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# BULK CHEMICAL COMPOSITION OF SOŁTMANY CHONDRITE

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**Abstract:** The authors examined the bulk chemical composition of the Sołtmany chondrite which fell on April 30th, 2011 in Northern Poland. Based on the analysis of 47 elements, it was concluded that Sołtmany is representative of L-type of ordinary chondrites. However, compared to the average values observed in other L-type ordinary chondrites, Sołtmany displays higher content of Ni, P, Cd, Pb, and As. The Ni and P content closely resembles typical values for H-type ordinary chondrites. Furthermore, Sołtmany displays other distinct properties including very low Zn content and lower contents of Mo and Zr than the average values found in other L-type ordinary chondrites. Consistent with other L-type ordinary chondrites, the absolute content of REE in Sołtmany is higher than that of CI-type carbonaceous chondrites while the REE trend lines for both Sołtmany and CI-chondrites are similar.

Due to similar times of year of when both falls took place and the proximity of their strewn fields, the chemical composition of Sołtmany was compared with that of Jesenice, an L6 ordinary chondrite which fell on April 9th, 2009 in Europe. The analysis led to a conclusion that Sołtmany and Jesenice are not launch-paired. Nevertheless, even though they do not represent fragments of the same meteoroid, their origin on a common parent body (an asteroid – planetesimal) cannot be conclusively ruled out on the sole basis of their bulk chemical composition.

**Key words:** Meteorite, ordinary chondrite, L chondrite, bulk composition, meteorite fall, observed fall

## INTRODUCTION

Sołtmany meteorite fell on April 30th, 2011 at 6:03 am CEST in Sołtmany village (Warmińsko-Mazurskie Province, Poland; 54°00.53'N, 22°00.30'E). The meteorite was classified as an L6 ordinary chondrite with a weathering grade W0 and a shock stage S2 (Karwowski et al., 2011; Karwowski, 2012). A chemical composition analysis was performed during Sołtmany's original classification. The purpose of this study was to validate Sołtmany's classification results which were based solely on the chemical composition of its respective mineral phases and structural features (Karwowski, 2012). The results of the analysis conducted during classification were further compared with the magnetic susceptibility data which had been also used to classify Sołtmany (Rochette et al., 2012). Yet, the primary purpose of this analysis was to provide a more comprehensive study of Sołtmany's chemical composition than the work done during the original classification.

## SAMPLES AND METHOD OF CHEMICAL ANALYSIS

Four small fragments of Sołtmany with the total weight of 12.8 g, provided by Mr. Marek Woźniak, were used for chemical composition analysis. The fusion crust was separated from these fragments and the remainder was crushed and grinded in an agate mortar at the Geological Laboratory of the Institute of Mining Engineering of Wrocław University of Technology. The ground sample of 10.2 g was further submitted for chemical analysis to the Acme Analytical Laboratories Ltd. facility in Vancouver, Canada. The chemical data

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was obtained by means of ICP-MS and XRF analysis. ICP-MS was used to determine the content of the major and trace elements (including REE). XRF analysis was used to measure the nickel content which was too high to be accurately determined by the ICP-MS. The content of volatile elements (C and S) was measured by means of the Leco method.

## RESULTS AND DISCUSSION

The consolidated results of Sołtmany's bulk chemical composition analysis are presented in table 1. Out of 59 analyzed elements, the content of Be, Cs, Sn, Ta, Th, U, W, Sb, Bi, Ag, Hg, and Tl could not be properly determined as the measured values were below the analytical method's detection limits. Consequently, only the content of 47 elements was measured in Sołtmany chondrite (Tab. 1).

