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Photo on cover: A recreation of the pre-impact shape of Sołtmany based upon the four largest fragments of the chondrite (prepared by Wojciech Tunikowski)





JOURNAL INFORMATION

Meteorites provides a coherent international forum for the publication of research in the field of meteoritics and its related disciplines. The topics of interest range from, but are not limited to, meteorites and other kinds of extraterrestrial matter and their sources of origin through the examination of the mineral resources of the Solar System, to tektites, impactites, and impact structures.

Meteorites invites the submission of articles covering the broadly defined field of meteorites. In addition to publication of research results, however, authors are encouraged to share and present astronomical, petrological, mineralogical, geochemical, and isotopic data on all groups and types of meteorites. *Meteorites* is intended to serve as a basic reference source for in-depth analyses and compilations on particular meteorite groups and their parent bodies, as well as the genesis and evolution of the Solar System, as well as other planetary systems.

Considering the progress of human space exploration and conceivable colonization of other planets, this data will likely play an important role in the recognition and exploitation of extraterrestrial mineral resources. Therefore, in light of the potential benefits, *Meteorites* editors have no intention of rejecting paper submissions pertaining to the research of meteorites with provisional names and pending classifications, esp. prior to their approval by the Committee on Meteorite Nomenclature of the Meteoritical Society.

Meteorites invites the publication of important papers intended as reference sources for other researchers, as well as compilations and interpretations of other works on meteorites of lesser scientific importance and their parent bodies. Not only does *Meteorites* welcome submissions of research descriptions and results regarding 'rare' meteorites, and topics such as newly-discovered extraterrestrial mineral species, but it also gladly accepts articles covering more common groups of meteorites. Due to their relatively low scientific value in terms of current research trends, many interesting research results are quietly filed away into archives instead of being published in leading scientific journals.

Our intention is not to compete with existing journals, but to add to the currently limited publication space for researches on meteorites. *Meteorites* editors will gladly accept any reliable research results, including submissions that are virtually impossible to publish in today's existing journals due to the apparent mediocrity of the specimens studied. At *Meteorites*, we believe that even profoundly studied meteorites can have a significant and relevant bearing on our knowledge and understanding of the Solar System. *Meteorites* will, in time, develop into a repository of data and knowledge available for everyone with an interest in extraterrestrial matter.

Our purpose is to develop a new interdisciplinary journal covering the multitude of subject matters involved in meteorite research. Due to an insufficient amount of publication space, the increasing number of specimens available for research, and a growing list of research centers, only a small percentage of valuable submissions is ever brought to publication.

Through the Open Access publications, *Meteorites* aims to support academic work and to act as an accessible research data center. *Meteorites* is available free of charge in print or digital document. Each paper is thoroughly reviewed by experts in the field. Submissions should be sent directly to the e-mail address of the secretary: meteorites@pwr.wroc.pl. Authors are required to follow the guidelines available at http:// www.meteorites.pwr.wroc.pl



FROM THE EDITORS

It is with great pleasure that we present the longawaited double issue of the 2nd volume of *Meteorites*. This issue marks the close of the 2nd year of journal publication. By decision of the editor-in-chief, this issue focuses exclusively on the Soltmany L6 chondrite. Soltmany fell on April 30th, 2011 and was found shortly thereafter. The meteorite struck a farm building, punching a hole through the roof before shattering upon impact with a set of concrete steps. A witnessed meteorite fall is always a rare phenomenon, especially within Poland. The location of Sołtmany's fall allowed for a quick recovery of its fragments and their prompt submission for analysis. It is worth noting that samples of the meteorite were delivered to laboratories in Europe and Canada within just a few days after impact, enabling us to gather highly valuable data on this new meteorite from Poland.

Unfortunately, featuring only one chondrite effectively required gathering papers which needed to be written "on demand", leading to a delay in publishing this issue of *Meteorites*. Yet, given the interesting content of this issue, we believe that was the right direction to take. We also hope that with the help of our authors and reviewers, we will be able to make up for this delay.

The Sołtmany chondrite is the 9th witnessed fall of a meteorite in Poland, yet the first one in the 21st century, and of the petrographic type L6. A few other observed meteor events did not yield new meteorite finds. Only three witnessed falls are officially recorded to have fallen in Poland during the 20th century: Grzempach (1910), Łowicz (1935), and Baszkówka (1994). Four witnessed falls occurred in the 19th and one in the 18th century.

Even though L6 chondrite falls are rather common, only three of them had been witnessed in the 21st century in all of Europe prior to the fall of Sołtmany: San Michele (2002), Villalbeto de la Peña (2004), and Jesenice (2009). Notably, the fall of Jesenice took place in the same month as that of Sołtmany, which may indicate an origin from the same body. Regrettably, due to lack of data, we cannot determine the orbit of Sołtmany's meteoroid prior to its entry into the Earth's atmosphere. Nevertheless, the results of chemical and isotopic analysis presented in this issue of *Meteorites* prove conclusively that these two chondrites did not share a common parent meteoroid or stream of meteoroids.

The detailed account of the fall that follows this letter is the only non-peer-reviewed article in this issue of *Meteorites*. We decided to publish it, as it provides an interesting insight into the location of the fall, as well as an account of the actual event. We also show the exact location of impact on maps with various scales (Fig. 1). The site lies in the Northern part of Poland, near the shore of the Wydmińskie Lake in Sołtmany village. The village belongs to the Kruklanki Commune of Giżycko County in the Warmińsko-Mazurskie Province.

On the following pages, we also present 3D images that recreate the shape of this chondrite before it fell through the roof and violently collided with the concrete steps. The enclosed 3D glasses should be used for a full viewing experience.

On the website of *Meteorites* (www.meteorites.pwr. wroc.pl), you can view additional 3D images as well as animated 3D models of the meteorite intact prior to impact. All 3D images and animations were created by Wojciech Tunikowski based on 3D scans of the four largest fragments of Sołtmany conducted in the Laboratory of 3D Scanning and Modeling in the Institute of History of Architecture, Art and Technology of the Faculty of Architecture of Wrocław University of Technology in Poland.

After over 2 years since the fall, we invite you to explore the models of the intact Soltmany meteorite and read the articles that introduce a broad spectrum of results of its analysis. This double issue of *Meteorites*



Fig. 1. The fall location of the Soltmany L6 chondrite

represents the current state of knowledge on Sołtmany. We departed from the practice of publishing a single article encompassing the standard set of data and conclusions, e.g. as was pursued for the Jesenice L6 chondrite. Instead, this issue of *Meteorites* is a comprehensive compilation of independently-written articles which also cover studies not commonly performed on meteorites, and on ordinary chondrites in particular. With great delight, we encourage you to read the very last article in this issue by Philippe Schmitt-Kopplin and team. The authors present the results of organic



Fig. 2. A recreation of the pre-impact shape of Sołtmany based upon the four largest fragments of the chondrite (prepared by Wojciech Tunikowski)



Fig. 3. Another view of the pre-impact shape of Sołtmany (prepared by Wojciech Tunikowski)



Fig. 4. Yet another view of the pre-impact shape of Sołtmany (prepared by Wojciech Tunikowski)



Fig. 5. A 3D view of the reconstructed Soltmany chondrite (prepared by Wojciech Tunikowski)



Fig. 6. Another 3D view of the reconstructed Soltmany chondrite (prepared by Wojciech Tunikowski)



Fig. 7. Another 3D view of the reconstructed Soltmany chondrite (prepared by Wojciech Tunikowski)



Fig. 8. Yet another 3D view of the reconstructed Soltmany chondrite (prepared by Wojciech Tunikowski)

matter analysis in Soltmany, which we see as a delectable "dessert" of the current issue of *Meteorites*.

Analyses of the physical properties of meteorites (including chondrites), albeit published more often, are also relatively rarely available. We are happy to present the related articles by Marian Szurgot and co-authors and Pierre Rochette with co-authors. We would also like to highlight the article by Łukasz Karwowski, which not only offers insight into the mineral composition and texture of the Soltmany meteorite and its parent rock, but also provides a rarely published comprehensive description of the stone's fusion crust. The fusion crust is the result of friction between the meteoroid and air molecules during its passage through the Earth's atmosphere. It is an important topic, as ablation in the atmosphere is the final process forming the mineral composition and texture of the outer part of the meteorite. Last, but certainly not least, we highly recommend the remaining articles for further essential information on the mineral, chemical, and isotopic composition of this chondrite. These papers deal with the size of Sołtmany's parent meteoroid before its entry into the Earth's atmosphere, the age of its parent body, and the time the meteoroid spent exposed to solar radiation, from the moment of its escape from its parent body until it fell to the surface of the Earth. Once again, it should be emphasized that it was the quick recovery and submission of samples between a few and a dozen days after impact that made many of these analyses possible.

The editor-in-chief, who was privileged to coordinate the studies of Sołtmany, would like to express his gratitude to everyone who offered their help with quick collection of the fragments of the meteorite and the necessary effort to prepare the samples for analysis. Acknowledgement is also in order to everyone who conducted often non-standard analyses and made their results available for publication in this issue of *Meteorites*. Finally, we would like to thank the reviewers who played a key role in ensuring the scientific integrity of the articles. Given the quantity and scope of performed analyses, we may hazard the statement that Sołtmany is now likely the most comprehensively-studied meteorite from Poland.

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ACCOUNT OF CIRCUMSTANCES SURROUNDING THE FALL OF A METEORITE IN SOŁTMANY VILLAGE

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REPORT FROM THE PLACE OF THE EVENT

Site

A tourist farm owned by Mrs. Alfreda Lewandowska in the village of Sołtmany. Sołtmany belongs to the administrative district of Kruklanki, within Giżycko County. The exact GPS coordinates of the fall site are 54°00'31,5"N, 22°00'17,86"E (taken from a GPS unit and validated against maps available at geoportal. gov.pl).

Time

The event took place on April 30th, 2011 at approximately 06:03 am local time.

Meteorite

The meteorite turned out to be an ordinary chondrite, a type of stone meteorite. The stone penetrated a wooden roof and came to rest on a concrete step. Upon impact, it broke into several pieces, the largest of which, a so called "main mass", weighed -813 grams. The total known weight of the meteorite is at -1066 grams.

The probable trajectory of the object was determined from the two terrestrial points of contact. It was flying almost vertically (at an angle of 2–3 degrees) from the North-East.

Photographic records

Photographs of the specimen and the impact site were taken on May 2^{nd} and 3^{rd} , 2011. They are enclosed at the end of this article.

SOŁTMANY – ACCOUNT OF OUR VISIT

On Sunday, May 1st, 2011, Andrzej Pilski, astronomer and meteorite collector of the Frombork Astronomical Observatory, notified the authors of a reported meteorite fall near Giżycko.

The event took place on Saturday, April 30th, at approximately 6:06 am. Andrzej asked if we could drive to the scene of the meteorite impact. By that evening, he confirmed the stone's whereabouts and provided the first photographs of the alleged meteorite. There was no doubt as to the origin of the stone. On May 2nd, we drove to Frombork to settle the facts. Our objective was to gather as much information as possible

including witness statements and photographic evidence of both the scene and fragments of the meteorite. We aimed to acquire samples in order to have the stone analyzed and classified. We were also to inquire as to whether the main mass could be potentially purchased by the Frombork Museum. Our contact in Giżycko was Roman Rzepka, a fellow meteorite enthusiast. He was the same person who informed Andrzej Pilski about the fall.

On May 1st, Mr. Rzepka and his wife were the first to reach the scene of event. They introduced us as they were already acquainted with the landlady. Mr.

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Rzepka also accompanied us on the way to Sołtmany, around 30 kilometers from Giżycko.

Upon arrival, we noticed a hole in the roof. Chunks of asbestos from the roof and wood chips from planks were scattered around the place. We examined the stone and the fragments which had broken apart when the stone had hit the concrete stair. Then we wrote down the account of the fall and acquired samples for study. Unfortunately, it was already too late to take additional photographs of the stone.

We also had a conversation on the desired future of the meteorite with its owner, Mrs. Alfreda Lewandowska. It seemed appropriate for the stone to be placed into a museum collection. We purchased around 190 grams of the meteorite, the entire material that was available for sale. Mrs. Lewandowska kept some of the small fragments as "good luck charms," as she put it. She also advised that she had made a commitment to Andrzej Pilski that he would be offered the largest remaining piece ("main mass"). On the following day, we came back to Soltmany to secure photographic evidence. We took photographs of the stone and the scene of the event. Accompanied by the landowners, we also searched the surroundings of the shed. Unfortunately, we did not find any further fragments of the meteorite.

Alfreda Lewandowska's account of the fall:

April, 30th 2011

I always get up at 6 am without an alarm clock. [On that day] I was smoking and making coffee. I opened the window so that the smoke would not hover inside the kitchen. Then all of a sudden I heard something. At first, I did not know what it was. It sounded like a whiz-bang and was followed by a big boom. Actually, it was more like a long thud kind of noise. My son, Marcin, was in the bathroom. He heard it too even though the door was closed. We both ran out of the house. Marcin was literally wearing only one sock. We thought the house would collapse, but it was still standing. The buildings were intact apart from a hole in the shed roof, right over the door. We found loose asbestos lying near the shed and a big chunk of it hanging on a nail. Marcin thought that it must have been a bird which dropped something. I could not help noticing "what a bird would that have to be". We gazed into the sky looking out for planes as they often fly above our heads. But there was no sign of them. Although the sky was cloudless, the sun was not yet shining strongly.

5 meters away from the hole, by a pile of planks, I found a black stone. I picked it up. Was it warm? It definitely did not seem as cold as any other stone. It was just different, maybe a bit warmish. I held it in my hands for a while and then put it back on the ground. I was about to throw it, but in the end I put it back gently where I took it from.

We came back to the house. I looked at my watch. It was 6:06 am. We spent no more than 3 minutes outside. Later on I went to Giżycko to visit my daughter, Anita. "Mom, it is a meteorite," she pointed out immediately. Then I recalled having watched a documentary about meteorites on Discovery channel. It was hosted by a guy with long hair [it was likely Robert Haag].

Me and my daughter arrived back at home. Fragments of the stone were scattered over an area of 4-5 meters. Small pieces were laying near the concrete step. We picked them up. Additional fragments were later recovered by my daughter and son in law. We took the stone home and started pondering.

Mrs Alfreda, who is a direct and clear-headed person, also shared a peculiar observation with us.

My father used to stop by every day at 6 am to drink coffee with my husband. I was not getting up so early. My father passed away in June and my husband was gone one year later. I thought that this meteorite must be some kind of a sign. Maybe they were drinking coffee in heaven and dropped something?

Mrs. Alfreda, her daughter, and future son in law, searched the surroundings of the shed to no avail. The area is sparsely populated. According to Mrs. Alfreda (and other people living in the house), there were no other witnesses. None of the people living in the vicinity saw the fall or heard any sounds accompanying it.

OUR CONCLUDING REMARKS

1. The description of sounds accompanying the event (whistle and rumble, no explosions) indicates that only one stone was involved. There was no noise which would suggest a possible fragmentation. The rumble reported by the witness was likely caused by a sound wave.

2. The specimen displays the characteristics of orientation. The fragments fit together to form what appears to be a complete stone. It is quite oval in shape and fully covered with fusion crust. If any fragmentation occurred during atmospheric flight, it must have taken place at a high altitude.

3. The hole in the roof (through asbestos roofing and thick planks) and the markings in concrete left by the stone made it possible to estimate the direction and angle of the stone's flight. It came from the North-East and its trajectory was 2-3 degrees from vertical. The meteorite punched a perfect hole through a thick

plank without breaking it which indicates that the stone fell with a very high velocity. As the meteorite lost its initial cosmic velocity in the atmosphere, the trajectory of the fall was undoubtedly altered. Thus, the aforementioned angle should not be perceived as the angle at which the meteoroid entered the Earth's atmosphere. If we are to correctly calculate the trajectory of the last stage of flight, we must take into account that the impact into roof planks also could have altered both its angle and direction. Therefore, the estimated direction of the fall should be regarded as probable. We must also consider the influence of wind on the trajectory of the meteorite. If we assume free fall in the atmosphere as well as a simple model according to which a meteorite is a sphere of density of 3.35 g/cm^3 (average density of a chondrite), the weight of 1 kg and a friction coefficient of 0.45, falling down in a gravitational field, then the velocity of the fall must have been of at least 82 m/s (approx. 295 km/h).

4. The main mass of the meteorite is at approx. 813 grams with a total known weight of approx. 1066 grams. Respective weights of smaller fragments were provided by their owner. Thus, a number of specimens were not weighed by us. Some of them, treasured "as souvenirs," "for her daughter," etc. were wrapped in handkerchiefs. Small fragments may be yet to be found below the planks piled alongside the shed. We determined the weights of the main mass

On Tuesday, May 3rd, already at home, we took photographs of the specimens we had acquired and immediately transcribed this account. In the evening of that day, the first information was published online at http://wiki.meteoritica.pl.

We packed the first batch of samples and dispatched them to Prof. Tadeusz Przylibski in Wroclaw by a courier service. From thence, they were delivered to Marcin Cimala where they were cut and prepared for analysis. At the same time, Prof. Przylibski was looking for a research laboratory in Europe that would perform an analysis of short-lived isotopes in the meteorite. By establishing the CRE age (cosmicray exposure age), the scientists could determine for how long the meteoroid was exposed to cosmic rays in outer space as well as its initial mass upon entry into the Earth's atmosphere. Prof. Przylibski reached and some fragments using an electronic kitchen scale with an accuracy of 1 gram. We were not equipped with a laboratory scale. By combining the available data, we estimated the total known weight to approx. 1066 grams.

5. The fall took place at 6:06 am as per Andrzej Pilski's preliminary report. According to the witness statement of Mrs. Alfreda Lewandowska, she always gets up at 6:00 am sharp. When she was challenged on how she could be so sure it had been exactly 6:00 am, she replied that she always got up at 6 am without an alarm clock. It was 6:06 am when she came back in and she claimed that she and her son had been outside for around 3 minutes. **Thus, we should accept 6:03 am as the moment of the fall.**

6. The stone has the characteristics of an ordinary chondrite. It has a well-defined chondrite-like fusion crust and a very light interior exhibiting specks of iron and troilite. There are hardly any chondrules visible on fractured surfaces.

7. In our opinion, the fall was likely comprised of only one stone. The farm is located on a headland of the Wydmińskie Lake. An area of wet, soggy ground spreads behind the shed which does not lend itself to meteorite hunting. As the roof was under repair, the yard was cluttered with fragments of asbestos, pieces of planks, etc. The conditions hindered our search for small pieces of the meteorite.

DOCUMENTATION AND SAMPLES TRANSFER

an agreement with the Laboratori Nazionali del Gran Sasso in Italy and the analysis was to be performed by Dr. Matthias Laubenstein. There was one condition: the specimen had to be delivered by Wednesday, May 11th. For results to be meaningful, CRE age analysis should be conducted within two weeks of a meteorite's having fallen. The package arrived in Italy that Wednesday at 4 pm. On Monday, we gave a sample of the meteorite to Prof. Marek Lewandowski. He took it with him to Krakow where Prof. Pierre Rochette (of CEREGE, Aix-an-Provence, France) was taking part in a seminar. The professor measured the magnetic susceptibility of the meteorite.

We thereby accomplished our objective of making the meteorite available to scientists. This marked the beginning of the next, terrestrial, period in its long history.

ACKNOWLEDGEMENTS

We express our gratitude to the individuals and institutions whose contribution made this work possible. We express special appreciation to Mr. Roman Rzepka and his wife, Anna.



Fot. 1. The meteorite 76 hours after the fall. The interior of the stone does not show any signs of weathering. Visible damage to the surface of the stone is the result of striking many targets: roofing material, a concrete step, and, finally, the ground. The finders kept this meteorite in a handkerchief. More photographs on web page http://wiki. meteoritica.pl



Fot. 2. Main mass of the Soltmany chondrite on the concrete step before the shed. The stone is photographed at the place where it impacted and partly fragmented. It subsequently ricocheted approx. 4-5 meters before coming to rest. A small bright patch is visible on the step above the meteorite; this is the point where the meteorite struck the step



Fot. 3. The hole in the roof of the shed – the first place of contact between the Sołtmany meteorite and solid Earth



Fot. 4. Determining the final fall trajectory of the meteorite. The farm buildings stand along a SE-NW line



Fot. 5. The hole in the roof and the place where the meteorite was found (marked by arrows)



Fot. 6. Four of the meteorite fragments transferred for research (photo Tomasz Jakubowski)

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SOŁTMANY METEORITE

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Abstract: This paper presents the results of a mineralogical and petrological study of the Sołtmany meteorite, which fell on April 30, 2011 in northern Poland. The meteorite was found almost immediately after it fell and has been little altered by weathering. Sołtmany is not the only observed fall of an L6 chondrite over Europe in the past few years. The preceding fall of this type, Jesenice (Slovenia), was also witnessed in April of 2009. However, it was not until several weeks after the fall that the first specimen of Jesenice was found, whereas Sołtmany was collected after a few minutes and submitted for analysis within a couple of days. The author presents mineral and petrographic features and chemical characteristics of mineral phases in Sołtmany. The mineral components are represented by metallic phases (kamacite, taenite, tetrataenite, native copper), as well as chromite, olivine, low-and high-calcium pyroxene, feldspar, chlorine-bearing apatite, and merrillite. This study also describes the texture of the meteorite and takes notice of a low number of preserved chondrules and the presence of oval chondrule-like areas, which exhibit a metamorphosed, recrystallized texture. Sołtmany was classified as an L6 ordinary chondrite with a weathering grade of W0. A shock stage S2 was determined on the basis of undulose extinction and lack of planar fractures in olivine crystals.

Keywords: meteorite, ordinary chondrite, L6 chondrite, meteorite fall, hammer meteorite, Warmińsko-Mazurskie Province, Sołtmany village

INTRODUCTION

The meteorite fell on April 30, 2011 at 6:03 am (CEST) on the farm of Mrs. Alfreda Lewandowska in Sołtmany. The village is located in the Warmińsko-Mazurskie Province in northern Poland. The exact coordinates of the fall location are 54°00.53'N, 22°00.30'E. The meteorite punched a hole through the roof and hit the concrete steps leading to a farm building. The hole in the roof and the marks left in concrete suggest that the fall's final trajectory was nearly perpendicular to the Earth's surface. The circumstances of the fall and its recovery are described in detail in the introductory article to this volume of *Meteorites* (Woźniak & Woźniak, 2012).

The total known weight of Sołtmany was determined to be approximately 1066 g. Upon impact, the meteorite broke into two large pieces of 813 g and 155 g respectively, as well as numerous smaller fragments. A type specimen of 65 grams is held by the Faculty of Earth Sciences of the University of Silesia in Sosnowiec, Poland. A larger fragment of 120 grams is in possession of the Faculty of Geoengineering, Mining and Geology of the Wrocław University of Technology.

The previous witnessed fall of an L ordinary chondrite in Europe also took place in April. The event was witnessed on April 9, 2009 at 3:00 am (CEST) in Slovenia, near the Austrian border. The resulting meteorite was given the name of Jesenice and was classified as an ordinary chondrite of petrologic type L6 with a shock stage S3. Three stones comprising the weight of 3.611 kg were found within several weeks after the fall (Bischoff et al., 2011).

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MATERIAL AND METHODS

The macroscopic texture of Sołtmany is uniform and unbrecciated. The macrophotographs of the meteorite as well as the photographs of four fragments dedicated for research were presented by Woźniak & Woźniak (2012). The material for analysis consisted of two small fragments, being representative for the whole mass of the meteorite, four polished thin sections, and several specks partially covered with fusion crust. The meteorite was studied by means of optical microscopy in transmitted and reflected light. The specimens were also documented photographically. The quantitative analysis was performed by means of an electron microscope CAMECA SX-100, at the Laboratory of Microanalysis of Minerals and Synthetic Substances at the Faculty of Geology of Warsaw University. Further analysis of the fusion crust was conducted with a scanning electron microscope XL 30 ESEM-TMP PHILLIPS equipped with the EDAX analytical device at the Faculty of Earth Sciences of the University of Silesia in Sosnowiec.

FUSION CRUST

Soltmany is covered with a black, dark-brownish, and somewhat shiny fusion crust. As a result of its impact into the asbestos cement roof board and timber, scraps of construction materials are embedded into the fusion crust on some surfaces. Numerous fibers of chrysotile asbestos were identified among other materials. The surface texture of the crust is slightly rough, and it exhibits small vesicles. Under a magnifying glass, it is shiny and glassy. The thickness of the fusion crust was measured on cut sections and it varies slightly from 0.5 to 0.7 mm.

The scanning electron microscope image revealed additional characteristics of the fusion crust. It is highly textured, with close-grained vesicles set in between abundant protuberances (Fig. 1).

The vesicles are largely filled with the construction material from the asbestos cement board and meteoritic material from both the inside and outside of the meteorite. The observations were made on the surface of fragments of the fusion crust collected from the concrete floor where the meteorite had landed. The characteristics and composition of the vesicles can be best observed on cut cross sections of the fusion crust (Fig. 2).

It can be inferred that the vesicles represent the places where gases expanded during solidification of the fusion crust. The vesicles are connected to the remnants of gas bubbles inside of the fusion crust. Their shapes attest to their origin in liquid state during ablation of the surface of the meteoroid. The remnants of gas bubbles expand as deep as $50-60 \mu m$ into the fusion crust.

At larger magnification the rock reveals indistinct, densely-arranged dendritic crystals of spinel on the external surface of the fusion crust. The thin and long dendrite forms are mainly composed of iron, nickel and magnesium. The thicker and smaller dendrites, which take isometric forms, are rich in Fe, Cr, and Mg (Fig. 3). They likely match the chemical composition of chromite, yet, unlike the thin and long spinels, they are present only locally. Certain remnants of gas bubbles also contain dendritic crystals of a mineral that is similar in chemical composition to a nickel-iron spinel (trevorite). Unfortunately, a plausible explanation for its origin in the gas bubbles cannot be provided (Fig. 4).

