase rarely found in the ureilites (Mittlefehldt et al. 1998).

RESULTS

We present compositional data for up to 60 elements in four different fragments of Almahata Sitta in Table 1. For sake of completeness, we reproduce trace element data for fragment #7 originally presented by Jenniskens et al. (2009). We made an effort to analyze major and minor elements in the dissolved aliquot of fragment #7 used for trace element quantification. Upon analysis, it was apparent that either the dissolved sample was compromised during the half-year storage and/or the analyzed fragment was not a representative sample. So, we have not reported additional compositional information for fragment #7. To illustrate our concerns that fragment #7 is not well-sampled, we can compare the siderophile trace elements for fragment #7 and the other analyzed fragments. Mo, W, Pt and Ir are enriched by up to 10× what is typical of other fragments of Almahata Sitta. Since trace lithophile abundances seem relatively unaffected by the anomaly, we have concluded that our aliquot of fragment #7 potentially contained an anomalous amount of refractory metal, including Fe.

As stated in the Samples section, we received two fractions of Almahata Sitta fragment #4. Because each of these aliquots gave nearly identical results, we report the mean concentrations of the two in Table 1. When concentrations of major and minor elements are used to estimate variability due to sampling, within-fragment compositional variability ranged from 0.81-24% expressed as %-relative standard deviation (%-RSD). Mg and Fe varied at 0.94 and 5.8%-RSD, respectively. Al and Ca demonstrated relatively higher variabilities at 13 and 24%-RSD, respectively. Variation of minor elements Na, P, Cr, Mn, and Ni between these two chips were all <10%-RSD. Both K results were below limits of detection. The compositional variability in these two chips is comparable to that observed in two adjacent chips of polymict ureilite EET 83309 (Warren and Kallemeyn 1989).

The majority of the elements we have analyzed agree well with prior available literature values for ureilites. In the case of several elements generally analyzed by instrumental neutron activation analysis (INAA) discussed next, either upper limits or no values were available for comparison. Of particular interest are the following results:

Ba – Barium in ureilites rarely reaches the values found in fragments #7, #15, and #47, whereas our value for fragment #7 is more in line with literature data that generally reports < 30 ng/g with occasional excursions to the values we report for Almahata Sitta. However, we can find no reason to view our Ba values with more than the usual suspicion since the values were above limits of detection.

Ti – Previously reported Ti values determined by INAA are mostly upper limits (Warren et al. 2006, and references therein), which are typically reported to be well below 800 µg/g, which is in good agreement with our values that cluster around 200 µg/g, with a high value of 676 µg/g for fragment #15 (Table 1).

K – The volatile element K is typically present in low concentrations (<0.1 mg/g) in ureilites (Warren et al. 2006, and references therein) and Almahata Sitta is no exception. In the three fragments where it was determined, K concentrations were below our limit of detection (0.03 mg/g), which is in good agreement with prior findings.

Hf – Literature reports (Warren et al. 2006, and references therein) generally show that Hf contents in ureilites rarely reach greater than ~50ng/g, since upper limits for this element are again typically reported and our results for Almahata Sitta concur with typical values well below this (Table 1).

Despite the inherent variability of the volatile trace elements in differentiated meteorites our Bi, Zn, Te, Se, Cd, In, and Tl results accord well with data from ureilites previously analyzed by either radiochemical neutron activation analyses (RNAA) or INAA (Binz et al. 1975; Wang and Lipschutz 1995; Warren et al. 2006, and references therein). Values for elements which we were able to determine absolute concentrations (Bi, Zn, Te, Se, and Cd) or upper limits (Tl and In) are both bounded by literature values for ureilites.

As we will discuss further, with few exceptions, the elemental composition of Almahata Sitta is generally within prior values reported for ureilites. Deviations or compositional peculiarities are discussed in detail in the Discussion section.

DISCUSSION

Rare Earth Elements

We quantified all 14 extant Rare Earth Elements (REE) in each fragment of Almahata Sitta. Results are shown in Fig. 1. Overall, the REE abundances are low (<0.5×CI), except for results for fragment #15. The generally low concentrations are consistent with a ureilitic composition (Fig. 1). However, many ureilites possess a V-shaped REE pattern where La through Sm (the Light REE or LREE) are sequentially depleted, have a negative Europium anomaly, followed by a progressive enrichment moving stepwise from Gd to Lu (Heavy REE, HREE). REE in each of the four fragments of Almahata Sitta analyzed for this work do not show this V-shaped REE pattern, but rather are LREE depleted (Fig. 1), but none of the depletions retreat below 0.01×CI.