The results enabled the authors to accurately determine the bulk chemical composition of Sołtmany, as well as to compare its composition with the average values found in H, L, LL ordinary chondrites and CI carbonaceous chondrites. On the one hand, the new analysis validated Sołtmany's L-type ordinary chondrite classification (Karwowski et al., 2011; Karwowski, 2012; Rochette et al., 2012). On the other

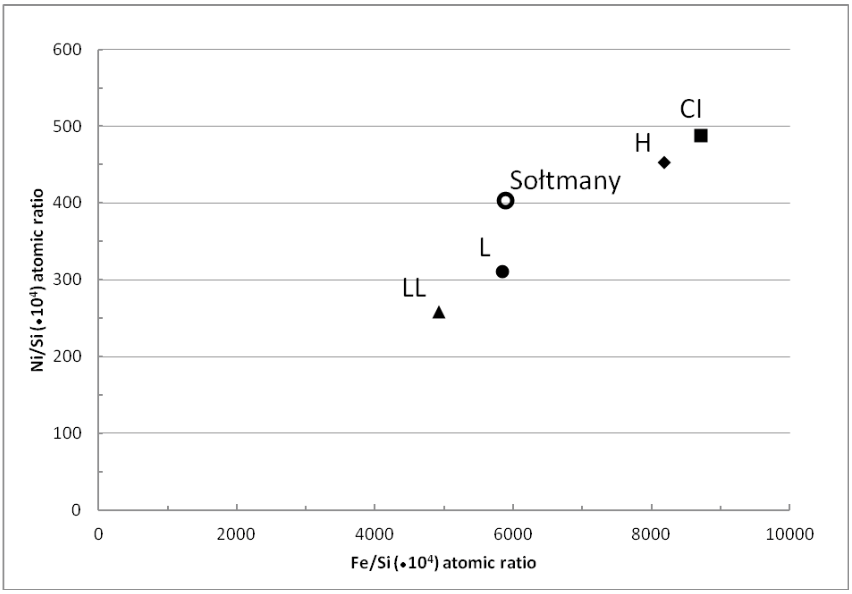



**Fig. 1.** The diagram of Ni/Si(•$10^4$) versus Fe/Si(•$10^4$) for Sołtmany chondrite in comparison to CI, H, L and LL chondrites (after Hutchison, 2006). The ratios are atomic

**Table 1.** Bulk chemical composition of Sołtmany ordinary chondrite. Right column contains values of detection limit (or analytical error)

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Si | | 18.83 | 0.01 | Ni | | 15 900 | 0.1 | W | | <0.5 | 0.5 | Sc | | 10 | 1 |
| Al | | 1.18 | 0.01 | Ba | | 5 | 1 | Mo | | 0.8 | 0.1 | Y | | 2.2 | 0.1 |
| Fe | | 22.02 | 0.04 | Be | | <1 | 1 | Cu | | 82.1 | 0.1 | La | | 0.5 | 0.1 |
| Mg | | 14.73 | 0.01 | Co | | 592.3 | 0.2 | Pb | | 0.1 | 0.1 | Ce | | 0.9 | 0.1 |
| Ca | | 1.37 | 0.01 | Cs | | <0.1 | 0.1 | Zn | | 22 | 1 | Pr | | 0.14 | 0.02 |
| Na | | 0.73 | 0.01 | Ga | | 6 | 0.5 | As | | 2.1 | 0.5 | Nd | | 1 | 0.3 |
| K | | 0.09 | 0.01 | Hf | | 0.1 | 0.1 | Cd | | 0.1 | 0.1 | Sm | | 0.25 | 0.05 |
| Ti | weight % | 0.07 | 0.01 | Nb | ppm | 0.5 | 0.1 | Sb | ppm | <0.1 | 0.1 | Eu | ppm | 0.08 | 0.02 |
| P | | 0.12 | 0.01 | Rb | | 2.5 | 0.1 | Bi | | <0.1 | 0.1 | Gd | | 0.29 | 0.05 |
| Mn | | 0.27 | 0.01 | Sn | | <1 | 1 | Ag | | <0.1 | 0.1 | Tb | | 0.05 | 0.01 |
| Cr | | 0.39 | 0.002 | Sr | | 13.3 | 0.1 | Hg | | <0.01 | 0.01 | Dy | | 0.4 | 0.05 |
| LOI | | -3.9 | 0.1 | Ta | | <0.1 | 0.1 | Tl | | <0.1 | 0.1 | Ho | | 0.09 | 0.02 |
| Sum | | 99.7 | 0.01 | Th | | <0.2 | 0.2 | Se | | 7 | 0.5 | Er | | 0.26 | 0.03 |
| $C_{TOT}$ | | 0.03 | 0.02 | U | | <0.1 | 0.1 | Zr | | 4.5 | 0.1 | Tm | | 0.04 | 0.01 |
| $S_{TOT}$ | | 2.12 | 0.02 | V | | 77 | 8 | Au | | 0.161 | 0.0005 | Yb | | 0.29 | 0.05 |
| | | | | | | | | | | | | Lu | | 0.04 | 0.01 |