In transmitted light, the fusion crust is mostly opaque or dark brown and semi-translucent. Narrow translucent areas composed of pyroxene and olivine grains are scattered throughout the fusion crust.

The electron microscopic examination of the fusion crust revealed three different parts (Fig. 5). The first part is the outermost layer and it is glassy and heterogeneous in texture. Locally, it is visibly rich in iron and magnesium. In other areas, it is equivalent in chemical composition to feldspathic glass and is enriched in alkali elements (Na, Ca, K), aluminum oxide, and silica. This external layer exhibits abundant pores and remnants of gas bubbles (mostly of volatile sulfur compounds). It is opaque in transmitted light due to the oxidized iron content (magnetite-bearing Ni), and other opaque mineral phases (mostly spinels).

The second layer of the fusion crust is partially transparent (to transmitted light) and it is thoroughly melted. The feldspar in the outermost part of the meteorite was the main fusing agent while ablation was taking place. The product of the softening process is strongly vitrified or isotropized that is a result of having reached the softening point of feldspar. It seems that the temperature reached by this layer was slightly above 1250 °C. Feldspar was completely vitrified or isotropized; pyroxene and olivine began to melt at the points of contact with feldspar glass (Fig. 6).



Fig. 1. Surface of the fusion crust. Numerous cavities can be observed. Some of the cavities are secondarily filled with µm-sized grains of both the construction material and the meteorite. SEM (mixed SE/BSE image)



Fig. 3. Spinels on the surface of the fusion crust. Thin, skeletal spinels are composed of Fe, Ni, and Mg. Somewhat more isometric depositions on the lower left-hand side of the image represent chromite spinels. SEM (mixed SE/BSE image)



Fig. 5. Stratified fusion crust. The outer glassy layer contains spinels (1). The next layer exhibits partially melted olivines and pyroxenes and melted feldspar (2). Abundant, thin, µm-sized veins of iron sulfide are a characteristic feature of the innermost layer, termed "black veins" in this study (3). SEM (BSE image)



Fig. 2. A cross section through the fusion crust. Note a vesicle connected with the remnant of a gas bubble. SEM (mixed SE/BSE image)



Fig. 4. Dendritic crystals consistent with the chemical composition of iron-nickel spinel (trevorite-type) in a cavity. SEM (mixed SE/ BSE image)



Fig. 6. Strongly melted layer of fusion crust with fragments of partially melted olivines (ol) and pyroxenes (px). The glassy fusion crust with µm-sized crystals of spinel can be observed at the bottom of the image. The upper part of the image shows the transitional zone to the "black veins" zone. SEM (BSE image)

The third layer of the fusion crust is a so called "layer of black veins". It is composed of fractured minerals of the meteorite. The cracks are filled with a sulfide (similar in composition to troilite) and metallic alloys. The cracks are so numerous that they appear to constitute a layer that is opaque to transmitted light. The so called "black veins" were observed in all silicates in the meteorite excluding feldspar grains. The thermal softening of feldspar at high temperatures is responsible for the lack of "black veins" in feldspar. The same heating cracked olivine and pyroxene crystals (Fig. 7). The cracks were secondarily filled by lowviscosity sulfide.

In transmitted light, the fusion crust is almost opaque, but in some places the same fusion crust appears to be a slightly translucent layer. Analytical studies using SEM-EDX demonstrate that the com-



Fig. 7. The layer of "black veins" present at the margin of an olivinerich chondrule. Sulfide veins are present in the olivine. Feldspar is devoid of FeS veins. A very thin layer of glassy fusion crust can be seen in the lower right corner. SEM (BSE image)



Fig. 9. Minor FeNi-metal within a grain of troilite. SEM (BSE image)

position of the vitrified fusion crust is heterogeneous and is subject to variation, especially in Mg, Fe, and Al content. The glass is primarily feldspathic. Nevertheless, outer, homogenous, glassy fragments of the fusion crust, which show neither the effects of crystallization, nor contain spinels, were also locally encountered (Fig. 8). They probably represent the last drops of glass, solidified in the final stages of ablation, which are similar in composition to feldspar with a significant admixture of iron. The fusion crust, however, primarily contains numerous dendritic crystals of spinel rich in iron, nickel and magnesium (Fig. 9).

The glassy layer smoothly turns into the next layer which is translucent in places. The amount of glass decreases towards the inside of the meteorite, that is, the zone of "black veins", and gives place to isotropized grains of feldspars. Olivines and pyroxenes are only



Fig. 8. The outermost layers of the fusion crust are homogenous and devoid of spinel microcrystals (glass). Remnants of gas bubbles are present and an area of partial melting can be observed in the upper right-hand part of the image. SEM (BSE image)



Fig. 10. Dendritic Fe-Ni-Mg spinels in a glassy area of the fusion crust. SEM (BSE image)

slightly melted (Fig. 6). Grains of troilite in this area are partially decomposed and contains zones where admixed iron is present (Fig. 9). The chemical composition of the troilite is variable. Some of the troilites contain up to approximately 1% Ni (Tab. 1).

The chemical composition of the feldspar glass varies locally and depends on the surrounding coherent minerals. The fusion crust is visibly thinner in places with metamorphosed, recrystallized textures, which are rich in pyroxene and poor in feldspar, as well as olivine crystals (Fig. 7). Small bulges on the surface are very often present in these places.

Dendritic spinels are commonly observed in the fusion crust (Figs. 3 and 10). Their chemical composition varies from that of magnetite to trevorite, as well as chromite. Due to their minute sizes, exact quantitative chemical analyses were not feasible. Only a qualitative analysis could be performed.

Although sparse, relict grains of chromite, belonging to the least fusible minerals of the meteorite, were identified in the external part of the fusion crust. An increase in chromium content was observed around chromite grains in the partially recrystallized area of the glassy fusion crust. They are less abundant in this area, but unoxidized sulfide and metallic grains occur as well. Their chemical composition can be found in Tab. 2. The metallic grains are mainly taenite and, less often, kamacite (Tab. 2, pos. 4, 5, 6 and 7). The grains rich in sulfur have a peculiar chemical composition. In some cases they are compositionally similar to pentlandite, but typically they have a non-stoichiometric behavior (Tab. 2, pos. 1, 2 and 3). Based on the thickness of the fusion crust, it can be argued that the flight of the meteoroid through the Earth's atmosphere was relatively short in duration. The meteoroid must have tumbled, as the main mass of Sołtmany does not show the characteristics of "orientation". The meteorite might have separated from a larger body at a relatively low altitude. The character of the fusion crust and its thickness which does not exceed 0.7 mm may attest to its secondary origin. Consequently, it can be inferred that further fragments of the meteorite might yet be found. Nevertheless, they are likely scattered over a wide area.

 Table 1. Chemical composition of Ni-rich sulfides (troilite) from the melting zone of fusion crust. Results in wt.%.

	S18	S19	S20	S21
Si	0.01	nd	nd	nd
Р	nd	nd	nd	nd
S	36.67	36.68	36.67	36.69
Fe	62.48	62.49	62.41	62.48
Ni	1.58	1.52	1.51	1.57
Со	0.19	0.17	0.18	0.18
Total	100.93	100.86	100.77	100.92
		at.%.		
Si	0.01	-	-	-
Р	-	-	-	-
S	49.88	49.91	49.94	49.90
Fe	48.80	48.83	48.80	48.80
Ni	1.18	1.13	1.12	1.17
Co	0.14	0.13	0.13	0.13
Total	100.00	100.00	100.00	100.00

nd - not detected

	1.	2.	3.	4.	5.	6.	7.
Si	0.06	0.14	0.02	0.01	nd	nd	nd
Р	nd	0.01	nd	0.01	nd	nd	0.01
S	25.37	6.99	25.66	nd	nd	0.01	0.01
Fe	3.37	90.05	64.98	71.97	94.50	93.94	64.07
Ni	71.56	2.34	8.70	27.93	6.11	6.02	36.50
Со	nd	0.28	0.24	0.27	0.96	0.76	0.25
Total	100.36	99.81	99.60	100.19	101.57	100.73	100.84
			at	.%			
Si	0.11	0.27	0.03	0.01	-	-	-
Р	-	0.02	-	0.02	-	-	0.01
S	38.17	11.59	37.80	-	-	0.02	0.01
Fe	2.91	85.76	54.97	72.82	93.36	93.56	64.68
Ni	58.80	2.12	7.00	26.89	5.74	5.70	35.05
Со	-	0.25	0.19	0.26	0.89	0.72	0.24
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 2. Chemical composition of non-stoichiometric sulfide (1-3) and metallic phases (4-7) in the fusion crust. Results in wt.%.

nd - not detected

METEORITE CHARACTERISTICS

The meteorite was macroscopically fresh a few days after the fall and exhibited exceptionally white interior with delicate tones of gray. After a few months, the surfaces that were not covered with fusion crust became visibly darker. Tiny rust spots appeared around the metallic grains of fragments that had been exposed to water during cutting. Initial observations under a binocular loupe led to the conclusion that the meteorite is a chondrite. Low metal abundances, but abundant troilite suggest a classification of L or LL group. Tiny metallic phases are sparsely distributed throughout the stone's light-coloured matrix. A number of rounded objects in the mm size-range were identified, resembling large chondrules at a cursory glance. Additional observations proved that they represent metamorphosed, recrystallized chondrules surrounded by tiny troilite grains. In thin sections, the clear identification of a number of relict chondrules is possible, proving conclusively that Soltmany is a chondrite.

Opaque minerals

Chemical microanalyses and microscopic observations in reflected light enabled the identification of opaque minerals. The main opaque phase is troilite. The metallic phases (kamacite and taenite) are also rarely accompanied by troilite (Figs. 11b,c), which seldom reaches more than a few mm in diameter. The chemical microanalyses led to the conclusion that the troilite had few measurable impurities (Tab. 3). Troilite inclusions over 2 mm in diameter are relatively sparse in the meteorite. More often, tiny grains of troilite constitute rims around recrystallized chondrules and mineral fragments.

Taenite and kamacite are the most abundant metallic phases. They sometimes coexist within grains (Figs. 11a,d) or form plessite (Figs. 11a,b). In plessite intergrowths, the kamacite is extremely poor in nickel (2.77 at.%), whereas the average nickel content



Fig. 11. Opaque minerals: a – grain of kamacite (ka) surrounded by lamellar taenite (tae); a (tetrataenite) rim on the kamacite-taenite boundary (t.tae); grain of plessite can be observed at the top of the image; b – plessite; Ni-poor kamacite in plessite; also visible is a grain of troilite (troi); c – taenite (tae) of lamellar texture surrounded by kamacite grains (ka) and troilite (troi); tetrataenite at the kamacite-taenite boundary (t.tae); d –taenite (tae) exhibiting a blotchy paragenesis with kamacite (ka) and tetrataenite grains (t.tae); all BSE images

	12	13	14	15a	16a
Fe	64.43	64.27	65.04	64.14	64.07
Ni	0.01	nd	nd	nd	nd
Со	nd	nd	nd	nd	nd
Mn	0.03	0.14	0.05	0.05	0.12
Ti	nd	0.02	0.01	0.05	0.01
Cr	nd	nd	0.01	0.01	nd
Cu	nd	nd	nd	nd	nd
S	36.78	36.59	36.65	35.95	36.29
Total	101.25	101.02	101.76	100.20	100.49
		at.	.%		
Fe ²⁺	1.01	1.01	1.02	1.02	1.01
Ni ²⁺	< 0.01	-	-	-	-
Co ²⁺	-	-	-	-	-
Mn ²⁺	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Ti ⁴⁺	-	< 0.01	< 0.01	< 0.01	< 0.01
Cr ³⁺	-	-	< 0.01	< 0.01	-
Cu ²⁺	_	_	_	_	_
S ²⁻	1.00	1.00	1.00	1.00	1.00
Total	2.01	2.01	2.02	2.02	2.02

Table 3. Chemical composition of troilite grains. The chemical formula was calculated for $S_{\Sigma=1}$. Results in wt.%.

nd - not detected

is slightly below 6 at.%. The kamacite contains a high Co content (from 0.61 to 0.99 at.%) with an average Co content of 0.7 at.% (Fig. 12). The high nickel phases contain significantly less Co.

Kamacite often forms individual grains distinct from taenite (Fig. 11c). The grains of taenite are vary from 16 to 37 at.% Ni. The taenite is heterogeneous. The taenite grains contain regions of plessite with higher Ni content than the surrounding areas (Figs. 11a,c). High-Ni phase, which is considered to be tetrataenite, was identified at the boundaries of kamacite and taenite grains (Figs. 11a,c, 13). The variability of the Ni to Fe ratio in the metallic phases is depicted in



Fig. 12. Correlation of Fe and Co content in the metallic phases of Sołtmany

Table 4. Chemical composition of Cu grains. Results in wt.%.

	1	2	3
Cu	95.83	94.72	95.01
Ni	1.89	1.90	1.86
Fe	3.52	3.44	3.51
Со	nd	nd	nd
Total	101.24	100.06	100.38
	at.	%	
Cu	94.06	94.07	94.08
Ni	2.01	2.05	2.04
Fe	3.93	3.89	3.88
Со	-	-	-
Total	100.00	100.00	100.00

nd - not detected

Fig. 13. Fields of kamacite, taenite, and tetrataenite are included on the diagram. The isolated intermediate values likely correspond to data gathered at phase or grain boundaries, which exhibit extremely variable nickel content. Such mineral associations of various FeNi phases are characteristic of metamorphic conditions and are typically associated with petrologic type 5 and 6, L and H ordinary chondrites (Reisener & Goldstein, 2003).

Metallic copper is present, mostly within taenite grains. However, small inclusions of Cu within kamacite grains and single grains within troilite inclusions were also identified. All of the Cu grains are homogenous. They contain ~2 at.% Ni and ~3.9 at.% Fe (Tab. 4).

Spinel identified as chromite is the last of the found opaque minerals. It occurs as small grains embedded within the silicate matrix. Inclusions of chromite within chondrules were also identified; however, these were smaller and unevenly distributed. Emulsion-type depositions of chromite were also quite abundant within chondrule feldspars (Fig. 14). The chemical



Fig. 13. Correlation of Ni and Fe content in the metallic phases of Sołtmany



Fig. 14. Emulsion-type depositions of chromite (light spots) in feldspar (fsp). A fragment of a porphyritic olivine (ol) – pyroxene (px) chondrule (POP). FeNi-metal is visible in the lower right-hand corner of the image. SEM (BSE image)

composition of these chromites corresponds to that of the larger inclusions. The chemical composition of selected grains of chromite can be found in Tab. 5. They are clearly enriched in Ti and Al.



Fig. 15. Fragment of an olivine-rich relict chondrule embedded in the recrystallized matrix. Transmitted light, crossed nicols

Silicates

Chondrules account for a small percentage of the volume of the meteorite. They are mostly incomplete and lack characteristic rimming. Chondrule fragments are



Fig. 16. Relict chondrules and chondrule-like areas of metamorphosed, recrystallized material in Sołtmany: a – barred-olivine chondrule (BO) surrounded by recrystallized matrix; b – barred-olivine chondrule (BO) on the edge of a thin section; note the anisotropy of feldspar (plag); c – chondrule-like recrystallized area composed of olivine, pyroxene, and plagioclase; d – radial, chondrule-like object of pyroxene and olivine, this is probably the relict of a former radial pyroxene (RP) chondrule; all images in transmitted light, crossed nicols

	1.	2.	S-5	S-6	S-7	Schr1.	Schr.2
SiO ₂	nd	nd	nd	0.02	nd	nd	nd
TiO ₂	3.13	3.19	2.73	3.12	2.81	3.13	3.19
Al ₂ O ₃	5.51	5.46	5.78	5.52	5.93	5.51	5.46
V ₂ O ₃	nd	nd	0.79	0.74	0.87	nd	nd
Cr ₂ O ₃	55.66	56.18	54.40	55.02	55.26	55.66	56.18
Fe ₂ O ₃	3.42	3.06	3.86	3.27	3.20	3.42	3.06
MgO	2.64	2.76	2.27	2.50	2.26	2.64	2.76
CaO	nd	nd	0.01	nd	nd	nd	nd
MnO	0.63	0.81	0.80	0.62	0.68	0.63	0.81
FeO	27.51	27.26	27.91	27.81	28.40	27.51	27.26
CoO	nd	nd	0.02	nd	0.05	nd	nd
NiO	nd	nd	0.03	nd	nd	nd	nd
ZnO	0.33	0.22	0.28	0.22	0.21	0.33	0.22
Total	98.83	98.94	98.88	98.84	99.67	98.83	98.94
			at.	%			
Si ⁴⁺	-	-	-	< 0.01	-	-	-
Ti ⁴⁺	0.08	0.08	0.07	0.08	0.07	0.08	0.08
Al ³⁺	0.23	0.23	0.24	0.23	0.25	0.23	0.23
V ³⁺	-	-	0.02	0.02	0.02	-	-
Cr ³⁺	1.57	1.58	1.54	1.55	1.55	1.57	1.58
Fe ³⁺	0.09	0.08	0.10	0.09	0.08	0.09	0.08
Mg ²⁺	0.14	0.15	0.12	0.13	0.12	0.14	0.15
Ca ²⁺	-	-	< 0.01	-	-	-	-
Mn ²⁺	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Fe ²⁺	0.82	0.81	0.83	0.83	0.84	0.82	0.81
Co ²⁺	-	-	< 0.01	-	< 0.01	-	-
Ni ²⁺	-	-	< 0.01	_	-	-	-
Zn ²⁺	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Total	2.97	2.97	2.97	2.97	2.97	2.97	2.97

Table 5. Chemical composition of chromite-type spinels. Results in wt.%. Chemical formula calculated according to 4O²⁻. Total sum of cations is 3

nd - not detected

also common (Fig. 15). Fan-shaped radial pyroxene chondrules (RP) were not identified.

Olivine-rich chondrules containing recrystallized small grains of plagioclase were the easiest to discern (Figs. 16a,b).

Chondrule-like accumulations of metamorphosed, recrystallized olivine and pyroxene (relict chondrules) are common (Figs. 16c,d). Grains with a peculiar texture occur in the vicinity of chondrules (Figs. 17a,b). The majority of the meteorite is composed of a mass that is recrystallized in texture, contains grains of variable size, and does not cantain chondrules (Fig. 18). Certain fragments are recrystallized and are very finegrained.

The silicate phases are represented by low-Ca pyroxene (hypersthene), Ca-pyroxene, olivine, and feldspar, both inside and outside of the chondrules. The variability in the chemical composition of respective minerals can be found in Tables 6 and 7. The analyses did not reveal any major variability in the chemical composition of pyroxenes in any constituents of the rock (e.g., chondrules, chondrule fragments, or silicate-rich areas having a metamorphosed, recrystallized texture). The whole rock appears to have a common, metamorphic origin. The chemical variability of the low-calcium pyroxenes is minimal. The average Fs content is 21.4 mol%. Fs varies between 21.02 and 21.91 mol%. High-Ca pyroxenes are similar in composition to diopsides, with Wo content between 44.23 and 46.28 mol% with an average of 45.3 mol%.

Olivines are also well equilibrated in this meteorite. No major variation in the chemical composition was observed between olivine from chondrules, recrystallized areas, and the matrix (Tab. 8). Fa content ranges slightly from 24.72 to 25.89 mol%, with an average of 25.5 mol%.

Minor amounts of feldspar are present in all silicates. It is present as plagioclase (oligoclase), rich in orthoclase component (Or: 4.65–7.86 mol%; Tab. 9). There is also no significant variation in the chemical composition of the feldspar. Plagioclase often occurs in higher abundances around certain metamorphosed, recrystallized areas (Fig. 19).

29	55.63	0.23	0.16	pu	0.14	0.57	13.91	0.54	0.96	28.62	pu	0.01	pu	100.77		1.981	0.006	0.007	I	0.004	0.008	0.414	0.016	0.037	1.519	Ι	< 0.001	I	3.992	1.970		1.87	77.11	21.02
28	55.96	0.21	0.12	pu	0.08	pu	14.16	0.53	0.71	28.68	pu	pu	pu	100.45		1.994	0.006	0.005	I	0.002	I	0.422	0.016	0.027	1.524	-	I	I	3.996	1.973		1.38	77.23	21.39
24	55.79	0.20	0.13	pu	0.09	pu	14.11	0.51	0.73	28.61	nd	nd	nd	100.17		1.993	0.005	0.006	I	0.003	I	0.422	0.016	0.028	1.524	Ι	I	I	3.997	1.974		1.41	77.23	21.36
19. ch	55.85	0.19	0.12	pu	0.09	0.05	14.37	0.50	0.70	28.71	nd	nd	nd	100.58	-	1.990	0.005	0.005	I	0.002	0.001	0.428	0.015	0.027	1.525	Ι	I	I	3.999	1.980		1.36	77.02	21.62
So20.	55.66	0.21	0.14	0.03	0.10	pu	14.46	0.25	0.77	28.36	nd	nd	nd	99.98	-	1.994	0.006	0.006	0.001	0.003	I	0.433	0.008	0.030	1.515	Ι	I	I	3.995	1.978		1.50	76.59	21.91
So18.	55.72	0.18	0.13	pu	0.09	0.30	14.06	0.50	0.75	28.75	nd	pu	nd	100.48		1.987	0.005	0.005	I	0.003	0.004	0.419	0.015	0.029	1.529	Ι	I	I	3.996	1.977		1.45	77.33	21.22
So16.	55.91	0.18	0.13	0.01	0.13	pu	13.94	0.49	0.68	28.87	0.02	0.01	pu	100.37		1.993	0.005	0.006	< 0.001	0.004	I	0.415	0.015	0.026	1.534	0.002	< 0.001	I	3.999	1.975		1.31	77.66	21.03
So14.	55.65	0.23	0.14	0.05	0.14	0.26	14.45	0.40	0.78	28.54	nd	pu	pu	100.64		1.985	0.006	0.006	0.001	0.004	0.004	0.431	0.012	0.030	1.517	-	I	I	3.996	1.978		1.51	76.70	21.79
So8.	56.00	0.16	0.09	0.07	0.14	pu	14.17	0.48	0.71	28.58	0.01	pu	0.06	100.47	at.%	1.996	0.004	0.004	0.002	0.004	I	0.422	0.015	0.027	1.519	0.001	I	0.002	3.993	1.968	mol %	1.38	77.16	21.46
So7.ch	55.67	0.17	0.16	pu	0.18	0.19	14.12	0.51	0.77	28.66	nd	nd	nd	100.43		1.987	0.005	0.007	I	0.005	0.003	0.422	0.015	0.030	1.525	-	I	I	3.997	1.976		1.50	77.17	21.33
So4.ch	55.94	0.15	0.13	0.07	0.10	pu	14.12	0.45	0.81	28.58	nd	pu	0.07	100.42		1.995	0.004	0.006	0.002	0.003	I	0.421	0.013	0.031	1.519	-	I	0.002	3.994	1.971		1.57	77.06	21.37
#8	55.63	0.23	0.16	pu	0.14	0.57	13.91	0.54	96.0	28.62	nd	0.01	nd	100.77		1.981	0.006	0.007	I	0.004	0.008	0.414	0.016	0.037	1.519	I	< 0.001	Ι	3.992	1.970		1.87	77.11	21.02
<i>L#</i>	55.96	0.21	0.12	pu	0.08	pu	14.16	0.53	0.71	28.68	nd	nd	nd	100.45		1.994	0.006	0.005	I	0.002	I	0.422	0.016	0.027	1.524	I	I	I	3.996	1.973		1.38	77.23	21.39
#5	55.79	0.20	0.13	pu	0.09	pu	14.12	0.51	0.73	28.62	nd	nd	nd	100.19		1.993	0.005	0.006	I	0.003	I	0.422	0.016	0.028	1.524	-	I	I	3.997	1.974		1.41	77.23	21.36
#1	55.85	0.19	0.12	pu	0.09	0.05	14.37	0.50	0.70	28.71	nd	pu	pu	100.58		1.990	0.005	0.005	I	0.002	0.001	0.428	0.015	0.027	1.525	I	I	I	3.999	1.980		1.36	77.02	21.62
	SiO_2	TiO2	Al_2O_3	V_2O_3	Cr_2O_3	Fe_2O_3	FeO	MnO	CaO	MgO	Na_2O	K_2O	NiO	Total		Si ⁴⁺	Ti^{4+}	Al^{3+}	V^{3+}	Cr^{3+}	Fe^{3+}	Fe^{2+}	Mn^{2+}	Ca^{2+}	Mg^{2+}	Na^{+}	K^{*}	Ni^{2+}	Total	Ca ²⁺ +Mg ²⁺ +Fe ²⁺		Wo	En	Fs