It has been shown with analyses of multiple fragments of Roosevelt County 027 that V-shaped patterns can exist within the same rock as LREE depleted patterns (Goodrich et al. 1987), but the evidence so far would seem to lean toward Almahata Sitta possessing solely a LREE depleted pattern. It is interesting to note that the slope of HREE elements (Gd > Lu) is steeper in the case of the highest depletion (Fig. 1). In contrast, the relative magnitude of the Eu anomaly does not correlate with degree of depletion. LREE elements (short of Sm) show very different patterns in each sample, with course grained samples apparently having the steeper LREE.

Polymict ureilites such as EET 83309, EET 87720, North Haig, and Nilpena are known to have REE contents that are generally higher than other ureilites, and Jenniskens et al. (2009) took the pattern for fragment #7, which does not fall below 0.1×CI, to support a polymict chemical affinity for Almahata Sitta. With the addition of our new data, especially for that of fragment #4, which was sampled at the same mg scale that most INAA REE data was gathered, this may not be the whole story. Our results for fragments #4 and #47 show a severely depleted LREE pattern were HREE contents barely manage to break 0.2×CI.

Since our primary concern was to obtain bulk compositional data, we preformed no leaching experiments like those of Spitz and Boynton (1991) on our samples; however, we can speculate on what such experiments would yield. We predict that a LREE enriched component is present and would be seen, that is, a HNO_3 leachate would present such a pattern. As mentioned by Goodrich (1992), the carrier of this LREE phase is probably present in variable amounts and it would appear that Almahata Sitta, at least with respect to the samples analyzed for this study, contain very little of this component.

Lithophiles

Figure 2 shows CI-normalized and, to remove the effect of volatiles (such as C) from the comparison, Mg-normalized abundances for several representative lithophile elements in Almahata Sitta, several polymict ureilites, and ranges of abundances within ureilites as a group. The general abundances are consistent with an ultramafic mineralogy being relatively enriched in Sc V, Cr, Mn, and despite its volatile nature, Zn (see Volatile Trace Elements section below).

There are 20 identified polymict ureilites known (Meteoritical Bulletin Database, 2009), and four (EET 83309, EET 87720, Nilpena, North Haig) of those have substantial compositional data available for comparison. Mittlefehldt et al. (1998) noted that polymict ureilites in general possess higher abundances of Al, Cs, K, Na, and Zn than average ureilites. The abundances of Cs and Zn in Almahata Sitta fragment #7 are all at the higher end of the ureilite composition and this observation was a factor in the classification of Almahata Sitta as a polymict ureilite (Jenniskens, et al. 2009). Here we find, that other fragments of Almahata Sitta do not necessarily share the same enrichments with fragment #7: samples of fragments #4, #15, and #47 analyzed by us tend toward compositions of a typical (monomict) ureilites.

We collected data for several other lithophile elements (Li, Y, Zr, Nb, Hf, Ta, Th, and U) that are not shown in Fig. 1 since little literature data was available for direct comparison. However, we can comment that the data omitted from Fig. 1 both reflect the ultramafic composition of ureilites and at the same time seem to parallel the compositional trends demonstrated by those elements shown in Figs. 1 and 2. For example, Y, Th, and U in fragment #15 are all higher than those found in the other fragments analyzed, as may be expected since REE are also enriched in that sample (Fig. 1).

Ratios of some important lithophile elements can shed light on the composition of Almahata Sitta. CI-normalized Ca/Al ratios in Almahata Sitta #4, #15, #47 are respectively 4.3, 9.5, and 6.3. These values are known to range from between 0.6-8.0 (Goodrich 1992**.** CI-normalized Mn/Mg ratios are respectively 0.73, 0.78, 0.70, which compare well with the typical value of ~0.7 in ureilites. CI-normalized Cr/Mg ratios in Almahata Sitta fragments are 0.61, 0.57, and 0.87. The values of fragment #15 is generally lower than those found in ureilites, which rarely have values lower than ~0.6 and, again, some degree of sampling error may account for this. However, overall, from the perspective of major and minor elements, Almahata Sitta is clearly a ureilite.

Finally, we feel it is necessary to point out that Almahata Sitta, does not in any way compositionally resemble LEW 88774, a thoroughly anomalous monomict ureilite (Chikami et al. 1997) that is enriched in Sc, Ca, V, and especially Cr.