**Table 2.** Bulk chemical composition and selected atomic ratios of Sołtmany chondrite in relation to the composition and characteristic atomic ratios of ordinary chondrites' groups and CI carbonaceous chondrites (after Hutchison, 2006)

| Chondrites / Element | | H | L | LL | Sołtmany | CI |
|---|---|---|---|---|---|---|
| Si | weight % | 16.9 | 18.5 | 18.9 | 18.83 | 10.5 |
| Ti | | 0.060 | 0.063 | 0.062 | 0.07 | 0.042 |
| Al | | 1.13 | 1.22 | 1.19 | 1.18 | 0.86 |
| Cr | | 0.366 | 0.388 | 0.374 | 0.39 | 0.265 |
| Fe | | 27.5 | 21.5 | 18.5 | 22.0 | 18.2 |
| Mn | | 0.232 | 0.257 | 0.262 | 0.27 | 0.19 |
| Mg | | 14.0 | 14.9 | 15.3 | 14.73 | 9.7 |
| Ca | | 1.25 | 1.31 | 1.30 | 1.37 | 0.92 |
| Na | | 0.64 | 0.70 | 0.70 | 0.73 | 0.49 |
| K | | 0.078 | 0.083 | 0.079 | 0.09 | 0.056 |
| P | | 0.108 | 0.095 | 0.085 | 0.12 | 0.102 |
| Ni | | 1.60 | 1.20 | 1.02 | 1.59 | 1.07 |
| Co | | 0.081 | 0.059 | 0.049 | 0.059 | 0.051 |
| S | | 2.0 | 2.2 | 2.3 | 2.12 | 5.9 |
| C | | 0.11 | 0.09 | 0.12 | 0.03 | 3.2 |
| Au (ppb) | | 215 | 162 | 140 | 161.1 | 144 |
| Atomic ratios | | H | L | LL | Sołtmany | CI |
| Mg/Si | | 0.957 | 0.931 | 0.935 | 0.904 | 1.068 |
| Al/Si($\bullet 10^4$) | | 696 | 686 | 655 | 653 | 853 |
| Ca/Si($\bullet 10^4$) | | 518 | 496 | 482 | 511 | 614 |
| Fe/Si($\bullet 10^4$) | | 8184 | 5845 | 4923 | 5881 | 8717 |
| Ca/Al | | 0.74 | 0.72 | 0.74 | 0.78 | 0.72 |
| Ni/Si($\bullet 10^4$) | | 453 | 310 | 258 | 404 | 488 |
| CI normalized Atomic ratios | | H | L | LL | Sołtmany | CI |
| Mg/Si | | 0.90 | 0.87 | 0.88 | 0.85 | 1.0 |
| Al/Si | | 0.82 | 0.81 | 0.77 | 0.77 | 1.0 |
| Fe/Si | | 0.94 | 0.67 | 0.56 | 0.67 | 1.0 |

hand, the analysis made it possible to determine the average chemical composition of Sołtmany which was proven to be slightly inconsistent with typical L-type ordinary chondrites and differentiate Sołtmany from other ordinary chondrites, as well as from CI carbonaceous chondrites.