Table 6. Chemical composition of representative low-Ca pyroxenes. Results in wt.%. Chemical formula calculated according to 60^{2-}

nd – not detected

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35	54.29	0.45	0.47	0.04	0.83	0.35	4.94	0.22	22.07	16.41	0.57	pu	pu	100.64		1.980	0.012	0.020	0.001	0.024	0.005	0.151	0.007	0.863	0.892	0.040	I	I	3.995	1.906		45.27	
25	54.17	0.52	0.51	0.02	0.98	0.13	5.63	0.20	21.55	16.37	0.56	pu	pu	100.64		1.978	0.014	0.022	0.001	0.028	0.002	0.172	0.006	0.843	0.892	0.040	I	I	3.998	1.907	-	44.23	
22.ch	54.26	0.51	0.44	pu	0.75	0.13	4.65	0.29	22.63	16.41	0.46	pu	pu	100.53		1.980	0.014	0.019	I	0.022	0.002	0.142	0.009	0.885	0.893	0.033	I	I	3.998	1.920	-	46.09	
21.ch	54.12	0.46	0.49	0.10	0.87	0.13	5.06	0.23	21.88	16.49	0.51	pu	0.01	100.33		1.979	0.013	0.021	0.003	0.025	0.002	0.155	0.007	0.857	0.899	0.037	I	< 0.001	3.998	1.911	-	44.85	
20.ch	54.14	0.51	0.47	0.09	0.82	0.51	4.80	0.30	22.11	16.52	0.50	pu	pu	100.77		1.974	0.014	0.020	0.003	0.024	0.007	0.146	0.00	0.864	0.897	0.035	I	I	3.993	1.907		45.28	
Sol7.	54.36	0.47	0.45	0.06	0.78	0.10	4.75	0.17	22.30	16.52	0.53	pu	pu	100.49		1.983	0.013	0.020	0.002	0.023	0.001	0.145	0.005	0.872	0.898	0.038	I	I	3.999	1.915		45.52	
Sol5.	54.39	0.42	0.42	0.04	0.81	pu	4.79	0.24	22.25	16.40	0.53	pu	0.02	100.31		1.987	0.011	0.018	0.001	0.023	I	0.146	0.007	0.871	0.894	0.038	I	< 0.001	3.998	1.911		45.58	
So9.	54.40	0.41	0.43	0.05	0.82	0.16	4.77	0.27	22.03	16.55	0.56	pu	0.05	100.50		1.984	0.011	0.019	0.001	0.024	0.002	0.146	0.008	0.861	0.900	0.039	I	0.002	3.996	1.906		45.16	
So6.ch	54.08	0.48	0.48	0.03	0.84	pu	4.95	0.28	21.88	16.46	0.53	pu	pu	100.01	at.%	1.983	0.013	0.021	0.001	0.024	I	0.152	0.009	0.860	0.900	0.038	I	I	4.000	1.911	mol%	44.98	
So5.ch	54.31	0.50	0.47	0.05	0.72	0.32	4.16	0.21	22.80	16.51	0.509	pu	pu	100.54		1.979	0.014	0.020	0.001	0.021	0.004	0.127	0.007	0.890	0.897	0.036	I	I	3.996	1.914		46.51	ĺ
. INCOURTS III 9	54.29	0.45	0.47	0.04	0.83	0.35	4.94	0.22	22.07	16.41	0.57	pu	pu	100.64		1.980	0.012	0.020	0.001	0.024	0.005	0.151	0.007	0.863	0.892	0.040	I	I	3.995	1.906		45.27	
a pyroxenes #6	54.17	0.52	0.51	0.02	0.98	0.13	5.63	0.20	21.55	16.37	0.56	pu	pu	100.64		1.978	0.014	0.022	0.001	0.028	0.002	0.172	0.006	0.843	0.891	0.040	I	I	3.998	1.907		44.23	
	54.26	0.51	0.44	pu	0.75	0.13	4.65	0.29	22.63	16.41	0.46	pu	pu	100.53		1.980	0.014	0.019	I	0.022	0.002	0.142	0.009	0.885	0.893	0.033	I	I	3.998	1.920		46.09	
1 01 1cp1csc11 #3	54.12	0.46	0.49	0.10	0.87	0.13	5.06	0.23	21.88	16.49	0.51	pu	0.01	100.35		1.979	0.013	0.021	0.003	0.025	0.002	0.155	0.007	0.857	0.899	0.037	I	< 0.001	3.998	1.911		44.85	
	54.14	0.51	0.47	0.09	0.82	0.50	4.80	0.30	22.11	16.52	0.50	pu	pu	100.76		1.973	0.014	0.020	0.003	0.024	0.007	0.146	0.00	0.864	0.897	0.035	I	I	3.993	1.907		45.28	
	SiO,	TiO,	Al_2O_3	V_2O_3	Cr_2O_3	Fe_2O_3	FeO	MnO	CaO	MgO	Na_2O	K ₂ O	NiO	Total		Si ⁴⁺	Ti^{4+}	Al^{3+}	V^{3+}	Cr ³⁺	Fe^{3+}	Fe^{2+}	Mn^{2+}	Ca^{2+}	Mg^{2+}	Na^{+}	$\mathrm{K}^{\scriptscriptstyle +}$	Ni^{2+}	Total	Ca ²⁺ +Mg ²⁺ +Fe ²⁺		Wo	

Results in wr % Chemical formula calculated according to $6\Omega^{2-}$ tative high-Ca nocition of r Table 7 Chemical co

nd – not detected

Soltmany meteorite

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	#1	#2	#3	#4	#5	9#	#2So1.	#3So2.	#4So3.	#5So13.	#6 So19	So13.	So19.	23.ch	26.duże	27.duże	30
SiO,	38.36	38.54	38.31	38.66	38.71	38.45	38.49	38.58	38.52	38.50	38.31	38.50	38.31	38.36	38.54	38.31	38.66
TiO_2	pu	pu	pu	0.01	0.02	0.02	pu	0.03	pu	pu	pu	pu	pu	pu	pu	pu	0.01
AI_2O_3	pu	pu	pu	pu	pu	pu	pu	pu	pu	pu	pu	pu	pu	nd	pu	pu	nd
Cr_2O_3	pu	0.03	pu	0.01	pu	0.02	pu	0.04	0.08	0.03	0.02	0.03	0.02	nd	0.03	pu	0.01
MgO	37.97	37.86	38.08	38.16	37.98	38.17	38.90	38.80	38.22	38.11	38.00	38.11	38.00	37.97	37.86	38.08	38.16
CaO	0.06	pu	pu	pu	pu	pu	pu	0.01	0.08	pu	pu	pu	pu	0.06	pu	pu	nd
MnO	0.46	0.51	0.50	0.49	0.48	0.52	0.53	0.56	0.43	0.41	0.38	0.41	0.38	0.46	0.51	0.50	0.49
FeO	22.94	23.22	23.43	23.58	23.73	23.95	23.10	22.91	23.11	23.66	23.49	23.66	23.49	22.94	23.22	23.43	23.58
NiO	pu	pu	0.06	pu	0.03	pu	pu	0.03	pu	pu	0.04	pu	0.04	nd	pu	0.06	pu
Total	99.79	100.16	100.38	100.91	100.95	101.13	101.02	100.96	100.44	100.71	100.24	100.71	100.24	99.79	100.16	100.37	100.91
								at	%								
Si^{4+}	1.003	1.005	0.999	1.002	1.003	0.997	0.995	0.997	1.001	1.000	1.000	1.000	1.000	1.003	1.005	0.999	1.002
Ti^{4+}	1	I	I	< 0.001	I	< 0.001	I	0.001	I	I	I	I	I	I	I	I	< 0.001
Al ³⁺	1	I	I	I	1	I	I	I	I	1	I	I	I	I	I	1	1
Cr^{3+}	1	0.001	I	< 0.001	I	< 0.001	I	0.001	0.002	0.001	0.001	0.001	0.001	I	0.001	I	< 0.001
Mg ²⁺	1.480	1.472	1.480	1.474	1.467	1.475	1.499	1.495	1.481	1.476	1.478	1.476	1.478	1.480	1.472	1.480	1.474
Ca ²⁺	0.002	I	I	I	1	I	1	< 0.001	0.002	1	I	I	I	0.002	I	I	I
Mn^{2+}	0.010	0.011	0.011	0.011	0.010	0.012	0.012	0.012	0.009	0.009	0.008	0.009	0.008	0.010	0.011	0.011	0.011
Fe ²⁺	0.502	0.506	0.511	0.511	0.514	0.519	0.499	0.495	0.502	0.514	0.513	0.514	0.513	0.502	0.506	0.511	0.511
Ni^{2+}		I	0.001	1	0.001	I	1	0.001	I	1	0.001	1	0.001	1	I	0.001	1
Total	2.997	2.995	3.001	2.998	2.996	3.003	3.005	3.002	2.998	3.000	3.000	3.000	3.000	2.997	2.995	3.001	2.998
																-	
Si^{4+}	1.339	1.342	1.331	1.336	1.339	1.328	1.324	1.329	1.336	1.334	1.333	1.334	1.333	1.339	1.342	1.331	1.336
Ti^{4+}	< 0.001	I	I	< 0.001	I	< 0.001	ı	0.001	I	I	I	I	I	< 0.001	I	I	< 0.001
Al^{3+}	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I
Cr^{3+}	< 0.001	0.001	I	< 0.001	I	< 0.001	I	0.001	0.002	0.001	0.001	0.001	0.001	< 0.001	0.001	I	< 0.001
Mg^{2+}	1.976	1.966	1.972	1.967	1.959	1.965	1.995	1.992	1.976	1.968	1.971	1.968	1.971	1.976	1.966	1.972	1.967
Ca^{2+}	0.002	I	-	0.000	I	< 0.001	< 0.001	< 0.001	0.003	< 0.001	I	< 0.001	I	0.002	I	I	I
Mn^{2+}	0.014	0.015	0.015	0.014	0.014	0.015	0.015	0.016	0.013	0.012	0.011	0.012	0.011	0.014	0.015	0.015	0.014
Fe^{2+}	0.670	0.676	0.681	0.682	0.687	0.692	0.665	0.660	0.670	0.685	0.683	0.685	0.683	0.670	0.676	0.681	0.682
Ni^{2+}	I	-	0.002	-	0.001	< 0.001	I	0.001	Ι	Ι	0.001	Ι	0.001	Ι	Ι	0.002	Ι
Total	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000
$Ca^{2+} + Mg^{2}$	$^{2+} + Fe^{2+} + N$	$4n^{2+} + Ni^{2+}$:															
	1.994	1.989	2.003	1.996	1.993	2.006	2.010	2.003	1.995	1.999	2.000	1.999	2.000	1.994	1.989	2.003	1.996
								mc	1%								
Мо	0.08	0.00	00'0	0.00	0.00	0.00	0.00	0.01	0.12	0.01	0.00	0.01	0.00	0.08	0.00	0.00	0.00
Fo	74.25	73.98	68.67	73.86	73.64	73.54	74.57	74.62	74.23	73.83	73.91	73.83	73.91	74.25	73.98	73.89	73.86
Fa	25.16	25.45	25.50	25.60	25.81	25.89	24.85	24.72	25.18	25.71	25.63	25.71	25.63	25.16	25.45	25.50	25.60
Te	0.51	0.57	0.55	0.54	0.52	0.57	0.58	0.61	0.47	0.45	0.42	0.45	0.42	0.51	0.57	0.55	0.54
Li	0.00	0.00	0.06	0.00	0.03	0.00	0.00	0.04	0.00	0.00	0.04	0.00	0.04	0.00	0.00	0.06	0.00
nd – not de	etected																-

Table 8. Chemical composition of representative olivines. Results in wt.%. Chemical formula calculared according to $4\Omega^2$

Łukasz Karwowski

	33.	68.39	22.57	0.01	2.17	0.62	0.07	8.92	1.02	103.78		2.897	1.127	< 0.001	0.099	0.003	< 0.001	0.733	0.055	4.916	0.888		82.53	6.24	11.09	0.14
	32.	60.09	21.33	pu	2.14	0.23	0.02	9.57	0.88	100.26		2.902	1.104	-	0.101	0.001	< 0.001	0.814	0.049	4.971	0.965		84.41	5.12	10.42	0.05
	sk.8.	66.90	22.21	pu	2.32	nd	pu	9.19	1.36	101.98		2.888	1.130	I	0.107	-	I	0.769	0.075	4.969	0.951		80.87	7.86	11.27	0.00
	sk.7.	65.53	21.30	pu	2.22	pu	pu	9.91	1.01	99.97		2.891	1.108	I	0.105	I	I	0.848	0.057	5.008	1.009		83.98	5.63	10.39	0.00
	sk.6.	65.95	21.31	nd	2.27	pu	0.13	9.91	0.83	100.41		2.896	1.103	I	0.107	I	0.002	0.844	0.046	4.998	0.999		84.42	4.65	10.70	0.23
	So12.	65.61	21.41	nd	2.27	0.23	pu	9.63	1.16	100.32		2.887	1.111	I	0.107	0.001	I	0.822	0.065	4.994	0.994		82.68	6.56	10.76	0.00
)	So11.	66.75	22.47	pu	2.26	0.50	pu	9.61	0.90	102.49		2.872	1.139	I	0.104	0.003	I	0.801	0.050	4.969	0.955		83.91	5.20	10.89	0.00
	So10.	66.45	21.83	0.02	2.19	0.28	0.01	9.26	0.96	101.01	at.%	2.894	1.120	0.001	0.102	0.001	< 0.001	0.782	0.054	4.955	0.938	mol%	83.36	5.71	10.92	0.01
	#15	65.61	21.41	pu	2.27	0.23	pu	9.63	1.16	100.32		2.887	1.111	I	0.107	0.001	I	0.822	0.065	4.994	0.994		82.68	6.56	10.76	0.00
	#14	66.75	22.47	pu	2.26	0.50	pu	9.61	0.00	102.49		2.872	1.139	I	0.104	0.003	I	0.801	0.050	4.969	0.955		83.91	5.20	10.89	0.00
2	#13	66.45	21.83	0.02	2.19	0.28	0.01	9.26	0.96	101.01		2.894	1.120	0.001	0.102	0.001	< 0.001	0.782	0.054	4.955	0.938		83.36	5.71	10.92	0.01
•	#2	68.39	22.57	0.01	2.17	0.62	0.07	8.92	1.03	103.78		2.897	1.127	0.001	0.099	0.003	0.001	0.733	0.055	4.916	0.888		82.53	6.24	11.09	0.14
-	#1	66.09	21.33	pu	2.14	0.23	0.02	9.57	0.88	100.26		2.902	1.104	I	0.101	0.001	< 0.001	0.814	0.049	4.971	0.965		84.41	5.12	10.42	0.04
		SiO_2	Al ₂ O ₃	MgO	CaO	FeO	BaO	Na_2O	K ₂ O	Total		Si ⁴⁺	Al ³⁺	Mg ²⁺	Ca^{2+}	Fe^{2+}	Ba ²⁺	Na^+	K^{+}	Total	$Ca^{2+} + Ba^{2+} + Na^{+} + K^{+}$		Ab	Or	An	Cs

Table 9. Chemical composition of representative plagioclases. Results in wt.%. Chemical formula calculated according to 80^{2-}

nd – not detected



Fig. 17. Metamorphosed, recrystallized fragments of Sołtmany: **a** – rounded, fine-grained object of metamorphosed, recrystallized material, probably a former chondrule; **b** – close-up of the finegrained interior of the object from Fig. 17a; the object is mostly composed of pyroxene (px) and (lighter in color) olivine crystals (ol); the dark spots represent grains of plagioclase. All SEM-images (BSE)

Table 10. Chemical composition of representative apatite crystals.
Results in wt.%. Chemical formula calculated according to
250^{2-} . H ₂ O is calculated as a rest of the total sum of chlorine
and fluorine

	41	#2	ЩС
	#2	#3	#0
SO3	nd	nd	0.06
P ₂ O ₅	41.68	38.24	41.81
SiO ₂	0.06	0.11	0.06
MgO	nd	nd	0.02
CaO	53.97	49.18	53.06
MnO	0.02	0.08	0.12
FeO	0.60	0.22	0.61
Na ₂ O	0.52	0.43	0.42
H ₂ O	0.56	0.33	0.72
F	nd	nd	nd
Cl	4.74	5.05	4.11
Total	102.15	93.63	100.97
	at	.%	
S ⁶⁺	-	-	0.01
P ⁵⁺	5.99	6.02	6.03
Si ⁴⁺	0.01	0.02	0.01
Mg ²⁺	-	-	0.01
Ca ²⁺	9.82	9.79	9.69
Mn ²⁺	< 0.01	0.01	0.02
Fe ²⁺	0.08	0.03	0.09
Na ⁺	0.17	0.15	0.14
OH-	0.64	0.41	0.81
F-	-	-	-
Cl-	1.36	1.59	1.19
Total	18.09	18.03	17.99

nd – not detected

	#4	#9	#10	#11	#13	#15	#16	#18
Na ₂ O	2.82	2.86	2.64	2.53	2.67	2.67	2.80	2.75
MgO	3.52	3.53	3.50	3.52	3.51	3.51	3.65	3.55
P ₂ O ₅	46.80	46.43	46.32	45.82	46.52	44.61	46.35	45.63
CaO	47.29	47.05	47.16	46.77	47.16	45.10	46.46	46.81
K ₂ O	nd							
MnO	0.02	0.03	0.01	0.05	0.10	0.04	0.01	nd
FeO	0.81	0.63	0.51	0.52	1.02	1.03	1.03	0.62
Total	101.26	100.53	100.14	99.21	100.98	96.96	100.30	99.36
				at.%				
Na ⁺	1.932	1.976	1.829	1.769	1.840	1.913	1.941	1.921
Mg ²⁺	1.857	1.874	1.866	1.895	1.858	1.935	1.945	1.912
P ⁵⁺	14.008	13.996	14.006	13.990	13.981	13.963	14.003	13.938
Ca ²⁺	17.914	17.950	18.049	18.073	17.939	17.867	17.767	18.097
K*	-	-	-	-	-	-	-	-
Mn ²⁺	0.005	0.011	0.002	0.016	0.029	0.013	0.002	-
Fe ²⁺	0.238	0.186	0.152	0.156	0.303	0.319	0.308	0.186
Total	35.954	35.993	35.905	35.899	35.949	36.012	35.965	36.053
0	56.00	56.00	56.00	56.00	56.00	56.00	56.00	56.00

Table 11. Chemical composition of representative merrillite crystals. Results in wt.%. Chemical formula calculated according to 560²⁻

nd – not detected



Fig. 18. Metamorphosed, recrystallized fragments in transmitted light (figs. a, c-f crossed nicols; fig. b one nicol)

Phosphates

Two phosphates, apatite and merrillite, were identified in Sołtmany. Apatite is sparse and occurs as small grains of chloro-hydroxyl apatite. The chemical composition of various apatite crystals can be found in table 10. Apatite is relatively pure in composition, as it does not contain detectable concentrations of rare earth elements (REE) and Sr. The apatite contained only a minor amount of FeO (0.5 wt.%). Merrillite is more abundant than apatite. It forms grains of significant sizes that are evenly distributed throughout the meteorite. The merrillite grains contained a significant amount of Fe. The position of Fe in the chemical structure of merrillite remains a matter of speculation. The substitution of Mg would be the most feasible position. Representative results of merrillite crystals analyses can be found in table 11.

METEORITE CLASSIFICATION AND CONCLUSION

Based upon the results of chemical analyses of pyroxenes and olivines, calculated average content of Fs in low-Ca pyroxene and olivine amounts 21.4 mol%. At the same time average Fa content in olivine equals 25.5 mol%. In accordance with the accepted classification of ordinary chondrites, Sołtmany is an L chon-



Fig. 19. Occurrence of plagioclase (fsp) around a fine-grained pyroxene (px) – olivine (ol) assemblage. SEM (BSE image)

drite (Hutchison, 2006; McSween & Huss, 2010). Following the petrological analysis of Sołtmany, per the Van Schmus-Wood classification (1967), the chondrite is of petrologic type 6. This agrees with the observed content of Co in kamacite, which ranges between 0.75 and 0.86 at.%. Sołtmany has a weathering grade of W0 using the weathering scale developed by Wlotzka (1993). This very fresh meteorite was found within minutes following its fall and was submitted for analysis in less than a week. A shock stage of S2 was assigned to the meteorite in line with literary convention (Stöffler et al., 1991; Bischoff & Stöffler, 1992), as more than 25% of the olivine crystals exhibited undulose extinction, but planar fractures were absent.

Sołtmany is the first Polish meteorite to be thoroughly analyzed immediately after its fall. It is also the most recent chondrite of this petrologic type that was recovered shortly after having fallen in Europe. The previous fall of a similar meteorite was witnessed in April 2009 in Slovenia. However, the Jesenice L6 ordinary chondrite was not found until a few weeks after the fall, and weathering processes had already begun.

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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 compo-

sition 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(•10⁴) versus Fe/Si(•10⁴) 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 Soltmany 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	uudd	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	mdd	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															
Κ	t %	0.09	0.01	Hf		0.1	0.1	Cd	e	0.1	0.1		Sm		0.25	0.05															
Ti	igh	0.07	0.01	Nb		0.5	0.1	Sb	udd	< 0.1	0.1		Eu		0.08	0.02															
Р	we	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 1	Ag	-	< 0.1	0.1		Тb		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 Er		0.09	0.02															
Sum		99.7	0.01	Th		< 0.2	0.2	Se		7	0.5				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															

Chond	rites	Н	L	LL	Sołtmany	CI
Element	\geq				, î	
Si		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	0.232 0.257		0.27	0.19
Mg	%	14.0	14.9	15.3 14.73		9.7
Ca	eight	1.25	1.31	1.30	1.37	0.92
Na	M	0.64	0.70	0.70	0.73	0.49
К		0.078	0.083	0.079	0.09	0.056
Р		0.108	0.095	0.085	0.12	0.102
Ni]	1.60	1.20	1.02	1.59	1.07
Со]	0.081	0.059 0.049		0.059	0.051
S		2.0	2.2	2.3	2.12	5.9
С		0.11	0.09	0.12	0.03	3.2
Au (ppb)		215	162	140	161.1	144
Atomic ratio	os	Н	L	LL	Sołtmany	CI
Mg/Si		0.957	0.931	0.935	0.904	1.068
Al/Si(•10 ⁴)	696	686	655	653	853
Ca/Si(•10 ⁴)	518	496	482	511	614
Fe/Si(•10 ⁴)	8184	5845	4923	5881	8717
Ca/Al		0.74	0.72	0.74	0.78	0.72
Ni/Si(•10 ⁴)	453	310	258	404	488
CI normaliz Atomic ratio	ed os	Н	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

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)

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 Ltype ordinary chondrites.

The affiliation of Soltmany 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 Soltmany 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 Soltmany 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 Soltmany'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 Soltmany 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 Soltmany and CI-type carbonaceous chondrites normalized to L ordinary chondrites (Fig. 2) shows a common trend. However, the absolute values for Soltmany 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 Soltmany 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,

element	Sołtmany	average L	range L		element	Sołtmany	average L	range L
Si	188 312	186 000	155 700-245 000]	РЬ	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	1	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
Р	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	1	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	1	Sc	10	8.1	2.16–16.6
Be	< 1	0.04	0.026-0.3	1	Y	2.2	1.8	1.4–3.84
Со	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	1	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]				·

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.

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 Soltmany and Jesenice. The dates of their falls also indicated the possibility of an origin on a common parent body. Sołtmany fell on April 30th, 2011 in Poland, whereas the fall of Jesenice was witnessed on April 9th, 2009 in Slovenia. However, having compared the data gathered for Soltmany 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. Soltmany 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)



Fig. 4. Summary of bulk chemical compositions of Sołtmany and Jesenice L6 ordinary chondrites. Both meteorites were witnessed falls in the 21st 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 Soltmany and Jesenice L6 ordinary chondrites, which

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Authors wish to thank reviewers – Professors: Ulrich Ott and Łukasz Karwowski for their interesting and valuable remarks and comments to previous version of our manuscript. Thanks to them we were able to significantly improve our paper. 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.

were seen to fall in Europe in the 21st century on April

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COSMOGENIC AND RADIOGENIC NOBLE GASES IN THE SOŁTMANY L6 CHONDRITE

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Abstract: We measured the concentrations and isotopic compositions of He, Ne, Ar, Kr, and Xe in a 60.36 mg sample of the Sołtmany meteorite (L6), which fell in northeastern Poland in 2011. The Kr and Xe data suggest a mixture of atmospheric contamination and Q. Using cosmogenic ²¹Ne and ³⁸Ar concentrations, Sołtmany's cosmic-ray exposure (CRE) age was determined to be ~29.2 Ma. The preatmospheric radius for Sołtmany was equal to or less than approximately 15 cm and the sample studied here most likely came from close to the preatmospheric surface of the meteoroid. While the ⁴⁰Ar gas retention age is about 4137 Ma, the ⁴He gas retention age is 1610 Ma, suggesting loss of a major ⁴He fraction likely during an impact and/or degassing event on the Sołtmany parent body prior to the ejection of the Sołtmany meteorite ~29.2 Ma ago.

Keywords: noble gas, cosmic ray exposure age, preatmospheric radius, gas retention age

INTRODUCTION

The L6 chondrite Sołtmany fell on April 30th, 2011 near the small village of Giżycko in the northeastern part of Poland. The meteorite penetrated the edge of a roof and was immediately recovered. The total mass of Sołtmany is about 1066 g (Karwowski et al., 2011).

In this study, we analyzed the concentrations and isotopic compositions of the noble gases He, Ne, Ar, Kr, and Xe in a 60.36 mg sample of Sołtmany. The goal of this work was to decipher the cosmic-ray exposure history of Sołtmany, i.e., the cosmic-ray exposure (CRE) age, the preatmospheric size, and the shielding depth of the studied sample, and to determine whether or not the new data fit into the existing exposure age histogram for L-chondrites (e.g., Wieler, 2002; Herzog, 2003). In addition, we studied the thermal history of Sołtmany and the meteorite's source region on its parent body by analyzing the cosmogenic ³He/²¹Ne ratio and the ⁴He and ⁴⁰Ar gas retention ages.

EXPERIMENTAL

We analyzed the He, Ne, Ar, Kr, and Xe isotopic concentrations of the L6 chondrite Soltmany. Noble gas extraction and mass spectrometric measurements of a bulk sample with a mass of 60.36 mg were performed at the University of Bern following standard procedures (e.g., Eugster et al., 1993; Huber et al., 2008; Leya et al., 2013). Briefly, the sample was wrapped in aluminum foil before being loaded into the all-metal (except for a glass window) noble gas extraction and

purification system. To reduce atmospheric surface contamination the sample was pre-heated in vacuum at about 100 °C for one day. The sample was degassed in one temperature step at 1750 °C in a Mo crucible and the evolved gases were cleaned by admission to different getters and a He-Ne fraction, an Ar fraction, and a Kr-Xe-fraction were separated from each other using activated charcoal held between -120 °C and -196 °C. The different noble gas fractions, HeNe, Ar,

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Table 1. Measured and cosmogenic He and Ne concentrations (10⁻⁸ cm³STP/g) and isotope ratios in bulk material of the L6 chondrite Sołtmany.