Siderophiles

Siderophile concentrations in ureilites are known to be inhomogeneous and quite variable within cm-distance subsamples of even the same meteorite (Rankenberg et al. 2008, and references therein). These variations have been known to be up to thousands of a percent, so some caution must be taken with bulk abundances within our small analyzed fragments. To compensate for sampling effects, we show our siderophile data as both CI- and Fe-normalized. Even so, we should point out that simply CI-normalized siderophiles and moderately siderophile elements in Almahata Sitta, typically fall within previously encountered values for ureilites.

Upon examining the data in Fig. 3, we can see that for especially Ir, Pt, Ni, Co, siderophile contents parallel one another. That is, for fragments high in one element, other siderophiles are also higher in abundance. We attribute this to the fact that siderophiles in ureilites seem to derive from at least two components (Boynton et al. 1976; Rankenberg et al. 2008). One component is characterized by super-chondritic abundances of refractory siderophile elements such as Ir and Pt, while the other component is closer to chondritic in composition. Aside from Ru, for which our uncertainty is larger than for other elements (Table 1), abundances of W through Ga (n=10, Fig. 3) all reflect similar contributions from these two components. However, as we increase in volatility and decrease in siderophilic character with Ag, Sb, As, and Sn, the contribution from the second, more volatile component is more variable. Overall, our additional data for siderophiles supports and augments the data available for the multiple, but common components of siderophile elements in ureilites.

We should point out that our values for Ag are higher than those previously reported for ureilites. The apparently high Ag values (Fig. 3) in our samples of Almahata Sitta may either reflect a low maximum value for Ag literature data rather than a bias within our results since the mean (n=22) Ag value for literature data is 18 ng/g, while our mean value and 2σ for four Almahata Sitta fragments is 30±12 ng/g, barely coinciding with reported values. We feel the origin of the discrepancy is a lack of ureilites that have quantified both Fe and Ag within the same analytical aliquot (n=0) rather than simply for the same meteorite (n=6), since the latter is what is shown in Fig. 3, but have indicated that these values are suspicious in Table 1.

Volatile Trace Elements

Mean concentrations of elements possessing greatest volatility in our 60 element suite are generally depleted in Almahata Sitta consistent with previous ureilite studies (Wang and Lipschutz 1995). The mean CI-normalized concentrations of four highly volatile trace elements for which we report absolute concentrations (Bi, Te, Se, and Cd) demonstrate a relatively flat trend with a mean value 0.050±0.002. CI-normalized concentrations for Tl and In are <0.06 and

<0.04, respectively. Zn, however, is an exception to this trend. Concentrations of Zn in our four fragments are significantly enriched with respect to the other highly volatile elements. The concentration of Zn and in fragment 47 approach CI concentrations. The mean CI-normalized Zn concentration for our four fragments is 0.53±0.32. High Zn concentrations have been attributed to its proxying for Fe^{2+} in olivine (Goodrich 1992). Together, results for these volatile trace elements do not reflect primary nebular processes but rather high temperature secondary evolution in their parent.

Ureilites, Polymict Ureilites, and Almahata Sitta

The current range of samples is still too small to discuss with confidence how the observed variations in composition may relate to meteorite texture, density, and other properties. However, Rumble et al. (this volume) found that Almahata Sitta fragments #4, #15, #44, #47, and #49 seem to cluster with respect to $\Delta^{17}O$ and hypothesized that this subgroup of fragments may record a localized volume within the Almahata Sitta parent asteroid. Although our samples were small, potentially introducing sample size bias effects, most Mg- or Fe-normalized respective lithophile and siderophile abundances of these samples do not cluster more closely together with themselves than with fragment #7 (e.g. Figs. 2 and 3). However, fragment #7 seems to resemble a more typical polymict ureilite composition, especially with levels of Rb, and Cs falling at the high end of ureilite composition (Fig. 2). High values of Rb and Cs were originally regarded as supporting evidence for a polymict classification by Jenniskens et al. (2009) and this observation holds for fragment #7, but from a chemical perspective does not hold for other fragments analyzed for this work. This implies that polymict and monomict ureilitic material can co-exist in the same asteroid on a few meter size scale. We did not have an opportunity to analyze any materials other than fragment #7 that lie outside the cluster of Δ^{17}O isotopic ranges defined by the subgroup of fragments #4, #15, #44, and #47 and this may be of interest for further study.