The L-type ordinary chondrite classification of Sołtmany was undoubtedly confirmed by the total content of iron (Tab. 2 and 3). Table 2 contains additional chemical properties which allowed for Sołtmany's classification as a L-type chondrite. However, further examination of the chemical data (Tab. 2) led to the conclusion that, with the exception of iron, the chemical composition of the elements is not consistent with the average values found in other L-type ordinary chondrites.

The affiliation of Sołtmany with other L-type ordinary chondrites is depicted on figure 1. The diagram also reveals a high Ni content, which is more characteristic of H-type ordinary chondrites. The P content in Sołtmany chondrite is also more closely aligned with H-type chondrites. These observations are consistent with the higher content of taenite and tetrataenite phases compared to kamacite, as well as significant content of merrillite and apatite, which was determined by Karwowski (2012) in the mineral composition of Sołtmany chondrite. The analysis of data from figure 2 and table 3 reveals further characteristic properties of Sołtmany's bulk chemical composition. The content of major elements is typical for L-type ordinary chondrites and thus confirms the accuracy of Sołtmany's original classification. Among these elements, however, the content of Ni and P is significantly higher than the values observed in other L-type ordinary chondrites (Fig. 2). Notably, the content of these two elements is similar to that of H-type ordinary chondrites (Tab. 2).

The content of the rare earth elements (REE) in Sołtmany diverges slightly from the average values observed in L-type ordinary chondrites (Fig. 2; Tab. 3). Of note are the higher levels of La and Nd, and the lower levels of Yb, Sm, Sc, and Y. The plot of REE abundances in Sołtmany and CI-type carbonaceous chondrites normalized to L ordinary chondrites (Fig. 2) shows a common trend. However, the absolute values for Sołtmany are consistent with the average values observed in L-type ordinary chondrites and higher than in CI-type carbonaceous chondrites. These results indicate the enrichment of L-type ordinary chondrites in REE in general, and of Sołtmany in particular, as opposed to CI-type carbonaceous chondrites. As far as the parent rock on the parent body of Sołtmany is concerned, it seems that this enrichment had a common origin and character for all the REE as the meteorite exhibits the ratios of respective REE which are characteristic for CI-type carbonaceous chondrites (Fig. 2).

The content of the remaining elements in Sołtmany exhibits a similar trend to that observed in CI-type carbonaceous chondrites (Fig. 2). Among these elements, the average content of Co, Ga, Rb, V, Cu, Se and Au shows the strongest affiliation with other L-type ordinary chondrites. On the other hand, Sołtmany exhibits the highest deficiency in Zn, Mo, and Zr compared to other L-type ordinary chondrites,

**Table 3.** Selected elements' abundances (ppm) in Sołtmany chondrite in relation to average (McSween & Huss, 2010), maximum and minimum abundances of these elements in L-type chondrites (based on data after Koblitz, 2010). The maximum and minimum values for L-type ordinary chondrites were determined on the basis of at least 6 data points for Pb and up to 744 data points for Co.