Sample	Mass	³ He	⁴ He	²⁰ Ne	²⁰ Ne/ ²² Ne	²¹ Ne/ ²² Ne	²¹ Ne _{cos}	$(^{22}\text{Ne}/^{21}\text{Ne})_{cos}$
Sołtmany	60.36	35.9	585	8.23	0.881	0.863	8.06	1.15

The 3 He and 4 He concentrations are corrected for blank contributions and instrumental mass discrimination (15.8%). The Ne data are corrected for instrumental mass discrimination (0.1%/amu) and interferences but not for blank contributions. Uncertainties are 5% for gas amounts and about 1% for isotope ratios.

and KrXe, were measured sequentially using a static noble gas mass spectrometer. The gas concentrations were determined by peak height comparisons with standards having known amounts of He, Ne, Ar, Kr, and Xe.

Procedural blanks were determined with the same extraction procedure as for the sample: by analyzing 40–60 mg of aluminum foil, which is similar in mass to that used to wrap the sample. These so-called aluminum blanks were used only for the blank correction of ³He and ⁴He. For Ne, Ar, Kr, and Xe, the data were used only to check whether or not the blank is of atmospheric composition. We subtracted the blank values for He, Ne, and Ar using a two-component deconvolution (see below). All isotope ratios have been corrected for instrumental mass discrimination, ²⁰Ne has been corrected for interferences from H₂¹⁸O and ⁴⁰Ar²⁺, and ²²Ne has been corrected for interferences from CO₂²⁺. Krypton and Xe in Sołtmany are essen-

Cosmogenic He, Ne, and Ar

The low ²⁰Ne/²²Ne ratio of 0.88, which includes blank contributions, indicates that the measured Ne is purely cosmogenic and contains no significant amounts of solar and/or primordial Ne. We made minor corrections for trapped Ne assuming that the trapped component is atmospheric contamination. The correction was performed using a cosmogenic ²⁰Ne/²²Ne endmember ratio of 0.82 ± 0.02, which is identical within uncertainties to the preferred value of 0.80 \pm 0.03 for chondritic meteorites (Eugster et al., 2007) and an atmospheric endmember with ²⁰Ne/²²Ne and ²¹Ne/²²Ne ratios of 9.80 (Eberhardt et al., 1965) and 0.02878 (Heber et al., 2009), respectively. Note, this and the following cosmogenic gas fractions are labeled with an index "cos". The trapped corrections for ²¹Ne and ²²Ne/²¹Ne are less than 1%. Cosmogenic ²¹Ne_{cos} and $({}^{22}\text{Ne}/{}^{21}\text{Ne})_{cos}$ are given in Table 1. Since there is no solar and/or primordial Ne we can safely assume that the measured ³He is entirely cosmogenic.

The measured ${}^{36}\text{Ar}/{}^{38}\text{Ar}$ ratio of 1.00 is higher than the cosmogenic ${}^{36}\text{Ar}/{}^{38}\text{Ar}$ ratio of ~0.63 (Wieler, 2002), indicating significant contributions of trapped

Table 2. Measured and cosmogenic Ar concentrations (10⁻⁸ cm³STP/g) and isotope ratios in bulk material of the L6 chondrite Softmany

Sample	Mass	³⁶ Ar	⁴⁰ Ar	³⁶ Ar/ ³⁸ Ar	³⁸ Ar _{cos}
Sołtmany	60.36	1.25	5 148	1.00	1.15

The Ar data are corrected for instrumental mass fractionation (0.5%/amu) and interferences but not for blank contributions. Uncertainties are 5% for gas amounts and about 1% for isotope ratios.

tially a mixture of atmospheric contamination, Kr and Xe from phase Q (noble gases host phase defined by Lewis et al. (1975)), and minor cosmogenic contributions. Since the deconvolution of the different Kr and Xe components suffered from the rather large uncertainties of the measured Kr and Xe concentrations, the Kr and Xe data are not discussed here. The noble gas concentrations and isotope ratios for He and Ne are given in Table 1. The data for Ar are given in Table 2.

RESULTS

Ar, either primordial and/or atmospheric. Considering the high petrographic type of Sołtmany (L6), we assume that the Ar is a mixture of trapped atmospheric contamination and cosmogenic Ar with 36 Ar/ 38 Ar ratios of 5.319 and 0.62, respectively. The correction for trapped 38 Ar is about 10%.

When discussing $({}^{3}\text{He}/{}^{21}\text{Ne})_{cos}$ as a function of $({}^{22}\text{Ne}/{}^{21}\text{Ne})_{cos}$, the value measured for Sołtmany plots (Fig. 1) slightly below the empirical correlation line given by Nishiizumi et al. (1980), indicating a ${}^{3}\text{He}$ deficit of about 25%. About 50% of the cosmogenic ${}^{3}\text{He}$ was originally produced as radioactive ${}^{3}\text{H}$ (e.g., Leya and Masarik, 2009), which β -decayed to ${}^{3}\text{He}$. ${}^{3}\text{H}$ is supposed to diffuse much faster than ${}^{3}\text{He}$; the deficit of 25% most likely indicates ${}^{3}\text{H}$ diffusive losses of about 50%. Such diffusive losses might indicate that Sołtmany had an orbit with a perihelion close to the Sun.

Note that noble gas data alone are not enough to uniquely restrict the size of the meteorite and the position of the studied sample. A possible way to determine the preatmospheric radius using only the cosmogenic 22 Ne/ 21 Ne ratio is given by the empirical



Fig. 1. (³He/²¹Ne)_c vs. (²²Ne/²¹Ne)_c (Bern plot). Also shown is the empirical correlation line for chondrites as given by Nishiizumi et al. (1980). The dashed lines represent the ±15% variations from this correlation

correlation from Bhandari et al. (1980). Unfortunately, this correlation is only valid in a certain range of nuclear track densities and nuclear track data are not available for Soltmany. However, radionuclide data measured via non-destructive γ -spectrometry (e.g., ⁵²Mn, ²²Na, ²⁶Al) and especially the absence of any detectable ⁶⁰Co activity indicate a preatmospheric radius of less than ~20 cm for Soltmany (Laubenstein et al., 2012). With this a priori information we can use the empirical correlation between the preatmospheric mass of a meteorite and its (²²Ne/²¹Ne)_{cos} ratio (Bhandari et al., 1980) and calculate a preatmospheric mass for Soltmany of about 36 kg. Using a bulk density for Soltmany of 3.475 g/cm³ (Szurgot et al., 2012), which is almost identical to the average density for L-chondrites of 3.35 g/cm³ (Britt and Consolmagno, 2003), we obtain a preatmospheric radius of about 13.5 cm, which perfectly confirms the radionuclide data (Laubenstein et al., 2012). With a preatmospheric mass for Soltmany of about 36 kg and the about 1 kg found on the Earth, only about 3% of the original mass made it to the Earth surface, which is lower than the average of 15-20% (Bhandari et al., 1980; Alexeev, 2004).

Having demonstrated that Sołtmany had a preatmospheric radius smaller than about 15 cm, we can safely use the empirical correlations between ²¹Ne_{cos} and ³⁸Ar_{cos} production rates and the shielding indicator (²²Ne/²¹Ne)_{cos} (Dalcher et al., 2013) to determine the CRE age of Sołtmany. With the measured (²²Ne/ ²¹Ne)_{cos} ratio of 1.15, we obtain a ²¹Ne production rate of 0.285×10⁻⁸ cm³STP/g/Ma. Using now the ²¹Ne_{cos} concentration of 8.06×10⁻⁸ cm³STP/g (Table 1) we calculate a CRE age based on cosmogenic ²¹Ne, T₂₁, of 28.3 Ma. Doing the same exercise with cosmogenic ³⁸Ar_{cos}, we calculate a production rate of $0.0384 \times 10^{-8} \text{ cm}^3 \text{STP/g/Ma}$ and with the ³⁸Ar_{cos} concentration of $1.15 \times 10^{-8} \text{ cm}^3 \text{STP/g/Ma}$ we obtain a CRE age based on ³⁸Ar, T₃₈, of 30.0 Ma, which is in good agreement with T₂₁. The average value for the CRE age for Soltmany is 29.2 Ma (N = 2) with an uncertainty of about 10%.

The exposure age histogram for L-chondrites shows a major peak at 40 Ma and three minor peaks at 5 Ma, 15 Ma, and 28 Ma (e.g., Wieler, 2002). However, Herzog (2003) argues that there is only one strong peak for the L-chondrites at about 40 Ma and a possible peak at about 5 Ma. The author also suggests that, instead of the peak at about 15 Ma, there is a broad hump between 20–30 Ma with a maximum at about 28 Ma. Our estimate of the CRE age for Sołtmany of 29.2 Ma supports this argument.

Radiogenic ⁴He and ⁴⁰Ar

As discussed above, Sołtmany lost ³He and/or ³H, possibly due to solar heating at small perihelion distances. In addition to the loss of cosmogenic gases, radiogenic gases (e.g., ⁴He and ⁴⁰Ar) can be lost either during impacts or other thermal events on the meteorite parent body and/or due to terrestrial weathering (e.g., Scherer & Schultz, 2000). Since Sołtmany is an observed fall, any losses due to terrestrial weathering should be negligible.

To estimate the radiogenic ⁴He abundance, measured ⁴He is corrected for cosmogenic using the relationship between (³He/⁴He)_{cos} and (²²Ne/²¹Ne)_{cos} given by Leya and Masarik (2009). The correction is about 26%. Note that we can estimate only an upper limit for the ⁴He age because of the assumption that all ⁴He (corrected for cosmogenic ⁴He) is of radiogenic origin. We did not correct ⁴He for a potentially trapped component. Using U and Th concentrations of 10 and 42 ppb, respectively, as measured by nondestructive γ -spectrometry (Laubenstein et al., 2012) we calculate a ⁴He gas retention age for Soltmany of about 1610 Ma (Tab. 3). Note that the values of U and Th are in good agreement with those of average concentrations for L-chondrites given by Wasson and Kallemeyn (1988), Lodder and Fegley (1998), and McSween and Huss (2010).

Using the measured ⁴⁰K concentration of 840 ppm for Sołtmany (Laubenstein et al., 2012), which is similar to the average ⁴⁰K concentration for L-chondrites of 858 ppm (Kallemeyn et al. 1989), and the measured ⁴⁰Ar concentration (Table 2) we calculate a ⁴⁰Ar gas retention age of 4137 Ma (Tab. 3). Interestingly, the ⁴⁰Ar gas retention age is relatively high, indicating that Sołtmany comes from a region of the L-chon-

Table 3. Cosmic ray exposure ages and gas retention ages for the L6 chondrite Soltmany (all in Ma)

Sample	T _{GCR} (³ He) ¹	T _{GCR} (²¹ Ne)	T _{GCR} (³⁸ Ar)	T _{ret} (⁴ He)	T _{ret} (⁴⁰ Ar)
Sołtmany	20.4	28.3	30.0	1610	4137

¹ The $T_{GCR}({}^{3}\text{He})$ age has been calculated using the correlation ${}^{3}\text{He}/{}^{21}\text{Ne}$ vs. ${}^{22}\text{Ne}/{}^{21}\text{Ne}$ (Dalcher et al., 2013) and the ${}^{21}\text{Ne}$ production rate used to calculate $T_{GCR}({}^{21}\text{Ne})$. All ages have uncerainties of about 10%.



Fig. 2. Ratio of cosmogenic exposure ages T_3/T_{21} vs. ratio of gas retention ages T_4/T_{40} . Meteorites plotting on the solid line with slope 1 (but off from the ratios of 1) lost ³He and ⁴He during the cosmic-ray exposure time. Meteorites lying to the left of the solid line (like in case of Sołtmany) lost radiogenic ⁴He before their cosmic-ray exposure, either at or before break-up of their parent body. Meteorites plotting to the right of the correlation line indicate trapped solar ⁴He. Data plotting in-between the two horizontal lines show no or only minor indications of ³He and/or ³H diffusive losses.

drite parent body that did not suffer degassing during the 470 Ma break-up event (e.g., Swindle and Kring, 2008). The ⁴⁰Ar gas retention age is about 2.5 times higher than the ⁴He gas retention age, indicating significant losses of radiogenic ⁴He (Fig. 2). Based on the radiogenic ⁴⁰Ar gas retention age, the estimated loss of radiogenic ⁴He is about a factor of 3.4. The estimated deficit of cosmogenic ³He is about 25%, which could be due to diffusive losses such as those that would be experienced by a ~15 cm diameter meteoroid with a relatively small perihelion distance. The same diffusion event(s) that led to this ³He deficit could also account for the loss of about 25% of the radiogenic ⁴He. If this is true, the radiogenic ⁴He concentration at the time of ejection of Soltmany from its parent body was about 540 cm³STP/g, i.e., still a factor of about 2.7 too low to bring ⁴He and ⁴⁰Ar gas retention ages into agreement. From the data we cannot decide when and how Soltmany lost its radiogenic ⁴He. It is conceivable that some radiogenic ⁴He, but none of the radiogenic ⁴⁰Ar, has been lost either in the asteroidal break-up event at 470 Ma and/or at the meteoroidforming event at 29.2 Ma.

CONCLUSIONS

We measured the concentrations and isotopic compositions of He, Ne, Ar, Kr, and Xe for Sołtmany, the L6 chondrite that fell recently in Poland. The Kr and Xe data are too uncertain to constrain the cosmic-ray exposure history of Sołtmany. Based on cosmogenic ${}^{21}\text{Ne}_{cos}$ and ${}^{38}\text{Ar}_{cos}$ concentrations, together with the $({}^{22}\text{Ne}/{}^{21}\text{Ne})_{cos}$ ratio, we determined a CRE age for Sołtmany of 29.2 Ma, a preatmospheric size of less than about 15 cm, and we conclude that the studied sample resided close to the preatmospheric surface of

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COSMOGENIC RADIONUCLIDES IN THE SOŁTMANY (L6) METEORITE

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Abstract: Cosmogenic radionuclides were measured in two specimens of the Sołtmany chondrite (L6) that fell on April 30, 2011. The first fragment (154.9 g) was measured 12 days after the fall and the second piece (120 g), 53 days after the fall. Both fragments were measured by means of non-destructive gamma ray spectroscopy. The first specimen was examined with an ultra-low background high purity germanium (HPGe) detector in a deep underground laboratory. A standard low-background HPGe detector was used to examine the second fragment in a ground level laboratory. Twelve cosmogenic nuclides were detected in the activity range of 0.030 m·Bq g⁻¹ until 1.5 m·Bq g⁻¹. Their activities place constraints on the exposure history of the meteorite and reflect the effect of solar modulation of galactic cosmic rays during the solar maximum. On the activities of expected radionuclides 60 Co (< 0.0075 m·Bq g⁻¹) and 44 Ti (< 0.023 m·Bq g⁻¹) only upper limits could be given. Soltmany is part of a group of only 14 meteorites where 52 Mn (5.591 d half life) could be determined.

Keywords: meteorite, ordinary chondrite, short-lived radionuclides, cosmogenic radionuclides, gamma-ray spectrometry, ⁵²Mn

INTRODUCTION

Cosmogenic radioactive and stable nuclides in chondrites have preserved important records of their exposure history during the last ten million years (e.g., Michel, 1999; Vogt et al., 1990; Caffee et al., 1988). The activity of the typical neutron-capture product, 60Co has been used as an indicator of meteorites' preatmospheric size (e.g., Eberhardt et al., 1963; Spergel et al., 1986), and the activities of spallation products, including ²²Na, ⁵⁴Mn, ²⁶Al, etc., reflect irradiation conditions such as cosmic-ray shielding (e.g., Bhandari et al., 1993; Michel et al., 1995), exposure age (e.g., Heimann et al., 1974; Herpers and Englert, 1983), and the total flux of cosmic-rays (e.g., Evans et al., 1982). Production rates of cosmogenic radionuclides are influenced by many parameters. They are dependent on the composition of the meteorite. Each cosmogenically produced radionuclide has only a few target nuclides from which they are produced. Each

radionuclide's production rate is determined by the abundances of its respective target nuclides (e.g. for ²²Na the target nuclides are Mg, Al, and Si, whereas for ⁵⁴Mn it is mainly iron, and for ⁶⁰Co it is mainly cobalt). Another important factor affecting radionuclide production is the size of the meteoroid. If the object is relatively small, the production rate increases with depth, to the body's center. Once the meteoroid's diameter exceeds approximately 80 cm, self-shielding limits radioisotope production in the inner part of the meteoroid and the production rates decrease towards the center. It is thus important to estimate, if possible, the so-called shielding depth of the sample, as it can significantly influence the production rate at the sample's depth within the meteoroid. Radionuclides and stable isotopes are produced by the interactions of both Solar (SCR) and Galactic (GCR) Cosmic Ray particles with extraterrestrial materials. These cosmogenic

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nuclide archives can be analyzed to give information about the history of both the object and the cosmic rays themselves. Production of cosmogenic nuclides by solar protons is limited to the top few centimeters of the lunar or meteorite's surface, while GCR particles penetrate deeply into an object. The contribution to the overall cosmogenic nuclide production due to secondary neutrons produced in GCR reactions is significant, especially at greater depths. Short-lived radionuclides such as ⁴⁸V (15.9735 d), ⁵⁶Co (77.236 d), ⁴⁶Sc (83.788 d), ⁵⁴Mn (312.13 d), and ²²Na (2.6027 a), have been used to estimate the solar proton fluxes in a single solar cycle, to determine the flux of an individual solar proton event, and to study solar modulation effects on the cosmic ray flux. Finally, there is variation of the flux of galactic cosmic rays due to time and space (orbit of the meteoroid). Long-term variations are usually averaged out in very long lived radionuclides. Short-term variations primarily affect shortlived radionuclides. Meteoroids exposed locally to the

influence of the Sun can exhibit enhanced concentrations of short-lived radionuclides due to the 11-year solar activity cycle. Thus, one would expect meteorites that fall during solar activity minima to have higher radionuclide concentrations than those that fall during solar activity maxima (see Evans et al. (1982) for an example).

In Poland, only one meteorite fall in addition to Sołtmany has been recovered in the last 20 years (Baszkówka, an L5 chondrite, fell August 25, 1994), and to our knowledge no measurements of γ -emitting radionuclides have been carried out on it.

In this paper, we present the results obtained by non-destructive γ -ray measurements of two specimens of the Sołtmany meteorite (chondrite (L6), fell April 30, 2011 in Sołtmany, a small village near Giżycko in northeastern Poland) and discuss its exposure history including the period of time immediately prior to its collision with Earth.

EXPERIMENTAL METHODS

The concentrations of short-lived cosmogenic radionuclides, as well as ²⁶Al (half-life = $7.17 \cdot 10^5$ a) and natural radioactivity were measured in a 154.9 g fragment of the Sołtmany meteorite at the STELLA (SubTerranean Low Level Assay) underground facility of the Laboratori Nazionali del Gran Sasso (LNGS) (Arpesella, 1996) in Italy. Measurements were started on an ultra low background high-purity germanium (ULB HPGe) detector (coaxial p-type, 120% relative efficiency, thin Cu window, shielded with 25 cm of lead and 5 cm of copper, flushed with radon-free nitrogen) within 12 days of the meteorite fall, so that short-lived radionuclides, such as ⁵²Mn (half-life =



Fig. 1. The larger fragment of the Sołtmany meteorite (154.9 g) examined at the LNGS.

5.591 days) and 48 V (half-life = 15.9735 days) could be detected. Unfortunately, too much time had passed since the fall to detect very short-lived nuclides such as ²⁴Na, ²⁸Mg, ⁴³K and ⁵⁷Ni (with half-lives of 15-38 hours), which have thus far been detected in only a few meteorite falls (Bhandari et al., 1989, Komura et al., 2002). The counting efficiencies of each radionuclide are calculated using a Monte Carlo code that has been validated through measurements and analyses of samples of well-known radionuclide activities and geometry. This method is described in more detail in Welten et al. (2012) and references therein. The uncertainties in the radionuclide activities are dominated by the uncertainties in the counting efficiency, which are conservatively estimated at 10%. This estimate is based on Monte Carlo simulations taking into account the uncertainty in geometry, density and chemical composition of meteorite specimens. The measurement period was about 21 days, from May 12th to 31st, 2011. The measured activities of the cosmogenic radionuclides in the Soltmany meteorite, normalized to the time of fall, are given in Table 1. U and Th were observed to have 6 (295.2 keV and 351 keV for ²¹⁴Pb; 609.3 keV, 1120.3 keV, 1764.5 keV and 2204.0 keV for ²¹⁴Bi) and 7 single peaks (338.6 keV, 911.2 keV, 964/968 keV for ²²⁸Ac; 238.6 keV for ²¹²Pb, 727.2 keV for ²¹²Bi, 583.2 keV and 2614.5 keV for ²⁰⁸Tl), respectively, and then the weighted average was calculated. Assuming secular equilibrium within the uranium chain between ²²⁶Ra (parent nuclide for ²¹⁴Pb and

²¹⁴Bi) and ²³⁸U (U), and within the thorium chain between ²²⁸Ra (parent nuclide for ²²⁸Ac), ²²⁸Th (parent nuclide for ²¹²Pb, ²¹²Bi and ²⁰⁸Tl) and ²³²Th (Th) concentrations for U and Th have been calculated. A second, prism-like piece of Sołtmany meteorite (120 g) was measured in a gamma spectrometric measurement at the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN), in Kraków (Poland). The measurements were completed using a 30% relative efficiency HPGe Ortec Pop-top detector equipped with a beryllium window, shielded by a 17 cm thick XIX century steel shield. The spectrometer was calibrated using a specially prepared source, which was designed to have very similar shape to the examined piece of meteorite, placed in the same position with respect to the detector. The source named ERL-1 contained washed, fine quartz sand carefully mixed with powdered uranium ore (from USAEC, NBL, Standard 3-B), monazite sand (from USAEC, NBL, Standard 7-A), and KCl (from POCH, analytical grade). A correction for the activity concentration in sand was applied.

The same mixture (ERL-1) was placed in a Marinelli beaker (800 g) in order to verify the calculated activity concentration of natural radionuclides in the prepared prism-like standard (the one approximating the shape and dimensions of analyzed piece of meteorite). The activity concentration in the ERL-1 standard was additionally verified by preparing a vessel in the form of a disc 50 mm in diameter and 5 mm tall, filled with the same ERL-1 mixture (17.48 g). It was measured against a multi-gamma standard used for air filter calibration (SZN-3, provided by Polatom, Świerk) of the same size, which contained a certified amount of ²⁴¹Am, ¹⁰⁹Cd, ⁵⁷Co, ¹¹³Sn, ¹³⁷Cs, ⁵⁴Mn, ⁶⁵Zn, ⁶⁰Co. This test gave results that were consistent within 25% deviation at maximum (for the radionuclides of the Th and U series it is below 10%), probably caused by sample heterogeneities. The measurement for the second, smaller piece lasted for about 6 days, from 22 to 28 June 2011, so approximately 53 days after fall of the meteorite (30 April 2011).

RESULTS AND DISCUSSION

The activities of cosmogenic nuclides at the time of fall are summarized in Table 1 in comparison to the data of other recent ordinary chondrites (Bhandari et al. 1989, Bischoff et al., 2011) as well as to a range of typical values taken from Evans et al., 1982, Cressy, Jr., 1970 and Shedlovsky et al., 1967. All values are decay corrected to the time of fall. The average composition for L chondrites as given in Wasson, J. T. and Kallemeyn, G. W. (1988) was used for the following discussion.



Fig. 2. The massic activities of ⁵²Mn as a function of the time of fall, taken from Table 2 and normalized to the average concentration of the target isotopes iron and nickel for each meteorite type (sourced from the publications listed in the caption of the table, and, if not available therein, from Wasson and Kallemeyn, 1988). Overlying is the neutron monitor data of Oulo in arbitrary units with monthly averages (Cosmic Ray Station of the University of Oulu, 2013).

COSMIC-RAY EXPOSURE HISTORY

The gamma-ray measurements of Soltmany show the presence of short-lived cosmogenic radionuclides with half-lives ranging from about 5.591 days (⁵²Mn) to 2.6027 years (²²Na). The presence of short-lived ⁵²Mn has been detected in only a handful of chondrites, including for example Itawa Bhopji (L3-5), Kobe (CK4), Mihonoseki (L6), and Torino (H6) (Bhandari et al. 2002; Komura et al. 2002; Shima et al. 1993; Bhandari et al. 1989). All available data for ⁵²Mn in meteorites together with the results from Soltmany are summarized in Table 2. The concentrations of shortlived radionuclides at the time of fall are a function of shielding conditions of the meteorite as well as of the solar modulation of the galactic cosmic-ray flux, which follows an 11-year cycle (Evans et al., 1982). As can be seen in Fig. 2 the data points of all meteorites (concentration of ⁵²Mn normalized to the Fe/Ni content of the meteorite) are rather well in agreement with the variations of the Solar Cycle. The value of Soltmany is lower than expected. Indeed, most of its short-lived radionuclides are somewhat lower than the range for medium-sized chondrites, such as Torino (R=20 cm), Bruderheim (R=30 cm), Mbale and Villalbeto de la Peña (R=35-40 cm), suggesting a pre-atmospheric radius of less than 20 cm for the Soltmany chondrite. As there are no calculations available for the production rate of ⁵²Mn in meteorites, we tried to establish an alternative way for checking the consistency of the available data for this radionuclide. From

the most recent measurements of cross sections for the production of ⁵²Mn and ⁵⁴Mn through reactions (p,x) and (n,x) on the main targets, iron and nickel (Sisterson and Vincent, 2006), one would expect a ratio of the activities of ⁵²Mn/⁵⁴Mn, somewhat smaller than about 0.4 in the meteorites, where both radioisotopes have been measured. This comes from the fact that 0.4 is the ratio of cross sections for the reaction path Fe(p,x)Mn, whereas for the reactions Fe(n,x)Mn the ratio is about 0.15. Most of the ⁵²Mn and ⁵⁴Mn are produced on the surface by the SCR protons and only a partly in the bulk of the meteorite by secondary neutrons, their amount depending also on the size of the meteorite. Thus, the overall ratio will be less than 0.4, but bigger than 0.15. If we do this exercise with the meteorites listed in Table 2, taking the data from the publications listed in the Table caption, we get as mean value 0.29 ± 0.15 , where the uncertainty is simply the standard deviation. This average agrees well with the expected results.