CONCLUSIONS

Almahata Sitta has a composition consistent with other ureilites. REE patterns in Almahata Sitta are LREE depleted, with negative Eu anomalies and HREE enrichments. The abundances of REE only reach CI values in the case of our sample of fragment #15. The LREE enriched V-shaped pattern found in many ureilites is absent within our samples of Almahata Sitta. Of the fragments analyzed for this work, trace lithophile results from fragment #7 seem to more closely resemble those of other polymict ureilites, but the abundances for the same elements in fragments #4, #15, and #47 seem to most resemble typical monomict ureilites. We have seen that CI and Fe normalized siderophile abundances in Almahata Sitta are consistent with a two component model of petrogenesis, with highly siderophile elements displaying parallel enrichments across all fragments and less siderophilic elements present in more variable abundances. Taken together, our results imply that polymict and monomict ureilitic material can co-exist in the same asteroid on the spatial scale of a few meters.

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Table 1. Bulk composition of four fragments of the Almahata Sitta ureilite.

element	unit	fragment #7[†]	fragment #4	fragment #15	fragment #47
Li	µg/g	1.7	1.0	0.95	1.3
Na	mg/g	NA	0.26	0.76	0.26
Mg	wt-%	NA	24.5	20.9	21.1
Al	wt-%	NA	0.262	0.477	0.148
P	mg/g	NA	0.74	1.6	0.49
K	mg/g	NA	<0.03	<0.03	<0.03
Ca	wt-%	NA	1.05	4.23	0.87
Sc	µg/g	9.0	9.2	20.2	7.8
Ti	µg/g	274	175	676	126
V	µg/g	84	87	118	88
Cr	mg/g	NA	4.18	3.34	5.02
Mn	mg/g	3.06	3.72	3.66	2.70
Fe	wt-%	NA	10.7	9.99	16.3
Co	µg/g	240	35	55	150
Ni	µg/g	NA	604	828	1890
Cu	µg/g	12	11	8.2	8.2
Zn	µg/g	105	154	88	307
Ga	µg/g	4.2	1.9	3.5	3.0
As	µg/g	1.0	1.0	≤ 0.3	1.1
Se	µg/g	1.0	1.5	0.9	0.8
Rb	ng/g	255	19	≤ 15	37
Sr	ng/g	551	613	1900	104
Y	ng/g	610	380	2600	180
Zr	ng/g	470	100 ± 20	1500	100
Nb	ng/g	180	20	30	30
Mo	ng/g	1600	110	300	300
Ru	ng/g	300	≤1340	380	NA
Ag	*ng/g*	*30*	*40 ± 10*	*20*	*30*
Cd	ng/g	NA	35	NA	NA
In	ng/g	NA	≤ 3	NA	NA
Pd	ng/g	140	30	60	60
Sn	ng/g	210	30 ± 10	20	60
Sb	ng/g	100	≤ 25	20	≤ 18
Te	ng/g	120	140	70	120
Cs	ng/g	19.2	0.4	2.0	2.5
Ba	ng/g	247	43 ± 12	421	273
La	ng/g	27	5.1	50	4.2
Ce	ng/g	58	17	130	10
Pr	ng/g	9.5	3.9	35	1.5
Nd	ng/g	48	27	254	6.7
Sm	ng/g	24	16	160	4.0
Eu	ng/g	5.6	5.1	22	0.8
Gd	ng/g	43	29	270	8.6
Tb	ng/g	10	7.1	62	2.5
Dy	ng/g	66	50	347	17.9
Ho	ng/g	19	13	90	5.8
Er	ng/g	65	42	259	21
Tm	ng/g	13	8.1	42	4.7
Yb	ng/g	81	54	256	35
Lu	ng/g	18	12	47	8.1

Table 1. *Continued*. Bulk composition of four fragments of the Almahata Sitta ureilite.

element	unit	fragment #7[†]	fragment #4	fragment #15	fragment #47
Hf	ng/g	14	5	53	3
Ta	ng/g	0.5	0.08	0.6	0.1
W	ng/g	300	11 ± 5	35	24
Re	ng/g	65	5	7	48
Ir	ng/g	700	50	90	340
Pt	ng/g	1000	70	100	500
Tl	ng/g	NA	≤ 9	NA	NA
Bi	ng/g	≤ 2	≤ 8	6	NA
Th	ng/g	2.5	0.3	8.2	1.2
U	ng/g	0.9	0.2	8.4	0.6

† Trace element results reproduced from Jenniskens et al. (2009) for sake of comparison. Small fragments of ureilites are relatively inhomogeneous for sample masses analyzed – see Methods section. For an estimate of intra-fragment homogeneity in the case of fragment #4, all sample replicates are within 24% relative standard deviation except where errors are listed. NA=not analyzed. Suspiciously high values (for Ag) shown in *italics* (see text).