| element | Sołtmany | average L | range L | element | Sołtmany | average L | range L |
|---|---|---|---|---|---|---|---|
| Si | 188 312 | 186 000 | 155 700–245 000 | Pb | 0.1 | 0.04 | 0.022–0.22 |
| Al | 11 805 | 11 600 | 3 500–114 000 | Zn | 22 | 57 | 1.25–362 |
| Fe | 220 210 | 218 000 | 78 900–892 000 | As | 2.1 | 1.36 | 0.11–21.4 |
| Mg | 147 286 | 149 000 | 112 900–230 000 | Cd | 0.1 | 0.030 | 0.0001–0. 875 |
| Ca | 13 724 | 13 300 | 3 200–272 000 | Sb | < 0.1 | 0.078 | 0.002–1.500 |
| Na | 7 344 | 6 900 | 52–17 000 | Bi | < 0.1 | 0.014 | 0.0001–0.516 |
| K | 913 | 920 | 40–4 150 | Ag | < 0.1 | 0.050 | 0.002–1.110 |
| Ti | 659 | 670 | 57–2 220 | Hg | < 0.01 | 0.03 | 0.015–11.9 |
| P | 1 222 | 1030 | 40–2 970 | Tl | < 0.1 | < 0.005 | 0.00003–0.21 |
| Mn | 2 711 | 2 590 | 44–9 350 | Se | 7 | 8.5 | 0.01–15.8 |
| Cr | 3 860 | 3 690 | 60–9 140 | Zr | 4.5 | 6.4 | 4.3–12 |
| Ni | 15 900 | 12 400 | 27–180 000 | Au | 0.161 | 0.156 | 0.0005–2.770 |
| Ba | 5 | 4.1 | 2.48–150 | Sc | 10 | 8.1 | 2.16–16.6 |
| Be | < 1 | 0.04 | 0.026–0.3 | Y | 2.2 | 1.8 | 1.4–3.84 |
| Co | 592 | 580 | 7–6 840 | La | 0.5 | 0.318 | 0.051–8.27 |
| Cs | < 0.1 | <0.5 | 0.002–2.27 | Ce | 0.9 | 0.970 | 0.064–17.1 |
| Ga | 6 | 5.4 | 2.8–77.1 | Pr | 0.14 | 0.140 | 0.07–0.27 |
| Hf | 0.1 | 0.17 | 0.08–0.29 | Nd | 1 | 0.700 | 0.021–1.57 |
| Nb | 0.5 | 0.4 | 0.39–0.55 | Sm | 0.25 | 0.203 | 0.004–3.15 |
| Rb | 2.5 | 2.8 | 0.51–7.6 | Eu | 0.08 | 0.080 | 0.063–0.26 |
| Sn | < 1 | 0.54 | 0.03–6.78 | Gd | 0.29 | 0.317 | 0.004–0.48 |
| Sr | 13.3 | 11 | 5–314 | Tb | 0.05 | 0.059 | 0.033–0.72 |
| Ta | < 0.1 | 0.021 | 0.01–0.082 | Dy | 0.4 | 0.372 | 0.006–0.71 |
| Th | < 0.2 | 0.042 | 0.03–0.186 | Ho | 0.09 | 0.089 | 0.046–0.13 |
| U | < 0.1 | 0.015 | 0.002–2.2 | Er | 0.26 | 0.252 | 0.009–0.36 |
| V | 77 | 75 | 2.7–122 | Tm | 0.04 | 0.038 | 0.024–0.06 |
| W | < 0.5 | 0.138 | 0.09–1.09 | Yb | 0.29 | 0.226 | 0.028–2.55 |
| Mo | 0.8 | 1.2 | 1.04–5.65 | Lu | 0.04 | 0.034 | 0.007–0.33 |
| Cu | 82.1 | 90 | 52–1540 | | | | |

whereas the highest noteworthy enrichment exists for Cd, Pb and As (Fig. 2).

The content of all the analyzed elements in Sołtmany is presented in table 3 along with their average values and the minimum and maximum values observed in other L-type ordinary chondrites. The content of Mo in Sołtmany deserves particular attention. It is lower than the values ever observed in any of the 64 analyzed L-type ordinary chondrites registered in the MetBase® database (Koblitz, 2010).

Figure 3 shows the content of selected elements in Sołtmany in order of decreasing volatility. The content of all these elements best matches their trends typical for L-type ordinary chondrites. Nevertheless, the presence of certain deviations was identified. As the authors already pointed out, the content of Ni is significantly higher. The content of La is also higher (Fig. 3).