Since ²²Na and ²⁶Al in chondrites are produced by very similar reaction mechanisms from major elements (Mg, Al and Si), the activity ratio of ²²Na to ²⁶Al, $P(^{22}Na)/P(^{26}Al)$, is rather independent of shielding conditions. However, due to the short half-life of ²²Na, its concentration in recent meteorite falls depends on the recent GCR flux, whereas the concentration of ²⁶Al reflects the average GCR flux over the past ~1 Ma. The ²²Na/²⁶Al activity ratio in observed chon-

Table 1. Massic activities of cosmogenic radionuclides (decay corrected to the time of fall) in the Sołtmany meteorite in comparison to the Jesenice L6 chondrite (Bischoff et al., 2011), the Torino H6 chondrite (Bandhari et al., 1989), and to a typical range for ordinary chondrites (taken from Evans et al., 1982). The first two columns give the results for the specimens measured at LNGS (12 d after fall) and IFJPAN (53 d after fall), respectively. Uncertainties given are combined standard uncertainties with the expansion factor of k=1. (n.a. is standing for not available).

		Activity concentration in [mBq g ⁻¹]						
Radionuclide	Half-life	Sołtmany	Sołtmany	Jesenice	Torino	Typical range for		
		(LNGS)	(IFJ PAN)	(sample F9)	(sample A)	chondrites		
⁵² Mn	5.591 d	0.17 (3)	< 320	n.a.	0.338 (30)	0.15-0.43		
⁴⁸ V	15.9735 d	0.300 (24)	< 3.2	n.a.	0.346 (25)	0.083-0.57		
⁵¹ Cr	27.703 d	0.83 (9)	< 11	n.a.	1.27 (12)	0.47-1.83		
⁵⁹ Fe	44.495 d	0.03 (1)	< 1.1	n.a.	< 0.058	n.a.		
⁷ Be	53.22 d	1.28 (11)	< 5.4	6 (1)	0.98 (10)	0.50-2.05		
⁵⁸ Co	70.38 d	0.094 (8)	< 0.50	0.24 (7)	0.183 (12)	0.017-0.28		
⁵⁶ Co	77.236 d	0.081 (7)	< 0.55	0.20 (6)	0.128 (13)	0.050-0.15		
⁴⁶ Sc	83.788 d	0.138 (11)	< 0.44	0.23 (7)	0.173 (33)	0.033-0.17		
⁵⁷ Co	271.8 d	0.156 (12)	< 0.29	0.18 (4)	0.272 (17)	0.043-0.29		
⁵⁴ Mn	312.13 d	1.26 (9)	1.53 (14)	1.4 (2)	2.02 (3)	0.47-2.17		
²² Na	2.6027 a	1.51 (11)	1.28 (12)	1.4 (2)	1.33 (2)	0.67-4.33		
⁶⁰ Co	5.2710 a	< 0.008	< 0.25	< 0.037	0.047 (5)	0-1.67		
⁴⁴ Ti	60.0 a	< 0.023	< 0.19	0.03 (1)	0.037 (7)	n.a.		
²⁶ Al	717000 a	0.82 (6)	0.87 (10)	0.8 (1)	0.900 (18)	0.63-1.33		

Meteorite	Fall (Date and Time	Туре	Activity concentration of ⁵² Mn	Solar activity
	at Coordinated Universal Time (UTC))		in $[mBq \cdot g^{-1}]$	-
Saint- Séverin	June 27, 1966, 14:40 UTC	LL6	0.25 (10)	Solar maximum
Lost City	January 4, 1970, 02:14 UTC	H5	0.6 (2)	Solar maximum
Dhajala	January 28, 1976, 15:10 UTC	H3	0.47 (7)	Solar minimum
Aomori	June 30, 1984, 04:50 UTC	L6	0.23 (7)	Solar minimum
Kokubunji	July 29, 1986, 10:00 UTC	L6	0.52 (8)	Solar minimum
Torino	May 18, 1988, 12:40 UTC	H6	0.338 (30)	Solar minimum
Mbale	August 14, 1992, 12:40 UTC	L5-6	0.28 (8)	Solar maximum
Mihonoseki	December 10, 1992, 12:00 UTC	L6	0.35 (4)	Solar maximum
Kobe	September 26, 1999, 11:21 UTC	CK4	0.20 (3)	Solar minimum
Morávka	May 6, 2000, 11:52 UTC	H5	0.22 (3)	Solar maximum
Itawa Bhopji	May 30, 2000, 08:15 UTC	L3-5	0.16 (3)	Solar maximum
Devgaon	February 12, 2001, 10:30 UTC	H3-4	0.19 (3)	Solar maximum
Mifflin	April 14, 2010, 03:07 UTC.	L5	0.4 (2)	Solar minimum
Sołtmany	April 30, 2011, 04:03 UTC	L6	0.17 (3)	Solar minimum

Table 2. Massic activities of ⁵²Mn (decay corrected to the time of fall) in meteorites, including the Sołtmany meteorite. The data sets are ordered in ascending order for the date of fall. The data for the meteorites other than Sołtmany are taken from (Cressy, 1970; Cressy, 1971; Bhandari et al, 1978; Heusser et al., 1985; Yabuki et al., 1985; Bandhari et al., 1989; Shima et al., 1993; Jenniskens et al., 1994; Neder et al. 2001; Bhandari et al., 2002; Komura et al., 2002; Murty et al., 2004; Kita et al., 2013)

drite falls are generally in the range from 1-2 (Evans et al. 1982; Bhandari et al. 2002), with most of the variations being due to variations in the GCR flux as a function of the time of fall within the 11-year solar cycle. Higher ²²Na/²⁶Al ratios may be due to a complex CRE history, as shown by the high ratios in Jilin (4.4 ± 0.4) (Heusser et al., 1985), Dhajala (2.2 ± 0.2) (Bhandari et al., 1978) and Kobe (2.0 ± 0.2) (Komura et al., 2002), chondrites with well documented complex CRE histories, or due to a large contribution of SCR produced ²²Na, as is the case for the very small Salem LL chondrite (Evans et al., 1987). The average value of (1.8 \pm 0.2) for the ²²Na/²⁶Al ratio in the Soltmany meteorite is consistent with what is expected as the fall occurred during the actual period of the end of minimum solar activity and the beginning of the new maximum solar activity (see e.g. Bhandari et al., 2002).

Cosmogenic ⁶⁰Co in chondrites is predominantly produced by capture of thermal neutrons on ⁵⁹Co, a reaction pathway that is very sensitive to size and depth (Spergel et al., 1986). The Sołtmany meteorite shows no ⁶⁰Co activity above the sensitivity of the detector (< 0.008 mBq·g⁻¹), which according to Eberhardt et al., 1963 (normalizing the activity concentration of ⁶⁰Co to the Co content of the meteorite) suggests that the preatmospheric size of this meteorite was small (radius < 15 cm) or that the specimen was located near the surface region of the meteoroid.

Summarizing the results, when we compare the radionuclide concentrations with cosmic ray production estimations for ²⁶Al (Leya and Masarik, 2009),

⁶⁰Co (Eberhardt et al., 1963), ⁵⁴Mn (Kohman and Bender, 1967), and ²²Na (Bhandari et al., 1993, Murty et al., 1998), the best agreement is obtained (in the sequence of the given isotopes) for pre-atmospheric radii of less than 15 cm, less than 15 cm, less than 13 cm and less than 15 cm. These numbers are obtained by interpreting the measured massic activities as production rates (PR). Those values are then compared to the calculated production rates for different radii of meteorites at different depths given in literature, and interpolating the measured values yields corresponding radii of the measured meteorite. The strongest constraint comes from ⁶⁰Co, because the production rates observed for the other radionuclides would also be consistent with exposure in deep shielding positions at radii beyond 100 cm. Our estimations are based upon the average flux of primary cosmic ray intensity; no corrections have been applied for potential deviations. In any case, this effect would result in even smaller radii due to enhanced PRs at least for the relevant periods for ²²Na and ⁵⁴Mn production before the fall of Soltmany.

For the primordial radionuclides, the measured concentrations of U = $(10 \pm 1) \cdot 10^{-9}$ g·g⁻¹ and Th = $(42 \pm 2) \cdot 10^{-9}$ g·g⁻¹, are consistent with the average L-chondrite concentrations given in Wasson and Kallemeyn (1988), Lodders and Fegley (1998), and Mc-Sween and Huss (2010). The measured ⁴⁰K activity yields a K content of $(840 \pm 60) \cdot 10^{-6}$ g·g⁻¹, also consistent with average L-chondrite values given in the same literature as above.

SUMMARY

Twelve cosmogenic nuclides (⁵²Mn, ⁴⁸V, ⁵¹Cr, ⁵⁹Fe, ⁷Be, ⁵⁸Co, ⁵⁶Co, ⁴⁶Sc, ⁵⁷Co, ⁵⁴Mn, ²²Na, and ²⁶Al) were measured via "extremely" low background γ -ray measurement of the Soltmany meteorite. Three additional nuclides (⁵⁴Mn, ²²Na, and ²⁶Al) were counted at ground conditions. For the activities of ⁶⁰Co, and ⁴⁴Ti, only upper limits were determined. The low activities of neutron-induced ⁶⁰Co (< $0.008 \text{ mBq}\cdot\text{g}^{-1}$) and spallation reaction products suggest two possibilities: 1) the preatmospheric size of this meteorite

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was rather small (r < 15 cm) or 2) this fragment was from near the surface region of a bigger meteoroid. Soltmany is one of only 14 meteorites in which the concentration of ⁵²Mn has been quantitatively measured and published. The rather low content of this very short-lived radionuclide, together with the fact that the other short-lived radionuclides are somewhat lower than the average of similar meteorites, suggests that the meteorite was rather small before entering the Earth's atmosphere.

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THERMOPHYSICAL PROPERTIES OF THE SOŁTMANY METEORITE

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- Abstract: Bulk density, porosity and thermophysical properties of the Sołtmany meteorite have been determined. The mean bulk density of the meteorite is $3.475 \cdot 10^3 \text{ kg/m}^3$, mean bulk density of the crust is $4.3 \cdot 10^3 \text{ kg/m}^3$, grain density $3.71 \cdot 10^3 \text{ kg/m}^3$, and porosity $6.4 \pm 0.4\%$. Mean specific heat capacity determined by DSC in temperature range between 223 and 823 K increases from 595 to 1046 J/(kg·K), and is equal to 728 J/(kg·K) at room temperature. Specific heat capacity of various samples is in the range 705–769 J/(kg·K) at room temperature. Thermal capacity of Sołtmany chondrite is equal to $2.53 \cdot 10^6 \text{ J/(m}^3 \cdot \text{K})$, thermal diffusivity $(1.5-1.8) \cdot 10^{-6} \text{ m}^2/\text{s}$, and thermal conductivity $3.9-4.5 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ at room temperature. Differential scanning calorimetry revealed two reversible phase transitions in the Sołtmany's troilite: α/β transition at 423 K, and β/γ transition at 596.6 K.
- Keywords: chondrite, differential scanning calorimetry (DSC), specific heat capacity, thermal capacity, thermal diffusivity, thermal conductivity

INTRODUCTION

Thermophysical properties are important physical properties of terrestrial and extraterrestrial matter. Unfortunately, little effort has been spent in recent years to determine the thermal properties of meteorites, terrestrial planets, asteroids and moons (Beech et al., 2009; Opeil et al., 2010, 2012; Szurgot, 2003, 2011a,b, 2012a,b,c,d; Szurgot et al., 2008; Szurgot & Wojtatowicz, 2011; Szurgot & Polański, 2011), and only a few important materials have been studied and published in XX-th century (Matsui & Osako, 1979; Osako, 1981; Yomogida & Matsui, 1981, 1983; Gosh & McSween, 1999). Measurements and analysis of various physical properties are necessary for characterisation of new extraterrestrial objects, supplied by meteorite falls, which represent matter unprocessed by terrestrial environment. These data can be used for understanding, modelling and interpreting the origin and evolution of a meteorite's parent body (planetesimals, asteroids, and terrestrial planets) in the Solar System. Our recent data on specific heat capacity, and heat capacity of the terrestrial planets: Mars, Earth, Mercury, and Venus, selected asteroids including Vesta, Ceres, and Eros, and Earth's Moon, as well as other natural satellites (Szurgot, 2012a,b,c,d, 2013) can be used to describe the thermal characteristics of Solar System objects. Modelling thermal evolution of asteroids and planets requires precise experimental data on various thermophysical properties of meteorites (Gosh & McSween, 1999; Chaumard et al., 2012).

Specific heat capacity, heat capacity, thermal capacity, and thermal diffusivity are important quantities used to investigate meteorites, and other Solar System objects. Specific heat capacity, Cp (J/(kg·K)), represents the heat energy required to change the temperature of a unit mass of a substance by one unit of temperature at a constant pressure ($Cp = M^{-1} \cdot dQ/dT$).

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Heat capacity, C (J/K), represents the energy required to change the temperature of the whole mass of an object (e.g. asteroid, planet, or comet) by one unit of temperature ($C = dQ/dT = C_p \cdot M$). Thermal capacity, $C_{volumetric}$ (J/(m³·K)), represents the energy required to change the temperature of the unit volume of a substance ($C_{volumetric} = V^{-1} \cdot dQ/dT = C_p \cdot \rho_b$, where ρ_b (kg/m³) is bulk density of substance, e.g. density of extraterrestrial rock).

Three other thermophysical properties play important roles in modelling the thermal evolution of asteroids: thermal conductivity K (W·m⁻¹·K⁻¹), thermal diffusivity D (m²/s), and thermal inertia Γ $(J \cdot m^{-2} \cdot s^{-1/2} \cdot K^{-1})$. Thermal conductivity represents the ability of a substance to transport of heat, and governs the flow of heat through a material at steady-state. Thermal diffusivity is the property governing transient heat flow, when temperature varies with time. D can be measured directly by measuring the time it takes for a temperature pulse to traverse a specimen of known thickness when a heat source is applied briefly to the one side; or can be determined indirectly using the relation between *D* and *K*; $D = K/C_{volumetric} = K/(C_p \cdot \rho_b)$, i.e. by calculating the ratio of thermal conductivity and thermal capacity (Ashby et al., 2007). Thermal inertia quantifies the ability of material to store and retain daytime heat, and is calculated as the square root of product of thermal conductivity and thermal capacity $\Gamma = (K \cdot C_p \cdot \rho_b)^{1/2} = (K \cdot C_{volumetric})^{\frac{1}{2}}$.

Our early interest in studying thermophysical properties of meteorites began with the measurements and data collection of specific heat capacity, thermal diffusivity, and bulk density of various meteorites (Szurgot, 2003; Szurgot et al., 2008). These activities are still an important part of our work. We continue measuring, collecting and analyzing data, especially those concerning physical properties of new meteorites. In the last few years we have been looking for interrelations between various physical properties of meteorites, various tendencies and dependencies. Establishing relationships between specific heat capacity and bulk density of meteorites, and between thermal capacity and bulk density of meteorites at room temperature was the first finding (Szurgot, 2011). Measurements of diffusivity of twenty meteorites by laser flash method revealed linear relationship between thermal diffusivity and bulk density of meteorites at room temperature (Szurgot & Wojtatowicz, 2011), and analysis of data by Osako (Osako, 1981) has shown that the linear relationship exists not only at RT but also at low temperatures: 100 K, and 200 K (Szurgot & Wojtatowicz, 2011). An analysis of our experimental data (Szurgot, 2011b), and of the literature data (Opeil et al, 2010) revealed a relationship between thermal conductivity and density of meteorites at room temperature, and at low temperatures (Szurgot, 2011b). The above mentioned relationships have been applied for predicting and estimating the thermophysical properties of meteorites (Szurgot & Polański, 2011), terrestrial planets, asteroids, as well as natural satellites (Szurgot, 2012a,b,c,d, 2013). Opeil and co-workers discovered the relationship between thermal conductivity of stony meteorites and their porosity (Opeil et al., 2012), thus enabling one to predict thermal conductivity of a meteorite when its porosity is known. We will apply the relation in this paper.

Differential scanning calorimetry (DSC) is a useful technique for measuring the specific heat capacity of extraterrestrial matter, temperature of phase transformations, and enthalpy changes in terrestrial and meteoritic minerals. Our preliminary DSC measurements indicate that troilite thermometry can be the promising tool for meteoritic investigations, especially for chondrite investigations. We are convinced on significant possibilities of troilite thermometry.

The Soltmany meteorite was classified as an equilibrated ordinary chondrite L6 class (shock stage S2, weathering grade W0) (Karwowski et al., 2011). Preliminary compositional data are as follows: olivine Fa_{25.6}, low-Ca pyroxene Fs_{21.9}Wo_{1.5}, high-Ca pyroxene $En_{46.6}Fs_{8.8}$ Wo_{44.6}, feldspar Ab₈₅Or₅An₁₀, kamacite (Fe 95.87, Ni 5.23, Co 0.74 wt.%); troilite (Fe 50.23, S 49.69 at.%) (Karwowski et al., 2011). The meteorite also contains accessory minerals: chromite, Fe-Cl apatite, and metallic Cu in taenite (Karwowski et al., 2011). The aim of this paper was to determine various thermophysical properties of the Soltmany chondrite such as specific heat capacity, thermal capacity, thermal conductivity, thermal diffusivity, the bulk density and porosity of the meteorite, and to reveal and analyse phase transitions in Soltmany troilite. Presented data on the above mentioned physical properties are especially meaningful as the meteorite was sampled just one week after its observed fall (30th April, 2011), so the mineral composition and texture of the meteorite were not influenced by terrestrial processes.

EXPERIMENTAL

The Soltmany samples were bought by members of The Polish Meteorite Society from Mrs. Alfreda Lewandowska, the meteorite's finder. The meteorite samples were prepared as polished slices with weights

ranging from 0.5 g to 3 g, or as small pieces of irregular shape weighing about 20 mg each.

The bulk density ρ_b of the samples was determined by the Archimedean method from the relation:

$$\rho_{b} = [W_{air} / (W_{air} - W_{propanol})] \cdot \rho_{propanol}$$
(1)

where W_{air} is the weight of the sample in air, $W_{propanol}$ is the weight of the suspended sample on the sling in isopropanol, and $\rho_{propanol}$ is the density of isopropanol. The estimated relative error in the measurement of ρ_b of Sołtmany meteorite interior samples is about 2–3%, and of the crust about 5%.

The grain density ρ_g was determined using the expression:

$$\rho_{\sigma} = \rho_{b} / (1 - P), \qquad (2)$$

where ρ_b is the bulk density, and *P* is porosity. The porosity *P* of the meteorite, a measure of the connected void space within its interior is defined as *P* (%) = $(1 - \rho_b/\rho_g) \times 100$ (Consolmagno et al., 2008; Beach et al., 2009).

The porosity P of the Soltmany samples was determined by measuring the mass of the dry meteorite, and mass of the wet meteorite, i.e. the meteorite saturated with isopropanol. The porosity P (%) was determined using the relation:

$$P(\%) = V_{p}/V_{m} = (m_{p}/m_{m}) \cdot (\rho_{b}/\rho_{propanol}), \qquad (3)$$

where V_p is the volume of propanol present in the meteorite's voids and cracks, V_m is the volume of the meteorite sample, m_p is the mass of the propanol inside the meteorite, m_m is the mass of the dry meteorite, ρ_b is the bulk density of the meteorite, and $\rho_{propanol}$ is the density of isopropanol at room temperature ($\rho_{propanol} =$ 785 kg/m³). The measurement accuracy using this technique is estimated to be about 7%.

The porosity measurements were conducted at ambient temperature between 20 and 30 °C, usually at 25 °C, at humidity between 50 and 70%. To measure the weights, first the dry meteorite was measured, then the meteorite was saturated with propanol. The sample was dipped in propanol for about 2-5 min. ensuring enough time had elapsed to saturate the spaces. Measurements were conducted on the initially dry meteorite which was subsequently suspended in propanol and measured at intervals. The weight gradually increased with time due to the propanol filling all cracks and pores until the weight stabilized and the specimen was assumed to be saturated. Measuring the weights with high precision is required to determine the porosity. Since drying of the sample by blowing warm air leads to reversible data for m_m in subsequent measurements, we believe that all of the propanol left interior of the meteorite. However, since some enclosed spaces in the meteorite may still contain propanol, the porosity measurements are more estimates than a precise determination. We likely estimate the lower limit of the porosity, and verification of these results seems to be desirable.

The specific heat capacity Cp of the small (c.a. 20 mg) samples and temperature of phase transitions were determined by a differential scanning calorimeter Q200 produced by TA Instruments (USA). The instrument was calibrated for both temperature and heat flow using indium (melting temperature 156.6 °C) and synthetic sapphire standard respectively with well characterized Cp in the broad range of temperatures. In DSC measurements of Cp of the Sołtmany's samples the following expression was used:

$$C_p = Cp_{sp} \cdot (H/Hsp) \cdot (m_{sp}/m_m), \tag{4}$$

where Cp_{sp} is a specific heat capacity of sapphire standard at particular temperature, m_{sp} is the mass of sapphire standard, m_m is the mass of meteorite sample, Hsp is the heat flow (mW) of the sapphire standard, and H is the heat flow of the meteorite specimen. Samples, with approximately the same mass as the sapphire were sealed in aluminum pans and analyzed in the temperature range between -70 and 560 °C at the heating rate of 20 °C/min under nitrogen flow of 50 ml/min. Specific heat capacity of larger samples was determined using double-walled calorimeters. The relative error in the measurement of C_{p} of Soltmany meteorite is 3-4% for DSC, and 5-6% for the double-walled calorimeters. Calibration of the double-walled calorimeter were conducted during our earlier measurements of specific heat capacity of the Morasko iron meteorites (Szurgot et al., 2008) during which selected materials with well-known capacities were measured.

Volumetric heat capacity, (thermal capacity, heat capacity per unit volume), $C_{volumetric}$ (J/(m³·K) was determined using the relation:

$$C_{volumetric} = C_p \cdot \rho_b, \tag{5}$$

where C_p (J/(kg·K)) is the specific heat capacity, and ρ_b (kg/m³) is the bulk density of meteorite.

The relationship between thermal conductivity K and bulk density ρ_b of meteorites (Szurgot, 2011b), and between thermal conductivity and porosity (Opeil et al., 2012) have been applied for estimation of thermal conductivity (eqs. (6) and (8)), and relationship between thermal diffusivity D and bulk density of meteorites (eq. (9)) (Szurgot & Wojtatowicz, 2011) for determination of thermal diffusivity of the Sołtmany meteorite at room temperature.

According to the linear fit we have:

$$K = A \cdot \rho_b + B, \tag{6}$$

where K is thermal conductivity (W·m⁻¹·K⁻¹), ρ_b (kg/m³) is the bulk density of meteorite, and coefficients A and B are constant for a given temperature: A = (8.81 ± 0.61)·10⁻³ W·m²·kg⁻¹, B = -26.7 ± 2.8 W·m⁻¹·K⁻¹ at 298 K; A = 3.92·10⁻³ W·m²·kg⁻¹, B = -8.50 W·m⁻¹·K⁻¹ at 200 K (Szurgot, 2011b). Constants A and B at 200 K were established by Szurgot who used Opeil and co-workers' data (Opeil et al., 2010; Szurgot, 2011b).

According to Opeil and co-workers, the K of a stony meteorite depends on porosity P (Opeil et al., 2012) and can be expressed by the relation:

$$K = 3.6 + 6.8/P,$$
 (7)

where *K* is thermal conductivity $(W \cdot m^{-1} \cdot K^{-1})$ at 200 K, and *P* is the porosity *P*(%). Since *K* at 200 K for ordinary chondrites L class is usually about 4% higher than at 300 K (Opeil et al, 2012), we have *K* for Softmany's meteorites at room temperature:

$$K = 3.46 + 6.53/P.$$
 (8)

Thermal diffusivity is a linear function of bulk density and may be expressed by the empirical equation:

$$D = E \cdot \rho_b + F, \tag{9}$$

where *D* is thermal diffusivity $(10^{-6} \text{ m}^2/\text{s})$, ρ_b (kg/m³) is the bulk density of meteorites, and coefficients *E* and *F* are constants for a given temperature: $E = 2.49 \cdot 10^{-9}$ m⁵·kg⁻¹·s⁻¹, $F = -7.11 \cdot 10^{-6}$ m²/s at 298 K (Szurgot & Wojtatowicz, 2011), $E = 2.11 \cdot 10^{-9}$ m⁵·kg⁻¹·s⁻¹, $F = -6.24 \cdot 10^{-6}$ m²/s at 200 K. Constant *E* and *F* at 200 K were established by Szurgot and Wojtatowicz who used experimental data by Osako (Osako, 1981; Szurgot & Wojtatowicz, 2011). Using a well-known relationship (Ashby et al., 2007):

$$K = C_{p} \cdot \rho_{b} \cdot D = C_{volumetric} \cdot D, \qquad (10)$$

between *K*, and C_p , *D*, and ρ_b one can determine *D* by the relation:

$$D = K/C_{volumetric} \tag{11}$$

Uncertainty in DSC measurements of temperature of α/β solid-state transition in troilite is 0.1–0,2 K, and β/γ transition 1–2 K.