Fig. 1. REE abundances in four fragments of Almahata Sitta. REE patterns of Almahata Sitta show the depleted patterns associated with ureilites but also possess relatively depleted LREE patterns. Although many ureilites possess V-shaped REE patterns where La-Sm are progressively depleted from values similar to the HREE, this feature is absent in Almahata Sitta.

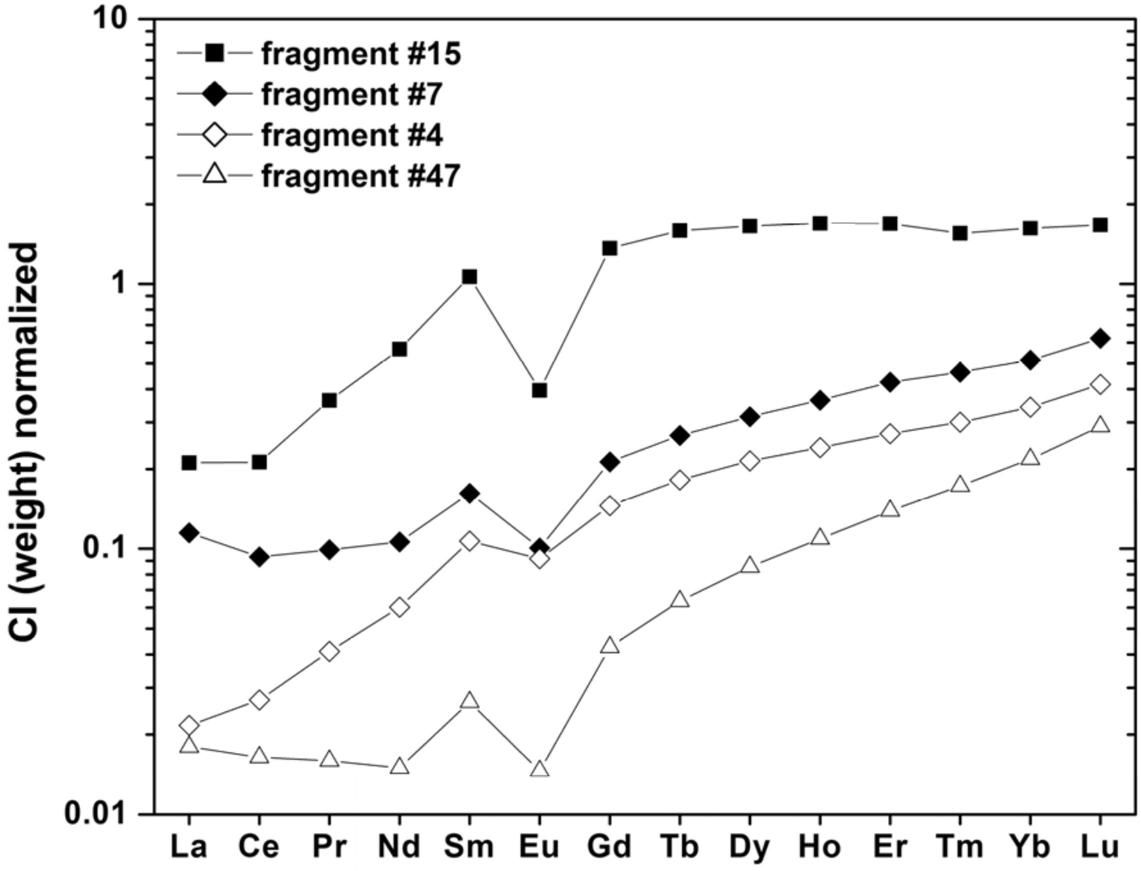

Fig. 2. CI- and Mg-normalized lithophile element abundances in four fragments of Almahata Sitta and, where available, polymict ureilites. Ranges of literature values are shown as horizontal lines. A mean of the Mg concentration (22.2%) of the other three fragments was used for normalization of fragment #7 data and a mean value for Mg in ureilites was used for normalization of literature Sr, Rb and Cs rather than individual values since few determinations exist for both the element in question and the normalizing element in the same sample.