Two ordinary chondrites classified as the L6-type have fallen in Europe in the 21$^{st}$ century. As the two falls took place within the last four years, the authors decided to compare the bulk chemical composition of Sołtmany and Jesenice. The dates of their falls also indicated the possibility of an origin on a common parent body. Sołtmany fell on April 30$^{th}$, 2011 in Poland, whereas the fall of Jesenice was witnessed on April 9$^{th}$, 2009 in Slovenia. However, having compared the data gathered for Sołtmany and the data published by Bischoff et al. (2011) (Fig. 4) for Jesenice, it was inferred that the differences in the bulk chemical composition of the two meteorites are substantial. They are especially pronounced as far as the content of Ti, Co, Zn, Se, Ce, Sm and Hf is concerned. Lesser differences exist for Sc, As, and La. Thus, the theory of a common origin on the same parent rock (in terms of tens – hundreds meters, that is from one meteoroid) should be rejected. Nevertheless, as both chondrites represent undifferentiated rocks (which did not undergo chemical homogenization) and exhibit chemical properties which are typical for L6 ordinary chondrites, their origin on a common parent body (an asteroid – planetesimal) cannot be conclusively ruled out on the sole grounds of their bulk chemical com-

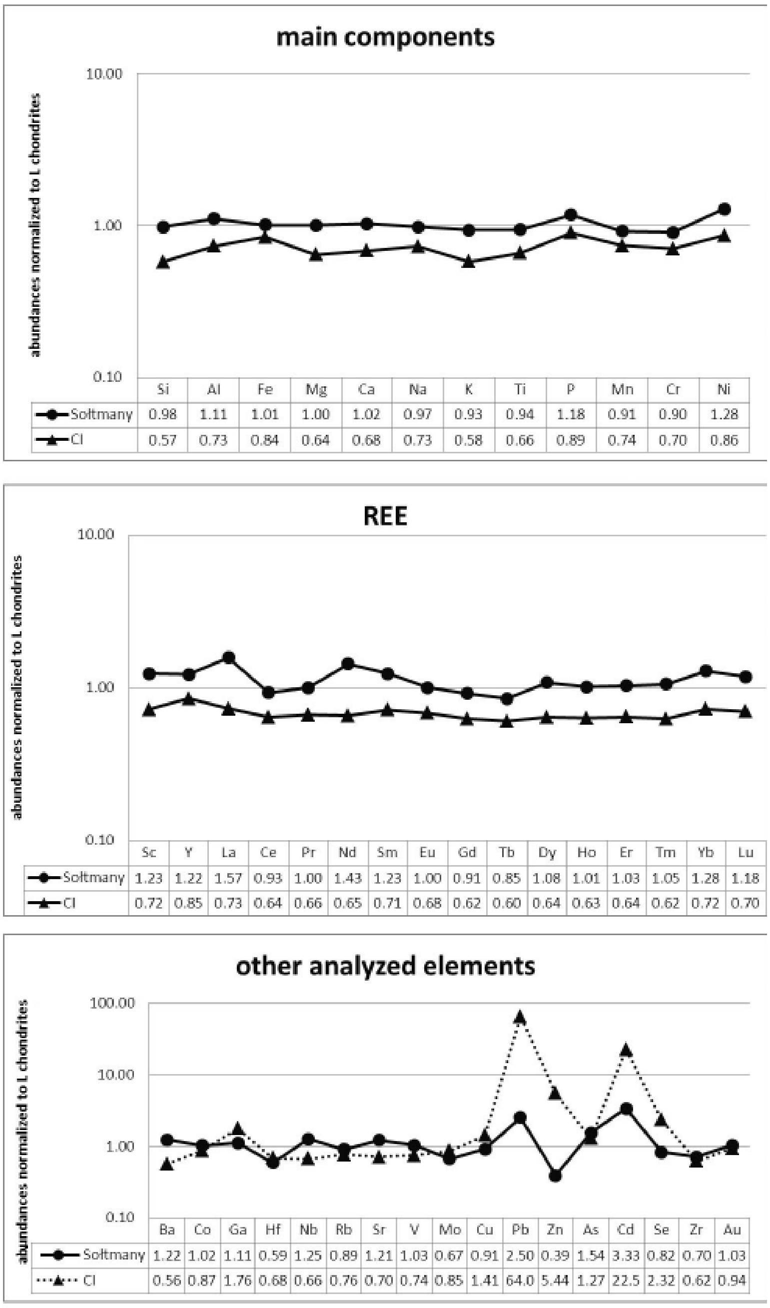



**Fig. 2.** Abundances of elements analyzed in Sołtmany chondrite normalized to L chondrites in comparison to CI chondrites' abundances (after McSween & Huss, 2010)

position. Results of cosmogenic radionuclides measurements also do not provide a definitive conclusion (Bischoff et al., 2011; Laubenstein et al., 2012). To solve this problem definitely one should make some astronomic calculation if it is possible to register a fall of Sołtmany chondrite from the Jesenice chondrite orbit. It needs further examinations and calculations.

## CONCLUSIONS

On the basis of bulk chemical composition analysis conducted by the authors, it was validated that Sołtmany is an L-type ordinary chondrite as concluded in the original classification. Notable results from the bulk chemical composition analysis include a high Ni content resembling that of H ordinary chondrites, and higher levels of P, Cd, Pb and As as compared against average values in L-type ordinary chondrites. Sołtmany also exhibits a lower content of Zn, Mo, and Zr compared to the average values observed in L-

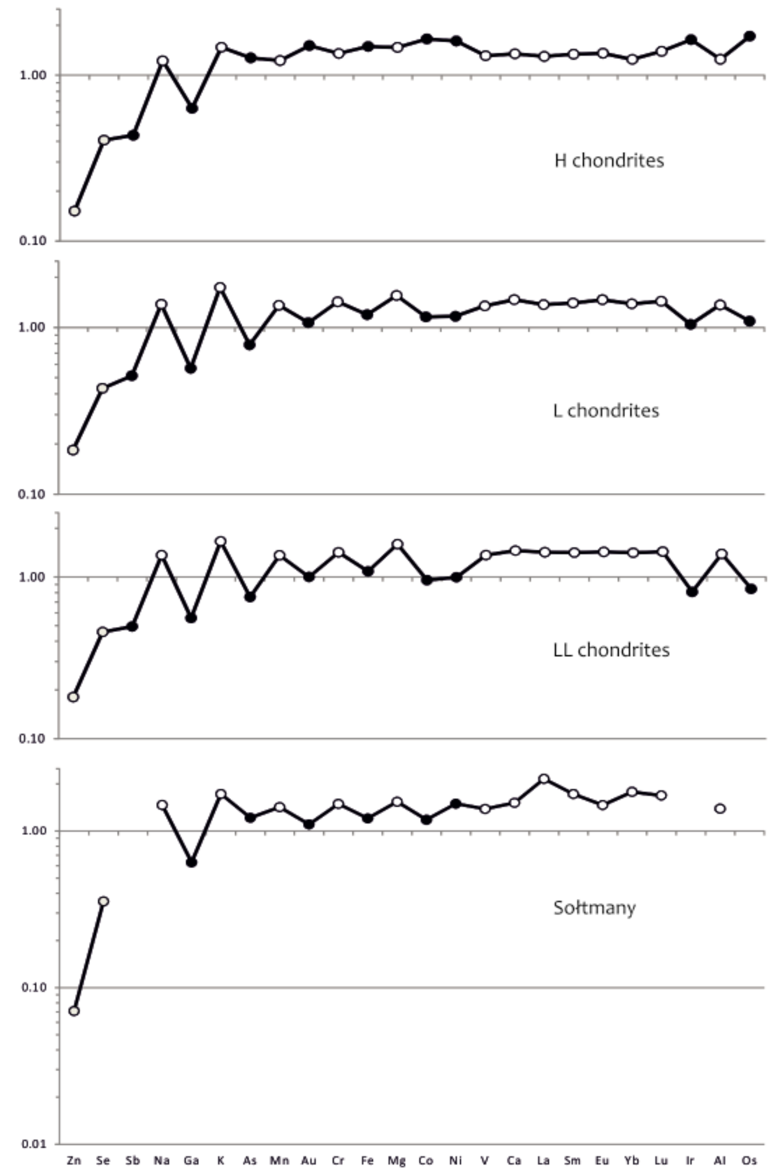
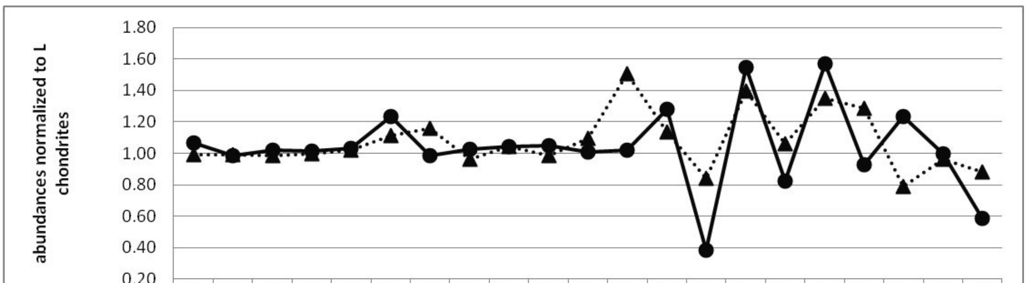