RESULTS AND DISCUSSION

Bulk density and porosity

In Table 1, data on bulk density and porosity of four samples of the Soltmany meteorite have been compiled. Samples A and B represent material from the meteorite's interior, and samples C and D material from the interior and of the fusion crust. It is seen that the bulk density of samples with crust is about 3% higher than samples A and B which represent the interior of meteorite. Table 1 reveals that the mean bulk density of Soltmany is equal to $3.475 \cdot 10^3$ kg/m³ and the mean bulk density of the fusion crust equals $(4.31 \pm 0.21) \cdot 10^3$ kg/m³. The density of the fusion crust was calculated using the ratio of volume of crust to the volume of interior. The calculation assumes that interior samples C and D have the same bulk density as the mean value of A and B samples. The data show that mean bulk density of the crust is about 24% higher than mean bulk density of the interior of meteorite.

Recent data on ordinary chondrites show that L chondrites have porosity in the range 4.4–10.4% (Opeil et al, 2012), but Yomogida and Matsui presented a wider range of 2.5–19.4% (Yomogida & Matsui, 1983). The average porosity of fresh falls is $(5.6 \pm 4.6)\%$ for L chondrites, and $(7.0 \pm 4.9)\%$ for H chondrites (Consolmagno et al., 2008). Table 1 shows that porosity of Sołtmany meteorite interior (samples A and B) is in the range 6.1-6.7%, and mean porosity is equal to $(6.4 \pm 0.4)\%$. Such values are within the range of L chondrites and H chondrites. On average L chondrites are slightly less porous than H chondrites, and Sołtmany's average porosity is slightly higher than average for L chondrites. Samples C and D containing crust have higher porosity (range 7.4–7.8%, mean 7.6 \pm 0.4%) than samples A and B representing the meteorite's interior, indicating that crust porosity is close to the average for H chondrites.

Knowing the mean value of bulk density and mean value of porosity enabled us to determine the grain density of the Sołtmany meteorite. The results show that average bulk density $(3.475 \cdot 10^3 \text{ kg/m}^3)$ and average grain density $(3.71 \cdot 10^3 \text{ kg/m}^3)$ of Sołtmany's interior are in the range of ordinary chondrites (Yomogida & Matsui, 1981, 1983; Consolmagno et al., 2008; Opeil et al., 2012). For L and H meteorite falls, the average bulk density is $3.37 \pm 0.18 \cdot 10^3 \text{ kg/m}^3$ and 3.42

average of \sharp	3–5 measuremen	osity of Softmany meteorite at	room temperature (300 K).	values of bulk density and poi	rosity represent the
Sample	Mass	Bulk Density Interior	Bulk Density Interior & Crust	Bulk Density <i>Crust</i>	Porosity
А	0.667 g	$3.48 \cdot 10^3 \text{ kg/m}^3$			6.1%
В	2.930 g	3.47.10 ³ kg/m ³			6.7%
С	1.160 g		3.57.10 ³ kg/m ³	4.16.10 ³ kg/m ³	7.4%
D	0.467 g		3.56·10 ³ kg/m ³	4.46.10 ³ kg/m ³	7.8%
Range		$(3.47-3.48) \cdot 10^3 \text{ kg/m}^3$	$(3.56 - 3.57 \cdot 10^3 \text{ kg/m}^3)$	(4.16-4.46)·10 ³ kg/m ³	(6.1–6.7) %
Mean		$3.475 \cdot 10^3 \text{ kg/m}^3$	$3.565 \cdot 10^3 \text{ kg/m}^3$	$4.31 \cdot 10^3 \text{ kg/m}^3$	(6.4±0.5) %

(200 12) 171 C 1 11 Table a

± 0.19.10³ kg/m³ respectively (Consolmagno et al., 2008). For L meteorites falls, the average grain density is $3.56 \pm 0.10 \cdot 10^3$ kg/m³, for H meteorite falls is 3.72 $\pm 0.12 \cdot 10^3$ kg/m³ (Consolmagno et al., 2008). Since grain densities of freshly fallen ordinary chondrites are connected with the iron content, the Soltmany meteorite fall indicates relatively high iron content.

Both the average bulk density and average grain density of Sołtmany chondrite are high. Sołtmany's average bulk density is higher than L chondrites, and higher than H chondrites, while Soltmany's grain density is higher than L chondrites, and close to H chondrites. It is expected that for fresh falls, grain density alone can be used to distinguish between L and H types (Consolmagno et al., 2008). Our measurements conducted on Soltmany samples, one year after the fall, indicate high iron content, but overlapping range of values of porosities. However, bulk and grain densities make it difficult to conclusively determine whether the Soltmany meteorite is either an L or H-type chondrite. The test data seems to indicate that Soltmany is closer to H chondrites than L chondrites. Values of average bulk density and average grain density of the Soltmany L chondrite may be higher than expected values for L chondrites as the result of higher Ni content in metal grains (and in bulk chemical composition). The content of Ni in Soltmany's bulk composition and specifically in its metal grains is typical for H rather than L chondrites (Karwowski, 2012; Przylibski & Łuszczek, 2012).

It is also noteworthy, that the fusion crust is characterized by higher density and simultaneously higher porosity compared to the interior of the meteorite. The reason of higher porosity is the observed presence of vesicles on the surface connected to the gas bubbles inside of the fusion crust. This texture was formed during ablation of the meteors it flew across the Earth's atmosphere and is the remnant of released volatile sulfur compounds formed as a result of sulfides (i.e. troilite) melting (Karwowski, 2012). On the other hand, the higher density of the fusion crust is a result of its mineral and chemical composition. Melts formed during ablation creating a glassy and crystalline fusion crust composed of heavy metals, like Fe, Ni, (Mg), and Cr (Karwowski, 2012). Sołtmany's fusion crust also reveals the presence of heavy minerals, like spinel and chromite. Smaller amounts of silicates (pyroxenes and olivines) and silicate glass (feldspar), in relation to interior of the meteorite (Karwowski, 2012), is the cause of higher density of its fusion crust.

Thermophysical properties of Soltmany meteorite

Specific heat capacity

In Table 2, data on room temperature values of specific heat capacity Cp of three small samples of Soltmany meteorite are presented. Values of Cp presented here where determined by DSC technique. It is seen that specific heat capacity of various samples is in the

range 705-769 J/(kg·K), and the mean specific heat capacity is equal to 728 J/(kg·K) at room temperature. Measurements of Cp for larger samples by double-walled calorimeters gave values: sample A: Cp = 727 J/(kg·K), sample B: Cp = 641 J/(kg·K), sample C:

Table 2. Specific heat capacity Cp of Soltmany meteorite small samples at room temperature (300 K)

<i>Cp</i> /Sample	E	F	G	Range	Mean ± SD
Specific heat capacity J/(kg·K)	705	711	769	705–769	728 ± 35

Cp = 707 J/(kg-K), sample D: Cp = 768 J/(kg-K), and the mean $Cp = 711 \pm 53 \text{ J/(kg-K)}$. The mean value of Cp of the larger samples is somewhat smaller but comparable with the mean C_p of the smaller samples that were measured with better precision by DSC technique.

Szurgot established a relationship between specific heat capacity C_p and bulk density ρ_b of meteorites (Szurgot, 2011a). It can be used for estimation of specific heat capacities of meteorites at room temperatures. Figure 1 presents $C_p(\rho)$ relationship together with the mean value of C_p for Sołtmany meteorite (full square). It is seen that Sołtmany's specific heat capacity matches well the presented dependence.

 $C_p(\rho)$ may be approximated by the relation (Szurgot, 2011a):

$$C_p = a + b/\rho_b, \tag{12}$$

where *a*, and *b* are constants (a = 306 J/(kg·K), and $b = 1.31 \cdot 10^6 \text{ J/(K·m}^3)$).

Substituting $\rho_b = 3.475 \cdot 10^3 \text{ kg/m}^3$ into eq. (12) gives $C_p = 683 \text{ J/(kg·K)}$ for the Sołtmany meteorite, which is close to the experimental values determined by DSC (728 J/(kg·K)), and double-wall calorimeter measurements (712 J/(kg·K)). The results show that this calculated value of C_p is about 6% lower than C_p value determined by DSC (full square experimental point in Fig. 1), and about 4% lower than the C_p value determined by double-wall calorimeter measurements.

Table 3 presents values of Cp of three samples: E, F and G at various temperatures, and Figure 2 shows the $C_p(T)$ dependence for these samples. It is seen that the mean specific heat capacity determined by DSC in the temperature range between 223 and 823 K increases from 595 to 1046 J/(kg·K). C_p is equal to 595



Fig. 1. Dependence of specific heat capacity Cp on bulk density of meteorites (Szurgot, 2011a). The mean value of Cp for Sołtmany meteorite at room temperature is marked by the full square point. The vertical bar indicates scattering of measurements of Cp, and horizontal bars mark upper and lower Cp values

J/(kg·K) at 223 K, 728 J/(kg·K) at 300 K, 823 J/(kg·K) at 373 K, 908 J/(kg·K) at 473 K, 946 J/(kg·K) at 573 K, 964 J/(kg·K) at 673 K, 999 J/(kg·K) at 773 K, and 1046 J/(kg·K) at 823 K. Specific heat capacity of various samples is in the range 576–631 J/(kg·K) at 223 K, 705–769 J/(kg·K) at 300 K, and 936–1114 J/(kg·K) at 773 K. This means that relative changes in specific heat capacity differ about 9% at low temperatures and 18% at high temperatures.

Values of C_p for 100 K, and 200 K presented in Table 3 were determined by extrapolating the experimental data to the low-temperature region. For this calculation, eq. (13) representing the best fit has been used. At 100 K, we have mean $C_p = 327$ J/(kg·K), and at 200 K a mean Cp = 549 J/(kg·K). Cp at 200 K is more precisely determined than that at 100K since the neighbouring experimental point 223 K is very close to 200 K. In general, the scatter of Cp values reflects variation in the composition of the rock, caused by different contribution of various minerals to these small samples rather than measurements uncertainty.

Recent literature data on the low values tempearture for specific heat capacity of meteorites shows that the average C_p at temperatures of the asteroid belt objects is about half that of materials measured at room temperature (Consolmagno et al., 2013a,b; Beach et al., 2009; Opeil et al., 2012; Yomogida & Matsui, 1983). Since the ratio of mean C_p values at

Table 3. Specific heat capacity $C_p[J/(\text{kg-K})]$ of small samples (E, F, and G) at various temperatures of the Soltmany meteorite. C_p values in the temperature range 223–823 K were measured by DSC, and in the temperature range 100–200 K were calculated using eq. (13).

T(K)	E	F	G	Range	Mean
100	365*	241*	301*	241-365*	327*
200	536*	521*	579*	521-579*	549*
223	576	577	631	576-631	595
263	647	651	709	647–709	669
283	678	685	742	678–742	702
300	705	711	769	705–769	728
323	740	748	804	740-804	764
373	797	808	864	797–864	823
398	824	831	894	824-894	850
448	881	878	948	881–948	902
473	881	886	956	881–956	908
523	899	900	990	899–990	930
573	916	907	1014	907-1014	946
623	911	903	1033	903-1033	949
673	918	914	1059	914–1059	964
723	922	933	1087	922-1087	981
773	947	936	1114	936–1114	999
823	_	950	1141	950-1141	1046

*Extrapolated values, calculated by the fit expressed by eq. (13).



Fig. 2. Specific heat capacity Cp of three small samples of the Sołtmany meteorite at various temperatures. Sample E – open squares, sample F – open circles, sample G – full circles. Temperatures of α/β and β/γ solid-state transitions in troilite have been marked



Fig. 3. Mean specific heat capacity of Sołtmany meteorite (open circles), and Gao-Guenie chondrite (full squares)

100K and 300K for the Soltmany meteorite is equal to 0.45 ($Cp100/Cp300 = 327 \text{ J}/(\text{kg}\cdot\text{K})/728 \text{ J}/(\text{kg}\cdot\text{K})$ = 0.45), and the interpolation of Cp data for 150 K gives the ratio 0.60, this means that our results for the Soltmany meteorite confirm this finding.

Figure 3 presents Cp(T) dependence of Sołtmany meteorite (arithmetic mean of three samples E, F and G) and for comparison, Cp(T) dependence of Gao-Guenie chondrite (Beech et al., 2009). The results show that Cp of both ordinary chondrites, Sołtmany



Fig. 4. Specific heat capacity of Sołtmany meteorite as a function of temperature. (a) sample G, (b) mean value of *Cp* of the three samples E, F and G. The fits are given by eq. (13)

representing L group and Gao-Guenie representing H group, are very close to each other indicating that their mineral compositions are also similar. Notice that in Figs. 2, 3, and 4 that α/β , and β/γ solid-state transitions in troilite have no significant effect on the Cp(T) dependence.

The specific heat capacity of Soltmany meteorite samples measured in this paper can be fit by a quartic function:

$$Cp = A + BT + CT^{2} + DT^{3} + ET^{4}$$
(13)

The fits are shown in Fig. 4 and values of the coefficients A, B, C, D, and E for each sample are listed in Table 4.

Table 4. Values of coefficients *A*, *B*, *C*, *D* and *E* of the quartic fit to the specific heat capacity *Cp* of Soltmany meteorite samples. The fit is expressed by the equation $Cp = A + BT + CT^2 + DT^3 + ET^4$

Sample	А	В	С	D	E
E	259.4	0.4497	0.007742	-1.751.10 ⁻⁵	1.065.10-8
F	-131.2	4.183	-0.004639	-2,994·10 ⁻⁷	2.075.10 ⁻⁹
G	-82.7	4.443	-0.006376	3.532.10-6	$-1.767 \cdot 10^{-10}$
Mean	94.32	2.243	0.001651	-8.802.10-6	6.307·10 ⁻⁹

Phase transitions in Soltmany's troilite

Troilite, the mineral common in meteorites, undergoes two phase transitions upon heating to temperatures below its melting point (Alton & Gooding, 1993; Alton et al., 1993, 1994; Lauer & Gooding, 1996). α/β transition occurs at 411 ± 3 K, and β/γ transition at 598 ± 3 K (Chase et al., 1985). Our heat flow measurements revealed that the Soltmany samples contain troilite (FeS), whose two characteristic solid-state phase transformations were detected. The α/β transition, shown in Fig. 5 as a sharp endothermic peak, takes place during first heating scan at 149.93 °C, and is identical for all measured samples (quoted value is an average of four measurements, standard deviation is 0.39 °C). The averaged enthalpy change, ΔH of the α/β transition determined during the first heating scan was of 2.38 J/g, but the specimens displayed large variations in the ΔH values, SD amounts to 0.91 J/g (Tab. 5). Apparently non-uniform distribution of the FeS within the available meteorite fragments accounts for the considerable differences in the ΔH of particular samples (c.a. 20 mg each).

Heating the sample to 560 °C, then cooling it to -70 °C, followed by reheating results in reverse β/α transition at about 141.6 °C and again α/β transformation at 148.2 °C (Fig. 5) respectively. During the second heating scan, the α/β transition peak is slightly broader with similar Δ H, approximately 2.2 J/g, which indicates that the original structure of the troilite is essentially restored during cooling.

The β/γ transition occurs at about 323.5 °C (SD = 1.2 °C), as depicted in the inset to Fig. 5 for the first heating scan and is listed in Table 5. This β/γ transition is reversible as well.



Fig. 5. Heat flow changes during first heating, cooling and second heating scans of Sołtmany meteorite specimens measured by DSC. Inset: enlarged area depicting β/γ transition of troilite. Heat flow is measured in mW, but here are arbitrary units

An analysis of the *Cp* data shows that there is no drastic change in the *Cp* due to α/β transition of troilite at about 423 K (150 °C) (see Figs. 2, 3, where α/β and β/γ transitions are depicted). However, the other FeS transformation of β/γ at 596.5 K (323.5 °C) has little influence on the *Cp* at that temperature.

Data on temperature of solid-state transitions and enthalpy changes ΔH (J/g) for four samples of Soltmany meteorite are compiled in Table 5. The results show that the mean temperature of α/β transformation is 149.9 ± 0.4 °C, i.e. 423.0 ± 0.4 K, and mean enthalpy change 2.38 ± 0.91 J/g. For temperature of transformation β/γ we obtained mean value 323.5 ± 1.2 °C, i.e. 596.6 ± 1.2 K.

Troilite content in chondrites is about 5 wt% (Hutchison, 2004). Our preliminary data on the mean elemental and mineral contribution established by EDX spectrometry indicate that Sołtmany contains about 4 wt.% of troilite. The mean enthalpy change determined for α/β transformation (2.38 J/g) proves that troilite is present in Sołtmany as a small percentage of the overall meteorite.

We estimated the mean troilite content in our samples using values of temperature of α/β transition, and measured enthalpy change for the transition using both our, and literature data. According to Alton and co-workers data enthalpy change for α/β transition in troilite is equal to 42.5 J/g at transition temperature 423K (Alton et al., 1994), i.e. at the mean transition temperature established for the Sołtmany meteorite. Using the mean value of enthalpy change $\Delta H = 2.38$ J/g and dividing it by 42.5 J/g gives 5.6 wt.% of troilite in the meteorite, on an average. The range of values of troilite content is, however, much broader, between 4 and 8.6 wt.% (see fifth column in Table 5).

Our estimation of troilite content ($5.6 \pm 2.1 \text{ wt.\%}$) seems to be correct since values of enthalpy changes 1.7-3.65 J/g are in agreement with results of Lauer and Gooding (Lauer & Gooding, 1996). Extrapolation of their data indicates that FeS is of the order of 5-10 wt.%. These results support our opinion that Soltmany has a heterogeneous distribution of FeS.

It is well-known that thermodynamic properties of α/β phase transformation in troilite, as revealed by DSC measurements of terrestrial troilite, depend on, and are important indicators of the thermal history of troilite. The transition temperature and enthalpy change for α/β transformation decrease with increasing maximum temperature of prior heat treatment (Alton et al., 1994). Calorimetric thermometry of

Sample	T (°C) for α/β	$\Delta H(J/g)$ for α/β	T (°C) for β/γ	FeS content (wt.%)
E1	149.9	1.73	322.2	4.1
Е	149.4	1.70	322.9	4.0
F	150.1	3.65	323.8	8.6
G	150.3	2.43	325.0	5.7
Mean ± SD	149.9±0.4	2.38±0.91	323.5±1.2	5.6±2.1

Table 5. Temperature of solid-state α/β , and β/γ transformations, transition enthalpy change ΔH , and estimated troilite content in Soltmany meteorite from thermodynamic data

meteoritic troilite is a very promising tool for meteoritic investigations. Transition temperature of α/β transformation of Sołtmany's troilite (423 K) is somewhat higher than that established by Alton and coworkers for natural (not previously heated) terrestrial, Del Norte troilite (420–422 K, mean 421 K), and is higher than mean temperature of α/β transformation for previously studied meteorites: EET83213 (L3, unmetamorphosed chondrite) 420.5 K, PAT91501 (L7, highly metamorphosed chondrite) 419 K, and is distinctly higher than that established for Mundrabilla octahedrite: 415.5 K (Alton et al, 1994).

Such a high value of temperature of α/β transformation of Sołtmany's troilite (423 K) indicates low temperature accretion of this chondrite (well below 1000 K), and/or low maximum temperature achieved by heat treatment (e.g. low temperature increase during collision). This is rather unexpected since petrology indicates that Soltmany belongs to the highly metamorphosed L6 chondrites (Karwowski et al., 2011). Our conclusion is supported by Lauer and Gooding data that L-chondrites record relict temperatures that do not exceeds 458 K (Lauer & Gooding, 1996). Comparison of our data with Lauer and Gooding data indicate that Soltmany's relict temperature could be even lower than 450 K. The low shock stage (S2) of Sołtmany chondrite (Karwowski et al., 2011) supports this possibility.

The FeS phase transition confirms rather low temperature values during the evolution of the Sołtmany L chondrite parent body and may support the scenario that its parent body was formed as the result of a collision between two partially molten objects (Hutchison, 1996; Sanders, 1996). This type of scenario was proposed by the author (TAP) and team for the Baszkówka L5 chondrite parent body (Przylibski et al., 2003).

We continued DSC measurements of α/β phase transformation in Soltmany's troilite on several new samples. The effect of the maximum temperature of controlled, laboratory heating and time of heating on the temperature of α/β phase transformation and on enthalpy change in Soltmany troilite was studied (Szurgot et al., 2013a). It was established that both annealing temperature and annealing time are crucial parameters in the troilite thermometry, and it was confirmed that the α/β phase transition data for the virgin samples indicate a low relict temperature (about 440K) of the Soltmany meteorite (Szurgot et al., 2013a). It was also established that the troilite present in the fusion crust indicates high relict temperature (about 1000 °C), which is caused by the aerodynamic heating due to atmospheric passage (Szurgot et al., 2013b). Our latest results prove the usefulness of troilite thermometry.

Thermal capacity, thermal conductivity and thermal diffusivity

In Table 6, data on thermophysical properties of the Sołtmany meteorite at room temperature 298–300 K, and data predicted for lower temperature (200K) have been compiled. Below, we will compare literature data on thermophysical properties of chondrites with the properties of the Sołtmany meteorite.

The specific heat capacity of Sołtmany is equal to $728 \pm 35 \text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ (mean value) and the *Cp* of chondrites at room temperature is in the range 630–920 $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ (Szurgot, 2003, 2011a). Measurements of specific heat capacity of Gao-Guenie chondrite (H5) gave *Cp* = 732–740 $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$, and of Jilin (H5) gave

 $Cp = 726 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$ (Beech et al., 2009). Both H chondrites have heat capacities comparable with the Sołtmany chondrite.

Yomogida and Matsui calculated Cp for H (714 J·kg⁻¹·K⁻¹) and for L chondrites (728 J·kg⁻¹·K⁻¹ at room temperature (Yomogida & Matsui, 1983). Their results show that H chondrites have slightly greater Cp than of L chondrites.

Matsui and Osako in their studies of thermal properties of Yamato meteorites established the following *Cp* values of various chondrites at room temperature: $364 \text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ (Y-7301; H4), 601 J $\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$

Droporty	Sołtmany	Sołtmany		
rioperty	Mean at 300 K	Mean at 200 K		
Specific heat capacity	728 J·kg ⁻¹ ·K ⁻¹	549 J· kg ⁻¹ ·K ⁻¹		
Thermal capacity	$2.53 \cdot 10^6 \text{ J/(m^3 \cdot K)}$ (eq. (5))	$1.91 \cdot 10^6 \text{J/(m}^3 \cdot \text{K})$ (eq. (5))		
	$3.9 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ (eq. (6))	4.7 $W \cdot m^{-1} \cdot K^{-1}$ (eq. (7))		
Inermal conductivity	$4.5 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ (eq. (8))	$5.1 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ (eq. (6))		
	$1.5 \cdot 10^{-6} \text{ m}^2/\text{s}$ (eq. (9))	$1.1 \cdot 10^{-6} \text{ m}^2/\text{s}$ (eq. (9))		
Thermal diffusivity	$1.8 \cdot 10^{-6} \text{ m}^2/\text{s}$ (eq. (11))	$2.6 \cdot 10^{-6} \text{ m}^2/\text{s}$ (eq. (11))		
		$2.7 \cdot 10^{-6} \text{ m}^2/\text{s}$ (eq. (11)		

Table 6. Thermophysical properties of the Soltmany meteorite at room temperature 298–300 K, and at 200K

(Y-74647; H4-5), 535 J kg⁻¹·K⁻¹ (Y-74371; H5-6), 603 J·kg⁻¹·K⁻¹ (Y-74191; L3) (Matsui & Osako, 1979). Their range of *Cp* is wide 364–603 J·kg⁻¹·K⁻¹, but values of *Cp* are significantly lower than values determined by other investigators. Theoretical specific heats calculated by these authors on the basis of chemical composition of meteorites are more reliable (*Cp* = 730 J·kg⁻¹·K⁻¹ for Y-7301 H4 chondrite, and *Cp* = 750 J·kg⁻¹·K⁻¹ for Y-74191 L3 chondrite). In general, they are about 1.2–2 times higher than corresponding experimental values.

The compilation of our data shows that the *Cp* of the Sołtmany meteorite at room temperature is within the range of values established for L and H chondrites. Our latest DSC data for the mean value of *Cp* of three new samples of the Sołtmany meteorite at 300 K gave the value 671 J·kg⁻¹·K⁻¹ (Wach et al., 2013) which is about 8% lower than 728 ± 35 J·kg⁻¹·K⁻¹ that was obtained in this paper (Tabs. 2 and 3). The preliminary data for mean *Cp* value of two samples of NWA 4560 ordinary chondrite gave the value 682 ± 15 J·kg⁻¹·K⁻¹ at 300 K (Wach et al., 2013). The comparison of *Cp* values for both these meteorites indicates that specific heat capacity of the Sołtmany L6 chondrite is close to the specific heat capacity of NWA 4560 LL3.2 ordinary chondrite.

Thermal capacity of the Sołtmany meteorite at room temperature equals $2.53 \cdot 10^6$ J/(m³·K), and is close to the mean thermal capacity of stony meteorites ($2.5 \cdot 10^6$ J/(m³·K; Szurgot, 2011a). It is also close to the thermal capacity of solid terrestrial materials ($3 \cdot 10^6$ J/(m³·K; Waples & Waples, 2004). This means that Sołtmany's thermal capacity is comparable with other stony meteorites, and comparable with terrestrial rocks.

Thermal conductivity of Soltmany at room temperature (300 K) was determined by the authors to be $3.9-4.5 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$. The latest literature data obtained by direct, precise *K* measurements of chondrites at room temperature revealed the range $0.5-5.2 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, for L chondrites $K=0.45-3.5 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$,

and for H chondrites the range $K = 1.4 - 3.2 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ (Opeil et al., 2012). *K* values determined by Szurgot for ordinary chondrites at 300 K amount to 1.5–4.5 $\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$, for Gold Basin (L4) he obtained K = 3.7 $\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$, and for El Hammami (H5) somewhat higher value $K = 4.5 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ (Szurgot, 2011b). Measurements of *K* by Matsui and Osako gave range of *K* values 0.66–1.13 $\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ for H chondrites, and 0.67 $\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ for Y-74191 (L3) chondrite (Matsui & Osako, 1979).