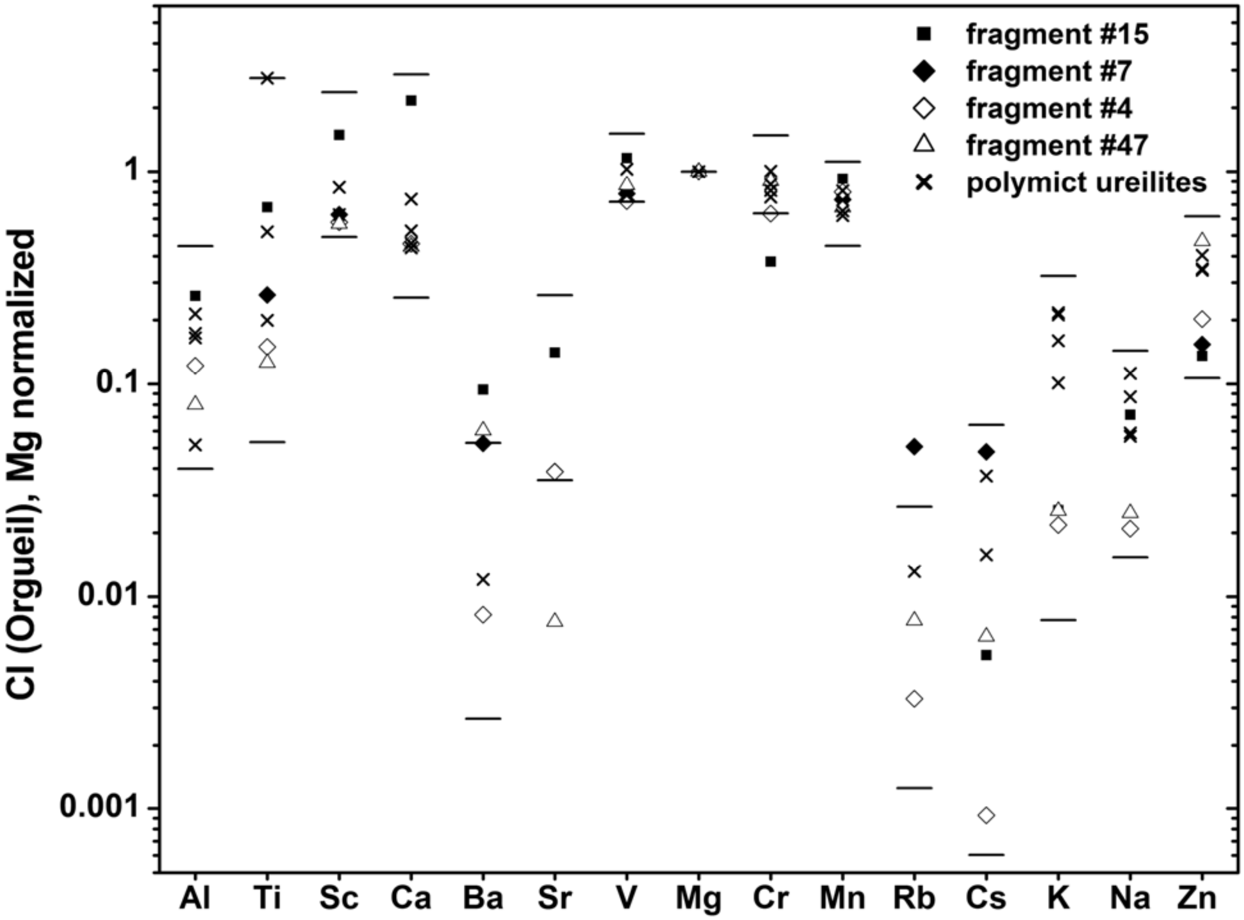

Fig. 3. CI-and Fe-normalized siderophile and moderately siderophile element contents in four fragments of Almahata Sitta compared with ranges of compiled literature values for ureilites. Elements are arranged in order of putative volatility. Ranges of literature values are shown as horizontal lines. A mean of the Fe concentrations (12.3%) of the other three fragments was used for normalization of fragment #7 data, which seems atypically enriched in siderophiles as a result of a compositionally unrepresentative fragment (see Results section). Generally, highly siderophile (e.g. Re, Ir, Pt, Ni, Co, Pd) elemental abundances parallel one another indicating a common reservoir of those elements in Almahata Sitta. The more volatile elements at the right show greater variability, probably reflecting a compositionally variable second chondrite-like complement of moderately siderophile elements.