**Fig. 3.** CI-normalized abundances of lithophile (open symbol), siderophile (black symbol) and chalcophile (gray symbol) elements of Sołtmany chondrite in relation to H, L and LL chondrites (after McSween & Huss, 2010)




| | Na | Mg | Al | Si | Ca | Sc | Ti | V | Cr | Mn | Fe | Co | Ni | Zn | As | Se | La | Ce | Sm | Eu | Hf |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sołtmany | 1.06 | 0.99 | 1.02 | 1.01 | 1.03 | 1.23 | 0.98 | 1.03 | 1.05 | 1.05 | 1.01 | 1.02 | 1.28 | 0.39 | 1.54 | 0.82 | 1,57 | 0,93 | 1.23 | 1.00 | 0.59 |
| Jesenice | 0.99 | 0.99 | 0.99 | 1.00 | 1.02 | 1.11 | 1.16 | 0.96 | 1.04 | 0.98 | 1.10 | 1.51 | 1.14 | 0.84 | 1.40 | 1.06 | 1,35 | 1.29 | 0.79 | 0.96 | 0.88 |

**Fig. 4.** Summary of bulk chemical compositions of Sołtmany and Jesenice L6 ordinary chondrites. Both meteorites were witnessed falls in the 21$^{st}$ century in Europe. Abundances are normalized to L-type chondrites (McSween & Huss, 2010). Chemical data for Jesenice were taken from Bischoff et al. (2011)

type ordinary chondrites. The content of REE is also slightly different than the average for L-type chondrites and exhibits a similar trend to that observed in CI-type carbonaceous chondrites. This implies that the process of enrichment of Sołtmany's parent rock in REE against CI chondrites was the same for all of these elements.

A comparison of bulk chemical composition of Sołtmany and Jesenice L6 ordinary chondrites, which were seen to fall in Europe in the 21st century on April 30th, 2011 and April 9th, 2009, respectively, led to a conclusion that these meteorites represent fragments of different parent rocks. Yet, even though they did not originate on the same meteoroid, their origin on a common parent body (an asteroid – planetesimal) cannot be conclusively ruled out on the grounds of their bulk chemical composition.

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