In regards to the low temperature K values, the porosity - thermal conductivity relation (eq. (7)) in Table 6 gives $K = 4.7 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ at 200 K, whereas using the relationship between thermal conductivity and bulk density (eq. (6)) (Szurgot & Wojtatowicz, 2011) gives $K = 5.1 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ at the same temperature. These *K* values are close each to other though obtained by two various relationships. They are reliable values, since they are close to the values established by direct K measurements of ordinary chondrites (Opeil et al., 2010, 2012), and close to K values determined by indirect measurements (Yomogida & Matsui, 1983; Szurgot, 2011b). Using direct measurements, Opeil and coworkers revealed the range of K values at 200 K for L chondrites $K = 0.5-3.2 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$, and $K = 0.8 - 3.5 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ for H chondrites (Opeil et al., 2012). Based on diffusing data, Yomogida and Matsui for 200K revealed the range of K values eq. (10) for L chondrites $K = 0.5-2.3 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$, and $K = 1.1-3.6 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ for H chondrites at 200 K (Yomogida & Matsui, 1983). An analysis of both low temperature and room temperature values of K shows that Soltmany meteorite thermal conductivity is within the range established for H chondrites, but close to the upper limit of *K* values noted for L chondrites.

Thermal diffusivity of Sołtmany amounts to $(1.5-1.8)\cdot10^{-6}$ m²/s at room temperature, and *D* of chondrites at room temperature is in the range: $(0.5-2)\cdot10^{-6}$ m²/s (Szurgot & Wojtatowicz, 2011). Yomogida and Matsui obtained a similar range $(0.1-1.2)\cdot10^{-6}$ m²/s for chondrites, $(0.1-1.1)\cdot10^{-6}$

m²/s for L chondrites, and $(0.2-1.2) \cdot 10^{-6}$ m²/s for H chondrites (Yomogida & Matsui, 1983). Osako established the following values of D at room temperature: $(0.55-0.75)\cdot 10^{-6}$ m²/s for L chondrites (Satsuna, Duwun, and Fukutomi), and 0.75.10⁻⁶ m²/s for H4 (Kesen) chondrite (Osako, 1981).

Comparison of room temperature values of various thermophysical properties of Soltmany meteorite

CONCLUSIONS

New data on the fundamental thermal properties of meteorites have been provided in this paper. The Soltmany meteorite, that fell in Poland on 30th April 2011, has been a very informative source of data. Modern and classical equipment allowed the authors to determine the following properties: specific heat capacity, thermal capacity, thermal diffusivity, thermal conductivity, bulk density and grain density as well as porosity of the interior and crust, temperature of α/β and β/γ reversible transitions in troilite, and enthalpy change during α/β troilite transformation. These data are useful for understanding, modelling and interpreting the origin and evolution of a meteorite's parent body and the ablative heating of meteoroids during their atmospheric passages.

Most of the above mentioned thermophysical properties have been determined for room temperature, but specific heat capacity was measured over a wide temperature range, between 223 and 823 K. C_p low temperature values for 200 K and 100 K were obtained by extrapolation. In general, the results show that the specific heat capacity, thermal capacity, thermal conductivity, thermal diffusivity, bulk density, and porosity of Soltmany meteorite are within the range of previously studied ordinary chondrites. According to the data, the thermophysical properties of this fresh chondrite are consistent with other L chondrites, though some properties, e.g. K data, may indicate H class chondrites.

DSC measurements are time consuming but very important in meteorite studies. Measurements of temperature dependency of specific heat capacity should be continued on samples of various sizes, especially on larger samples since this paper's results for small samples revealed a scatter in Cp values. This scatter is likely caused by the different compositions of the small specimens, especially differences in iron and troilite content. Optical inspection of these small samples revealed differences in the metal content, and measurements of temperature of α/β troilite transformation, and enthalpy change during this transition confirmed various troilite content in various samples. Detailed measurements of chemical composition of

with the properties of various chondrites allows one to draw the conclusion that specific heat capacity, thermal capacity, thermal conductivity, and thermal diffusivity of Sołtmany meteorite are within the range of chondrites. Although our analysis concerned mainly room temperature values, the same conclusion, as it is seen for K values, can be drawn from the available low-temperature values of thermophysical properties.

these small samples seem to be desirable. The question of how large the meteorite sample should to be in order to be representative for extraterrestrial rock which properties we determine is an open question in meteorite studies. This question also concerns the Soltmany measurements. Knowledge of both: modal composition of meteorite and specific heat capacities of their minerals enables one to calculate specific heat capacity of meteorite. Some researches (e.g. Yomogida & Matsui, 1983) prefer calculated Cp values rather than those measured, probably due to scatter in experimental values.

Direct measurements of thermal conductivity and thermal diffusivity of the Soltmany meteorite should be conducted at various temperatures, including room temperature. The authors are aware that the determination of room and low temperature values are preliminary data based on indirect determination. They are estimations based on recently established dependencies which need confirmation by new, direct measurements. In particular, thermal conductivity data based on relation between porosity and K (eq. (7) (Opeil et al., 2012) are worth confirming since experimental data revealed a wide range of K values even for similar samples (Opeil et al., 2012).

Differential scanning calorimetry revealed two reversible phase transitions in the Soltmany's troilite: α/β transition at 149.925 K, and β/γ transition at 323.49K. High value of α/β transformation temperature of Sołtmany's troilite indicates low temperature accretion of this chondrite, and/or low relict temperature 440–450 K. Troilite α/β phase transition data confirm rather low temperatures during the evolution of Soltmany L chondrite parent body, and supports the possibility that its formation is the result of two partially molten objects (Hutchison, 1996; Sanders, 1996). Further research on this phenomenon should be continued for other ordinary chondrities as well as other groups of meteorites. Troilite thermometry data may change our knowledge on the formation and evolution of planetesimals and asteroids in the Solar System.

Results presented here, and ongoing measurements prove the usefulness of troilite thermometry. Temperature of troilite α/β transition and enthalpy change in this transformation supply important information about troilite content. Our latest DSC measurements of troilite α/β transition have shown that FeS present in fusion crust indicates high relict temperature (about 1000°C), which is caused by the aerodynamic heating of meteoroid due to its atmospheric passage (Szurgot et al., 2013b). This means that we not only are able to estimate the fusion crust formation temperature but also estimate relict temperature recorded in various parts of the meteorite, in particularly relict temperature of fusion crust adjacent parts of meteorite, and those coming from the interior of meteorite far from the crust region. All these examples show that troilite thermometry is a very informative and promising method in meteorite studies.

We have presented our preliminary results concerning various thermophysical properties of the Sołtmany meteorite, an ordinary chondrite unaltered by terrestrial processes. The measurements are continued. The agreement between our results and the latest literature data indicate that all the measured, and estimated physical properties of Sołtmany meteorite: bulk density, grain density, porosity, specific heat capacity, thermal capacity, thermal conductivity, and thermal diffusivity are within the range of ordinary L and H chondrites though some indicate L and others indicate H chondrite.

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MAGNETIC CLASSIFICATION OF METEORITES AND APPLICATION TO THE SOŁTMANY FALL

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Abstract: We review the use of magnetic susceptibility measurements to classify meteorites, showing that magnetic susceptibility of meteorites vary over 3 orders of magnitude and shows often a narrow range for a given meteorite group, especially in chondrites. Weathering of metal may bias the magnetic classification. For ordinary chondrite falls, the method is quite robust, as shown by its application to the recent Sołtmany fall.

Keywords: magnetic susceptibility, meteorite classification, Sołtmany

INTRODUCTION

The magnetic classification of meteorites, based on the measurement of magnetic susceptibility, has been developed in CEREGE, following the pioneering work of the Helsinki group (e.g., Pesonen et al. 1993). The complete method has been presented in Rochette et al. (2003, 2008, 2009, 2010) for ordinary chondrites, non-ordinary chondrites, achondrites (except lunar meteorites), and lunar material, respectively. This method provides a more rapid determination of meteorite classification than do standard petrographic

techniques, although it cannot be used for meteorite classification as the only method. Unlike the traditional hand-magnet testing often promoted in meteorite recognition tutorials, the magnetic susceptibility method does not result in the resetting of natural remnant magnetization, thereby preserving potentially valuable scientific information (e.g., Gattacceca et al., 2004). A brief summary of the method and its application to the Softmany meteorite are presented here.

BACKGROUND

Mass-normalized magnetic susceptibility (χ in m³/kg) is a measure of the ability of a material to acquire magnetization in an inducing field. It provides an estimate of the bulk content of magnetic phases in a meteorite sample without any sample preparation, and can be performed on a wide variety of masses and shapes. Only a few grams of most meteorites are needed to obtain representative data, although, with homogeneous specimens, samples of several tens of mg can be measured for results consistent with larger samples. There is no upper limit of mass that can be analyzed, and, with the SM30 instrument, we have measured stones of over 10 kg. Several instruments can be used depending on sample size and shape, but the contact probe SM30 is the most versatile (Fig. 1). However, for low mass or irregularly shaped samples, the SM30 is less precise than classical instruments, which require insertion of the sample within a coil. One source of uncertainty in magnetic susceptibility measurements is magnetic anisotropy, which can be quite strong in

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Fig. 1. Picture of SM30 while performing the "air" measurement on a large meteorite find from Atacama. Log χ value is obtained by substracting this air measurement from the one obtained at contact with the meteorite, and modeling the geometric correction following Gattacceca et al. (2004), using mass and bulk density. This geometric correction is required by the non-uniform field generated by the SM30 coil. In standard coils where the sample is inserted in a zone of uniform field inside the coil, this correction is not necessary, thus explaining the lower accuracy of SM30



Fig. 2. Mean of $\log \chi$ individual standard deviation (i.e. at the meteorite scale) versus standard deviation on mean meteorite value for achondrites groups, compared to chondrites and two sets of terrestrial magmatic rocks (after Rochette et al., 2003, 2008 and 2009). White and gray ellipses highlight the main trends for achondrites and chondrites, respectively

deformed meteorites. This effect can be compensated for by averaging measurements in several directions. Very metal-rich meteorites (especially iron meteorites) may be difficult to measure, due to probe saturation. Measurements are reported as the base-10 logarithm of χ , expressed in 10⁻⁹ m³/kg: a χ value of 10⁻⁶ m³/kg is thus represented as log $\chi = 3$. The accuracy on log χ of the SM30 probe is ~0.1; coil systems have circa ten times higher precision.

Magnetic susceptibility in meteorites is proportional to the amount of the constituent primary ferromagnetic phases, including Fe-Ni metal, schreibersite, cohenite, magnetite, and pyrrhotite. As pure phases, the proportionality factor is about the same for all these minerals, which give log $\chi \sim 5.7$. Pyrrhotite is an exception to the rule: it has a smaller effect on χ . Some weathering products, including maghemite, can also contribute to magnetic susceptibility. For meteorites with very low amounts of ferromagnetic minerals (log $\chi < 3$), paramagnetic minerals like olivine and pyroxene become major contributors to susceptibility.

An advantage of the analysis provided by magnetic susceptibility, compared to that provided by petrographic observation of sections, is that the volume investigated is the whole sample, and it does not depend on grain size. Opaque grains are often dispersed partly as sub-micrometer-sized inclusions that cannot be easily seen under the microscope.

CLASSIFICATION SCHEME

By performing log χ measurements and compiling measurements published by other teams (e.g., Smith et al., 2006; Kohout et al., 2008; Macke et al., 2011) in over 40 large meteorite collections around the world, we have assembled a database of over six thousand specimens. Analysis of several specimens per meteorite allows the determination of $\log \chi$ dispersion at the scale of individual meteorites; analysis of multiple meteorites allows the variation within meteorite groups to be determined (Fig. 2). Log χ dispersion at the individual-meteorite scale is usually quite low, except in achondrites such as aubrites. Dispersion at the group scale is also low for most chondrites (except CM, C2 and CV), with a range of $\log \chi$ from 2.3 to 5.6. These characteristics form the basis of the magnetic classification scheme (Fig. 3). Of course, a single parameter does not provide a unique classification, and other evidence should be used to narrow down the class, e.g. density (Consolmagno et al., 2006). For fresh ordinary chondrites, the scheme works well because the ranges of metal content are narrow and distinct for LL, L and H, although a few intermediate



Fig. 3. Mean log χ with standard deviation for the different chondrite groups. Only meteorite falls were used for ordinary chondrites (H, L, LL), CO and E means. The value obtained on Sołtmany is indicated by an arrow

cases exist (often designated as L/LL and H/L chondrites).

Terrestrial weathering complicates classification because it oxidizes metal, lowering log χ . Rochette et al. (2003), using a database of meteorites from the Sahara, estimated the lowering of log χ at about 0.1–0.2 per weathering grade (WG, as defined by Wlotzka, 1993), so that an H chondrite of weathering grade W3 can give the same value as an L chondrite of grade W1. Our data on Atacama meteorites presented in Fig. 4, for which WG was consistently estimated by a single person, show less dispersion than the dataset of Rochette et al. (2003). Thus, for ordinary chondrite finds, log χ must be combined with WG in order to classify the meteorites, although with somewhat less confidence than for falls.

Presently, for equilibrated ordinary chondrite finds for which manpower and funds to perform full petrographic and geochemical characterization is lacking, the Meteorite Nomenclature Committee of the Meteoritical Society accepts classifications based on $\log \chi$ plus visual inspection of sections.

The magnetic classification scheme is efficient in detecting anomalous chondrite samples in collections. These anomalies appear to be of two sorts: the misclassification of whole meteorites (e.g. Gattacceca et al., 2007), or the mislabeling of individual samples. We found that a significant number of historic meteorite samples were mixed up through the ages; for example, a number of L'Aigle (L6) specimens appeared to be H or L/LL chondrites (Consolmagno et al. 2006). It seems that in the early stages of meteorite science, meteorites were often considered to be "all the same" and became mixed up during exchanges among private collectors and museums. Unfortunately, we have also evidence that some mislabeling was the result of



Fig. 4. Log χ as a function of weathering grade for 110 ordinary chondrite finds from the Atacama desert. Circles are measurements for individual meteorites (solid = H, open = L). Squares are mean values for each weathering grade with associated standard deviation (solid = H, open = L). Diamonds denotes mean values for falls

thievery (replacing rare samples with more common ones or even terrestrial rocks of similar appearance). Such cases can be easily detected by our method, since most of terrestrial rocks (except for some basalts) are much less magnetic than the vast majority of meteorites. Most ordinary chondrite historic falls were classified by Mason (1963) using an X-ray diffraction fayalite value. This technique is not as precise as modern electron probe micro-analysis (EPMA), thus explaining some of the misclassifications found. It is interesting to note that all Antarctic meteorites we identified as having $\log \chi$ values inconsistent with their classifications were later proven to be misclassified (see ANTMET reclassification web page: http:// curator.jsc.nasa.gov/antmet/amn/amnfeb10/reclassifications.htm). For unequilibrated ordinary chondrites, magnetic classification may be more conclusive than EPMA classification. Indeed, the metal content of unequilibrated chondrites is homogeneous for given groups while silicate compositions are heterogeneous.

For achondrites, magnetic classification is less straightforward than for chondrites due to dispersion of log χ within single groups. For example, among the weakly magnetic groups (log χ near 3, including angrites, HEDs, and martian meteorites) strongly magnetic outliers exist (Fig. 5). Consequently, log



Fig. 5. Mean $\log \chi$ for the different achondrite groups. Meteorites excluded from the mean appear with crosses. The metal amount (wt.%) indicated is a maximum value. Among lunar and martian (SNC) meteorites a low and high group (l and h) are distinguished, together with a mean for lunar basalts (b)

 χ can be used to confirm that a meteorite is in the typical range of its group, but being outside this range may not indicate misclassification, and instead may be indicative of anomalous metal content. Until we measured lunar materials, we tended to consider that log $\chi < 2.5$ was only characteristic of terrestrial material (with one exception: the LAP 03719 aubrite, with a log χ value of 1.96). However, lunar meteorites (Ro-

chette et al., 2010) present a log χ range from 1.9 to 4.4, with the lowest values corresponding to anorthosites. An even larger range was found in Apollo and Luna materials, as negative χ values were obtained on some diamagnetic anorthosites (Cournede et al., 2012); in regolith breccias, log χ as high as 4.9 were observed.

MEASUREMENT OF SOŁTMANY

On May 12, 2011, soon after the fall of Sołtmany meteorite, we visited the meteorite collection of the Academy of Sciences in Krakow. Mr. Marek Wozniak kindly arranged for us to have access to 4.8 g of Sołtmany, in three fragments. Measurements performed in Krakow using a Bartington coil system yielded a mean $\log \chi = 4.71 \pm 0.04$. The low standard deviation is remarkable for such small fragments

Magnetic susceptibility is a practical and effective way to rapidly obtain an initial classification for meteorites without time-consuming laboratory work, i.e. on the field or while visiting a meteorite repository. We demonstrated this technique on the Sołtmany meteorite measured soon after its fall. It is also very useful for (down to 0.8 g). Log χ clearly indicates an L chondrite classification (Fig. 3), although the inferred metal amount is in the low range for L (average log χ for L falls reported in Rochette et al., 2003, is 4.87 ± 0.10). The L chondrite classification was later confirmed by EPMA. The high fayalite content of olivine, 25.6, is in the upper range for L, and is consistent with the low metal content.

CONCLUSION

detecting misclassified meteorites or mislabeled samples in collections. For hot and cold desert finds, it can help to determine pairings in the field (e.g. Folco et al., 2006; Gattacceca et al., 2011) and to focus subsequent petrographic work.

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MÖSSBAUER STUDIES OF SOŁTMANY METEORITE – PRELIMINARY RESULTS

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Abstract: In Mössbauer spectra of the Sołtmany meteorite we identified four iron-bearing minerals: olivine, pyroxene, kamacite and troilite. The distribution of iron among these minerals is different in the Sołtmany meteorite from this distribution in the Baszkówka meteorite. As Sołtmany and Baszkówka meteorites are ordinary chondrites type L (both falls), differences in the distribution of iron over the four main iron-bearing mineral phases could be the basis for a new classification of L-type ordinary chondrites. Small amounts of taenite were also observed in the Sołtmany meteorite. The ratio of iron in kamacite and taenite in the Sołtmany meteorite was found to be about 3. No Fe³⁺ could be detected.

Key words: Mössbauer spectroscopy, Sołtmany meteorite, Baszkówka meteorite, ordinary chondrites classification

INTRODUCTION

The application of Mössbauer spectroscopy to meteorites studies started shortly after the discovery of the Mössbauer effect. The first paper dealing with this subject was published in 1964 (Sprenkel-Segel & Hanna, 1964). Mössbauer spectroscopy has several advantages for investigating iron in meteorites: it distinguishes unequivocally between divalent (Fe²⁺) and trivalent iron (Fe³⁺), it may identify iron-bearing compounds and there is no oxidation or spin state of iron which is Mössbauer silent. Mössbauer spectra usually show a single spectral line (singlet) or a characteristic symmetric doublet for each non-equivalent position of iron atoms in the crystal lattice of non-magnetic compound and a characteristic sextet for each position of iron atoms in a magnetic compound. Components of Mössbauer spectra can serve as fingerprints, when the identification of an iron-bearing compound is done by comparing Mössbauer parameters obtained from Mössbauer spectra of an investigated sample to those of known materials.

Typical Mössbauer spectra of freshly fallen ordinary chondrites show a superposition of two doublets and two sextets. In Mössbauer spectra of weathered meteorites additional subspectra can be observed. Components of Mössbauer spectra are characterized by the following Mössbauer parameters: the isomer shift (IS), the quadrupole interaction parameter ($e^2qQ/2$, sometimes denoted as QS - quadrupole splitting for doublets), the line widths (w) and the value of the internal magnetic field (H). The values of the isomer shifts, quadrupole splittings and line widths are usually given in velocity units (mm/s) and the values of the hyperfine magnetic fields in kOe or in Tesla. The relative amounts of iron present in different mineral phases in a compound (which in total make 100%) are proportional to the relative areas of the corresponding subspectra. The application of Mössbauer spectroscopy to mineral samples is discussed in a review by Kuzman et al (2003).

In our laboratory Mössbauer studies of some different Polish meteorites were performed. Möss-

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bauer studies of the Baszkówka meteorite, classified as ordinary chondrite type L5, were published in 1998 (Gałązka-Friedman et al., 1998) and in 2001 (Gałązka-Friedman et al., 2001). Mössbauer studies of the enstatite meteorite Zakłodzie (Maliszewski et al.,

A finely powdered sample of the Sołtmany meteorite was obtained from Prof. Tadeusz Przylibski from Wrocław University of Technology. A Mössbauer spectra of this unaltered sample (sample S) was performed and then a permanent magnet was used to separate the magnetic phase from the non-magnetic phase. The original sample S was thus divided into two samples: SM – containing mainly the magnetic phase and sample SNM – containing mainly the nonmagnetic phase. Mössbauer measurements were then performed on these two samples.

Figure 1 shows the Mössbauer spectrum obtained from sample S. Four main subspectra are observed in this spectrum: two doublets and two sextets. The Mössbauer parameters obtained from the best fit to this spectrum are given in Table 1.

The identification of the minerals in each sample was performed by comparing the Mössbauer parame-



Fig. 1. Mössbauer spectrum obtained from sample S of the Sołtmany meteorite

2008) and the iron meteorite Morasko (Wojnarowska et al., 2008) were published in 2008.

Here we present preliminary results of Mössbauer studies of a new Polish meteorite, Sołtmany, classified as an ordinary chondrite type L (Karwowski, 2012).

MATERIALS AND METHODS

Mössbauer spectra of ⁵⁷Fe were obtained at room temperature using a conventional Mössbauer spectrometer. A 15 mCi ⁵⁷Co-in-Rhodium source, giving a narrow, un-split emission line, was used. The 14.4 keV gamma rays were detected by a proportional counter. The velocity scales were calibrated using an iron foil absorber at room temperature and isomer shifts are given relative to this absorber. The Recoil program written by Denis Rancourt (http://www.isapps.ca/recoil/) and "Full Static Hamiltonian analysis" were used to fit the experimental spectra.

RESULTS

ters given in Table 1 with data given in the Mössbauer Mineral Handbook (Stevens et al., 1998). This comparison showed that doublet 1 is a subspectrum due to iron in olivine, doublet 2 is due to iron in pyroxene, sextet 1 corresponds to iron in troilite and sextet 2 is with iron present in kamacite.

As seen in Table 1, the Mössbauer line-width in the subspectrum attributed to kamacite was somewhat broader than the line widths obtained in the other subspectra. We suspected therefore that sextet 2, which is the subspectrum identified as kamacite, might be composed of two subspecra, one due to kamacite and one due to another magnetic compound. We therefore tried to separate sample S, as described in the Materials and Methods section, into the magnetic (SM) and non-magnetic (SNM) part. The Mössbauer spectrum of sample SM is shown in Figure 2.

As seen from the figure, the magnetic separation was not perfect and in sample SM the four subspectra of olivine (gray in the figure), pyroxene (dark gray), troilite (red) and kamacite (green) are still present,

Table 1. Mössbauer parameters obtained from the best fit to the experimental spectrum of sample S. Mössbauer parameters are: IS – isomer shift, H – internal magnetic field, $e^2 q Q/2$ – quadrupole interaction parameter, w – HWHM (half width at half maximum), θ – angle between direction of magnetic field and the main axis of the electric field gradient and A – the share of iron atoms in the phase

	IS	Н	$e^2 q Q/2$	w	θ	А
	[mm/s]	[T]	[mm/s]	[mm/s]	[deg]	[%]
doublet 1	1.14(2)	-	2.94(2)	0.17(2)	-	60(1)
doublet 2	1.15(2)	-	2.11(2)	0.17(2)	-	26(1)
sextet 1	0.75(2)	30.9(2)	0.98(12)	0.14(2)	62(2)	9(1)
sextet 2	0.02(2)	33.5(2)	0.01(2)	0.22(2)	-	5(1)

Table 2. Mössbauer parameters obtained from the best fit to the experimental spectrum of sample SM. Mössbauer parameters are: IS – isomer shift, H – internal magnetic field, $e^2 q Q/2$ – quadrupole interaction parameter, w – HWHM (half width at half maximum), θ – angle between direction of magnetic field and the main axis of the electric field gradient and A – the share of iron atoms in the phase

	CS	Н	$e^2 q Q/2$	w	θ	A
	[mm/s]	[T]	[mm/s]	[mm/s]	[deg]	[%]
olivine	1.14(2)	-	2.94(2)	0.17(2)	-	56(1)
pyroxene	1.14(2)	-	2.10(2)	0.16(2)	-	32(1)
troilite	0.74(2)	31.1(2)	0.73(2)	0.13(2)	63(2)	4(1)
kamacite	0.02(2)	33.8(2)	0.05(2)	0.14(2)	-	6(1)
taenite	0.07(2)	32.1(2)	0.31(2)	0.10(2)	-	2(1)



Fig. 2. Mössbauer spectrum obtained from sample SM of the Sołtmany meteorite



Fig. 3. Mössbauer spectrum obtained from sample SNM of the Sołtmany meteorite

Table 3. Mössbauer parameters obtained from the best fit to the experimental spectrum of sample SNM. Mössbauer parameters are: IS – isomer shift, H – internal magnetic field, $e^2 q Q/2$ – quadrupole interaction parameter, w – HWHM (half width at half maximum), θ – angle between direction of magnetic field and the main axis of the electric field gradient and A – the share of iron atoms in the phase.

	CS	Н	$e^2 q Q/2$	w	θ	А
	[mm/s]	[T]	[mm/s]	[mm/s]	[deg]	[%]
olivine	1.14(2)	-	2.94(2)	0.16(2)	-	56(1)
pyroxene	1.15(2)	-	2.10(2)	0.17(2)	-	25(1)
troilite	0.76(2)	30.8(2)	1.00(2)	0.14(2)	62(5)	19(1)

yet the relative area of the subspectrum attributed to kamacite was somewhat higher. In the analysis of this spectrum we were able to fit another subspectrum whose parameters showed this to be due to iron in taenite (blue). The Mössbauer parameters obtained from this fit are given in Table 2. The Mössbauer spectrum obtained from sample SNM is shown in Figure 3. Three subspectra related to olivine, pyroxene and troilite could be seen. Mössbauer parameters obtained from this spectrum are given in Table 3. The subspectra related to two magnetic minerals, kamacite and taenite, are observed only in sample SM.

DISCUSSION

The meteorite Sołtmany was classified as an ordinary chondrite type L. We compared the Mössbauer results obtained for the Sołtmany meteorite with those obtained earlier for another Polish meteorite, also classified as ordinary chondrite type L – the Baszkówka meteorite (Gałązka-Friedman et al., 2001). In Table 4 the relative amounts of iron present in the mineral phases in four samples of the Baszkówka meteorite

(B1, B2, B3, B4) and in one sample of the Soltmany meteorite (S) are listed. B-mean gives the mean values of the iron contribution to the phases in Baszkówka (obtained from B1 to B4).

As only one sample of the Soltmany meteorite was investigated, we are not able to construct any distribution of the iron content of the main iron-bearing mineral phases present in this meteorite. It is therefore

Subspectrum	B1	B2	B3	B4	Bmean	S
kamacite	23	14	13	29	19.6 ± 3.8	4.5
troilite	25	28	33	26	28.5 ± 1.7	10
olivine	33	35	28	26	30.3 ± 2.1	59.5
pyroxene	16	21	24	18	19.8 ± 1.7	26
Fe ³⁺	3	2	2	1	2.0 ± 0.4	n.d.

Table 4. Iron distribution (atomic %) over mineral phases in four samples of the Baszkówka meteorite (B1-B4) and one sample of the Sołtmany meteorite (S).

n.d. - not detectable.

difficult to judge whether the differences between the relative amounts of iron present in the four mineral phases (kamacite, troilite, olivine, and pyroxene) in Baszkówka and Sołtmany meteorites are statistically significant.

To better visualize of the results listed in Table 4, Figure 4 was drawn. This figure shows the distributions of the iron content present in the Baszkówka meteorite in kamacite, troilite, olivine, and pyroxene. The area in grey shows the mean values (B-mean) and their uncertainties. The Gaussian curves show the probable distribution of each mineral phase in the Baszkówka meteorite. Each distribution diagram also contains a red arrow marking the relative iron content found in the one sample of the Sołtmany meteorite (sample S). These results show that the relative iron content in olivine in the sample of Sołtmany differs by about 7 standard deviations from the mean value of the iron content in olivine present in Baszkówka and 5.5 standard deviations from the iron content in troilite in the Baszkówka meteorite.

The relative iron content in kamacite and pyroxene in the sample of the Sołtmany meteorite differs by about 2 standard deviations from the analogue values in the Baszkowka meteorite. The above analysis suggests that the relative iron content in the four mineralogical phases of the Sołtmany and Baszkówka meteorites are significantly different. As these are only preliminary results, measurements of other samples of the Sołtmany meteorite are needed to confirm the results.



Fig. 4. Distribution of iron within different mineral phases from 4 different samples of Baszkówka meteorite

No Fe^{3+} was observed in the Mössbauer spectrum of the Soltmany meteorite. This lack of Fe^{3+} is likely due to the immediate preservation of the meteorite and transfer to conditions preventing oxidation. The results summarized in Table 2 show that in the Sołtmany meteorite the ratio between the contribution of iron in kamacite and taenite is about 3:1. For comparison, the similar ratio in a sample of the Morasko meteorite (Iron, IAB-MG) was 12:1.

CONCLUSIONS

Our preliminary results suggest that in the two ordinary L-type chondrite meteorites, Baszkówka and Sołtmany, there is a different distribution of iron over the four mineral phases typical for ordinary chondrites: olivine, pyroxene, kamacite, and troilite. This observation should be confirmed by additional Mössbauer measurements on a larger number of samples of the Sołtmany meteorite and it should also be verified whether similar differences are present in other L-type ordinary chondrites. In the future, Mössbauer investigations related to the ratio of iron (Fe^{2+}) in kamacite and taenite in different meteorites should also be explored. These simple Mössbauer studies could become the basis for formulating a new criterion for the classification of ordinary chondrites.

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CHEMICAL FOOTPRINT OF THE SOLVENT SOLUBLE EXTRATERRESTRIAL ORGANIC MATTER OCCLUDED IN SOŁTMANY ORDINARY CHONDRITE

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Abstract: By characterizing organic molecules of extra-terrestrial origin included in the Sołtmany meteorite, we also present the first results of the non-targeted chemical analysis of the methanol soluble organic matter present in an L6 ordinary chondrite. The structural characterization by means of ultrahigh resolution Fourier transform ion cyclotron mass spectrometry (FT-ICR-MS) with electrospray ionization (ESI) in negative and positive modes demonstrated an unexpected and astonishing chemical diversity with several thousand mass peaks that could be converted into C, H, N, O, S, and P elemental compositions. Molecular signatures were typically those of considerably oxygenated CHO and CHOS molecular series of primarily aliphatic character. ¹H nuclear magnetic resonance (NMR) spectroscopy confirmed the prevalent existence of pure and functionalized aliphatic spin systems of intermediate chain length ($C_{3.4}$ units), oxygenated aliphatics and a considerable diversity of oxygenated aromatics in the proton-based abundance ratio near 24 : 2 : 1. Although only residual organic matter allegedly survives in highly thermally altered L6 chondrites, the physical protection of organic matter in microcavities and traps between mineral surfaces might have supported and governed the chemistry with an apparent recalcitrance of extraterrestrial organic matter (EOM). Future studies of the organic matter in ordinary chondrites and its composition and structure in various regimes of (e.g.) temperature, radiation, pressure, and water content could shed light on these meteorites' formation and evolution.

Keywords: ordinary chondrite, extraterrestrial organic matter, carbon, nitrogen, sulphur, meteorite, Sołtmany, nuclear magnetic resonance spectroscopy (NMR), Fourier transform ion cyclotron resonance mass spectrometry (FT-ICR-MS)

INTRODUCTION

Chondrites comprise the most common types of meteorites and are expected to represent the most primitive ones as well. Chondrites have been processed to various degrees through thermal metamorphism, water alteration, and/or shock metamorphism. Their classification is mainly based upon their elemental and stable isotope compositions as well as their petrological characteristics, which enable one to reconstitute their history in accordance with the minerals present (Weisberg et al., 2006). Only limited information is available in the literature on the organic matter and carbon content speciation in ordinary chondrities. This carbon is mainly separated into three components: (i) soluble organic matter (SOM), (ii) insoluble organic matter (IOM) and (iii) graphite, either in metal grains or in the matrix. These carbon phases (easily recovered from primitive type 3 OCs like Semarkona) have been processed via intense thermal metamorphism in type

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6 chondrites. Several techniques are commonly used for examining the metamorphic gradation of organic matter in unequilibrated ordinary chondrites. Raman spectroscopy is one of these methods (Quirino et al., 2003), as are infrared spectroscopy (Kebukawa et al., 2011) and XANES at the carbon edge (Cody et al., 2008). However, Raman spectroscopy has reached its limits in higher petrologic types (5, 6), in which graphite is established as the main persisting form of carbon. The analysis of organic compounds has often been directed towards trace classes of organic compounds such as polyaromatic hydrocarbons and amino acid derivatives (Zenobi et al., 1992; Herd et al., 2011). These petrologic studies attempt to understand the early history of our solar system from the record preserved in meteorites (Alexander et al., 2001). It is well known that both water and carbon contents decrease with increasing petrologic type (Fig. 1). Studies

on solvent extractions of ordinary chondrites are rarely found in literature, and the few results illustrated in Fig. 1 show that the carbon content for L6 type meteorites analysed thus far is close to 0.25%. Soltmany is classified as an L6, W0, S2 type chondrite, which has experienced thorough thermal alteration (Karwowski et al., 2011; Karwowski, 2012). Measurable amounts of carbon were expected to remain within the meteorite, mainly as graphite.

The aim of this contribution was to present our preliminary results on the characterization of the methanol soluble organic fraction present in the Sołtmany L6 meteorite. Here, high-resolution organic structural spectroscopy, composed of Fourier transform ion cyclotron mass spectrometry (FT-ICR-MS) and NMR spectroscopy, revealed an astonishingly large chemical diversity of EOM with many thousands of distinct CHNOS elemental compositions.



Fig. 1. Carbon and water contents as a function of the petrologic groups and types of meteorites. As an L6 type chondrite, Sołtmany is expected to show low concentrations of total carbon in the same range as L6 ordinary chondrites conserved in Antarctica

EXPERIMENTAL SECTION

The Sołtmany ordinary chondrite fell on April 30, 2011 at 6:03 CEST through a roof and onto a concrete step in a farm in the village of Sołtmany, Poland, 54°00.53'N, 22°00.30'E (Fig. 2). On May 2, fragments of the stone were purchased and distributed among laboratories for examination. It was classified as an equilibrated ordinary chondrite (L6), W0, S2 (Karwowski et al. 2011; Karwowski, 2012) and some articles describe its mineralogy and petrography in more detail in this special issue on the Sołtmany fall.

A fragment was obtained for analysis from Tomasz Jakubowski and Prof. Tadeusz A. Przylibski, Wrocław University of Technology, Institute of Mining Engineering, Wrocław, Poland.

Sample preparation

Extracts for FT-ICR-MS analysis were prepared as described previously in Schmitt-Kopplin et al. (2010). An intact piece of dry meteorite weighing about 50 mg was briefly washed with methanol (rapid contact with 1 mL methanol that was subsequently discarded), immediately crushed in an agate mortar with 1 mL of LC/MS grade methanol, and transferred into an Eppendorf tube within an ultrasonic bath for 3 minutes. The tube was then centrifuged for 5 min. The supernatant methanol extract was directly used for FT-ICR-MS infusion. NMR samples were prepared similarly, but using CD3OD as the solvent (cf. NMR experimental section). Prior to the sample extraction, great care was used to clean the agate pillar with an ultrasonic bath and solvent. A blank sample was produced by following the same extraction procedure without a meteorite fragment, and this was analysed before and after each meteorite analysis. No significant peaks in the mass range of the meteorite extracts were observed; a detail of a blank mass spectrum is shown in Fig. 4.

Fourier transform ion cyclotron resonance mass spectrometry (FT-ICR-MS)

In order to fully exploit the advantages of FT-ICR-MS and maintain accuracy, we routinely perform internal calibration on arginine clusters prior to any analysis. Relative m/z errors were usually < 100 ppb across a range of 150 < m/z < 1,500. The average mass resolution ranged near 400,000 at nominal mass 400. It is noteworthy for readers not familiar with advanced mass spectrometry to understand that this exceptional mass accuracy and mass resolution allows us to assign the exact mass of molecular ions and their respective elemental compositions from mixtures – with better precision than the mass of an electron (which

amounts to $9.10938215 \times 10^{-31}$ kg or 1/1836.2 of the mass of a proton). Accordingly, two molecular compositions with mass differences smaller than that of a single electron mass can be differentiated. Mass peak amplitudes grow with the square root of the number of acquired transients, similarly to NMR spectroscopy (see insert principles of FT-ICR-MS). Soltmany methanol extracts spectra in our study were measured in negative and positive electrospray ionisation modes [ESI(-) and ESI(+)] under conditions described above (Schmitt-Kopplin et al., 2010); 2,000 scans were accumulated with a total of 4 million data points. The conversion of the exact masses into elementary compositions is shown in more detail in Tziotis et al., 2011. The representation of complex FT-ICR-MS datasets is explained in detail in a book chapter on environmental mass spectrometry (Schmitt-Kopplin et al., 2012); an in-depth analysis of complex secondary organic aerosol extracts and especially a van Krevelen diagram with model compounds indicated can be found in Schmitt-Kopplin et al. 2010.

Nuclear magnetic resonance spectroscopy (NMR)

Proton NMR spectra of methanolic meteorite extracts were acquired with a Bruker Avance NMR spectrom-



Fig. 2. The Soltmany "hammer" fall. Photos with courtesy from T. Jakubowski



Fig. 3. FT-ICR mass spectra of methanolic extract of Murchison CM2 in ESI(-), Sołtmany L6 in ESI(-) and ESI(+) (from left to right) ionization mode, showing (panels A-C) mass peaks in the range of 150 to 700 Daltons – a detailed region of nominal mass 319 of Murchison and Sołtmany in ESI(-) ionization mode is shown in Fig. 4, respectively. The corresponding inserted histograms show the relative abundances of the CHO, CHOS, CHNO, and CHNOS ions. (Panels C–E): mass resolved H/C diagram showing the chemical series of compounds according to m/z; (panels F-H) H/C versus O/C van Krevelen diagrams (Schmitt-Kopplin et al., 2010), revealing (panel D) the rather aliphatic oxygenated character of the Soltmany methanol extractable organic compounds compared to Murchison in ESI(–) mass spectra, whereas (panel H) van Krevelen diagrams of ESI(+) mass spectra revealed the relatively nitrogen- and sulphur-rich and low-oxygenated character of the Soltmany methanol extractable organic compounds (in orange and green colour respectively). In panel D through H diagrams, bubble size is related to the m/z intensity in corresponding mass spectra. The colour code indicates the respective CHO, CHNO, CHOS, and CHNOS molecules



Fig. 4. Detail of a 150 millimass region in the nominal mass 319 of Sołtmany L6 negative electrospray FT-ICR mass spectrum compared to the Murchison CM2 presented in our previous study (Schmitt-Kopplin et al., 2010) and the blank methanol extract without meteorite, showing the different signals with their annotations in elementary compositions in CHNOS and ¹³C –bearing isotopologues. Common elemental compositions in Sołtmany and Murchison chondrites are denoted with an asterisk "*". Also presented is the Venn diagram showing the presence of only a few common elementary formulas in both ESI(–) and ESI(+) mass spectra of the Sołtmany extract. Most of the formulas found with electrospray ionization are specific to the negative or positive ionization mode indicating considerable ionization selectivity in electrospray FTICR mass spectra.

eter at 800.35 MHz ($B_0 = 18.8$ T) and 283 K from a few mg of solid (extensively washed with CD₃OD) crushed under 3 mL CD₃OD (Merck, 99.95% ²H). ¹H NMR spectra were acquired following evaporation from approx. 70 µL CD₃OD (Merck, 99.95% ²H) solution with a 5 mm z-gradient ¹H / ¹³C / ¹⁵N / ³¹P QCI cryogenic probe in a sealed 2 mm Bruker MATCH tube. 1D ¹H NMR spectra were recorded with standard pre-saturation (noesypr1d) to attenuate present residual water (90° excitation pulses ¹H: 10 µs, 5 s acquisition time, 5 s relaxation delay, 1 ms mixing time, 4385 scans, 1 Hz exponential line broadening). A phase-sensitive, gradient-enhanced TOCSY NMR spectrum (mixing time 70 ms) with solvent suppression (dipsi2etpgpsi19) was acquired with an acquisition time of 1 s, a relaxation delay of 2 s, a spectral width of 9615 Hz (12 ppm), via echo-antiecho selection and sensitivity enhancement. 12 scans and 572 increments were acquired and computed to a 16k × 1024 matrix with 2.5 Hz exponential multiplication in F2 and a $\pi/4$ shifted sine bell in F1. The NMR spectra of C₃H₈O (Fig. C; app. 2) were computed with Advanced Chemistry Development (ACD, Toronto, Canada) software, H NMR predictor, 2012 release.

RESULTS AND DISCUSSION

The analysis of the methanol extracts resulted in ~14,000 resolved mass peaks in ESI(-) mass spectra (Fig. 3B) and ~7,100 resolved mass peaks in ESI(+) mass spectra (Fig. 3C). In ESI(-) these were converted into initially ~4,100 elemental compositions of which ~3,300 could be confirmed considering the elements C, H, N, O, and S based on the NetCalc compositional approach presented in Tziotis et al., 2011. All of these compositions can be represented via van Krevelen diagrams showing the atomic ratios H/C versus O/C in a colour code for the CHO, CHNO, CHOS and CHNOS type of molecules and a dot size related to the intensity of the related peaks in the mass spectra; the isotopologues are not shown in this representation to avoid structural information redundancy. Soltmany methanolic extract showed a much lower number of mass peaks (and assigned elemental compositions) than did Murchison CM2 methanolic extract (described in detail recently in Schmitt-Kopplin et al., 2010), as illustrated in Fig. 3A. Great emphasis was placed on the cleanliness of working conditions, including comparison with blank samples (same extraction and analysis procedure without meteorite sample). These blanks were almost devoid of mass peaks, clearly demonstrating that the observed mass peaks were solely generated from the meteorite and not from (solvent and/or other) contaminations.

The classification of the elemental composition according to CHO, CHOS, CHNO and CHNOS molecular series showed the importance of highly oxygenated aliphatic sulphur containing compounds in ESI(-) mass spectra (green dots in Fig. 3) whereas, in ESI(+) mass spectra, sulphur compounds were found to exhibit higher aromaticity (lower H/C domain), probably of heterocyclic origin (Fig. 3H). In ESI(-) mass spectra, the CHOS compounds were equally abundant as the CHO compounds, with lesser contributions of CHNOS and CHNO molecules (Fig. 3C and 3D), whereas in ESI(+) mass spectra, many nitrogen containing compounds were nicely ionized as well. These CHNO molecules with low oxygen contents were found across the entire m/z range up to higher molecular masses (Fig. 3D–F).

Further detail of the ESI(-) mass spectrum is shown in Fig. 4 and directly compares to the well-described chemical diversity of the CM2 carbonaceous chondrite Murchison, presented recently in Schmitt-Kopplin et al., 2010. Some elemental compositions were found simultaneously in both Soltmany and Murchison (CHO and CHOS molecular series), across all nominal masses. Coarsely, the structural specificity corresponded to high amounts of nitrogen compounds (CHNO molecules) in Murchison and to large amounts of oxygenated hydrocarbons (CHO molecules) in the Soltmany meteorite. Electrospray ionization primarily ionizes polar compounds with concomitant selectivity in the type of molecules we can "see" with this analytical tool (Hertkorn et al., 2008); additional methods of ionization involving photoand laser-ionization, which also ionize hydrocarbons, are currently being developed and implemented. FT-ICR mass spectrometry provides unsurpassed resolution and assessment of chemical diversity; it allows for the differentiation of most elemental compositions with the elements C, H, N, O, and S up to a mass of around m/z 600 (Kim et al., 2006). However, this method commonly cannot discriminate between isomers (Hertkorn et al., 2007). It is important to note that the structural disparity of molecular ions grows with decreasing mass difference; i.e. more closelyspaced pairs of mass peaks exhibit ever-increasing mandatory compositional and structural dissimilarity (Hertkorn et al., 2008).



Fig. 5. Relative frequency distribution in the mass differences of Sołtmany methanolic extract as obtained with the functional network approach from ESI(-) FT-ICR mass spectra (Tziotis et al., 2010) indicating the count of the exact mass differences corresponding to the different functional groups ($-CH_2$, $-H_2$, -OH, $-CO_2$...). Also shown is the relative abundance of formulas bearing one to four sulphur atoms (S in $CHOS_{1.4}$ molecules) or nitrogen atoms (N in $CHN_{1.5}O$ molecules). The right panel shows the obtained 3D-network of the mass spectral data with a corresponding colour code. The clustering of colors and the different quality of arrangements within CHO (butterfly), CHOS (disk shape with scatter), CHNO (diffuse cloud) and CHNOS (aligned scatter) molecular series indicates structural preferences of sulphur- and nitrogencontaining chemical environments. The insert indicates some connectivities of the molecular ion $C_{15}H_{27}O^-$ provided in Fig. 4.

The elemental compositions were computed using a self-developed software presented previously (Tziotis et al., 2011), which enabled us to generate a compositional space based on the exact experimental mass data with better coverage than has been attained in classical analyses. This algorithm computes differences between two precise experimental masses corresponding to the various atoms (compositional approach) or functional groups (functional approach). The frequencies of these selected mass differences can be represented in diagrams such as those shown in Fig. 5. As is typical for mixtures of organic molecules, the main nominal transformations counted in the Soltmany meteorite were methylene, CH_2 ($\Delta m = \pm 14.0024$ Da), followed by H₂ (double bond equivalent, DBE, $\Delta m = \pm 2.1057$ Da). The structures present in the Soltmany meteorite were highly hydroxylated (OH) and carboxylated (CO_2) . Counting the number of sulphurs and nitrogens in all of the obtained elemental compositions showed that most of the CHOS/CHNOS molecules each contain only one sulphur. Nitrogen was found up to three times in CHNO/CHNOS compositions.

Finally, the experimental data can be visualized in a coloured network showing a rather loose structure (Fig. 5).

Non-target organic structural spectroscopy of Soltmany L6 chondrite methanolic extract, in which we attempted to unselectively characterize the soluble polar carbon present, has revealed the considerable chemical diversity of extraterrestrial organic matter (EOM). The short temporal lag period between the stone's fall, sampling, and data acquisition suggests the dominance of EOM with very limited, if any, terrestrial impurities present. FT-ICR mass spectrometry of EOM detects gas-phase molecular ions and allows for an unprecedented resolution of several thousands of molecular formulae directly out of the mixture, and the recognition of very minute quantities of individual molecular compositions. The use of electrospray ionization in FT-ICR mass spectrometry emphasized the detection of polar compounds and discriminated against hydrocarbons and other functionalized organic molecules with nearly absent exchangeable protons (Hertkorn et al., 2008). Hence, the already appreci-



Fig. 6. 800 MHz ¹H NMR spectrum of methanolic extract of Sołtmany meteorite with fundamental substructures indicated (cf. text) and expansion of aromatic NMR resonances shown ($\delta_{H} \sim 6.5...8.1$ ppm, cf. Figure 7, panel C). Unbroken trails denote proton NMR integrals of main substructure regimes [abundance ratio of unsaturated and doubly oxygenated CH (O₂CH) : singly oxygenated (OCH) : carbon-bound (CCH) ranged near 1 : 2 : 24]. Aliphatic carbonyl derivatives (i.e. probably carboxylic acids) accounted for nearly 7% of CCH proton NMR section integral ($\delta_{H} \sim 2.0 ... 3.1$ ppm; see Fig. 7). Fundamental aromatic substitution patterns, i.e. electron withdrawing carbonyl derivatives COX (COOH, COOR, CONH; 48% of aromatic integral), electron-neutral R (aliphatic and hydrogen; 23% of aromatic integral), and electron-donating OR (OH, OR, SR; 29% of aromatic integral) substituents, occupy typical chemical shift ranges indicated in color (Hertkorn et al., 2006; Perdue et al., 2007)

able chemical diversity discovered here very probably represents a very minimal assessment of molecular diversity actually present in the Sołtmany L6 chondrite. Compared with the Murchison CM2 organic chondrite, the organic chemical diversity in Sołtmany L6 chondrite appears more restricted; about half of Murchison's chemical compositions were common to both meteorites, whereas Sołtmany's unique compounds comprised roughly 10% of the total mass peaks.

Proton NMR spectroscopy, which analyses chemical environments of dissolved molecules, has allowed for a near-quantitative assessment of proton chemical environments at lower sensitivities than FT-ICR mass spectrometry. This method has revealed both the dominance of pure aliphatic spin systems (CC**H**) with short chain lengths (C_{3-4} units; in accordance with Remusat et al., 2005) in Soltmany L6 methanolic extract as well as the occurrence of oxygenated aromatics: nearly 80% of aromatics carried at least one oxygen, either as carbonyl derivatives (50%) or by means of direct oxygenation (30%). Aliphatic carboxylic acids comprised nearly 7% of aliphatics, based on proton NMR section integral (Fig. 6).

More precisely, NMR spectra of the Sołtmany meteorite were acquired in deuterated methanol (CD₃OD) in order to suppress the otherwise huge solvent NMR resonance ($\delta_{\rm H}$ = 3.30 ppm. ¹H NMR

NMR chemical shift, δ_H [ppm]	10-5	5-3.1	3.1-0.5
key substructure	$C_{sp}^{2}\underline{H}$	ОС <u>Н</u>	СС <u>Н</u>
relative abundance [%]	3.8	7.5	88.7

Table 1. Section ¹H NMR integral of non-exchangeable protons in Sołtmany methanolic extract (Fig. 6)

spectroscopy only detects HCD2OD; Fig. 6), given the rather low abundance of meteorite organic matter in solution. The ¹H NMR spectrum of Sołtmany extract (Fig. 6) depicted non-exchangeable protons; all exchangeable protons (i.e. –XH, with X: O, N, S in common functional groups such as –OH, –COOH, and –NH–) were superimposed on the residual water resonance (HDO, $\delta_{\rm H}$ = 5.02 ppm), which has been suppressed here for improved visibility of Sołtmany's organic matter.

The total range of the proton NMR chemical shift was first divided into purely aliphatic groups (CC**H**; heteroatoms \geq 3 bonds away from hydrogen; $\delta_{\rm H}$: 0...3.1 ppm), singly heteroatom-containing groups (OC**H**; heteroatoms two bonds away from hydrogen, most likely oxygen; $\delta_{\rm H}$: 3.1...5.0 ppm) and unsaturated chemical environments [C_{sp}²**H**; hydrogen bound to sp²-hybridized carbon, i.e. olefinic (here: $\delta_{\rm H} \sim 5.3$ ppm), and aromatic protons ($\delta_{\rm H} \sim 6.5...8.0$ ppm)].

Proton NMR spectra were in essence quantitative. Sołtmany's methanolic extract featured large abundances of aliphatic protons. Additionally, about onetenth of non-exchangeable protons were bound to heteroatoms (likely oxygen) and a minor suite (< 5%) of unsaturated protons was also observed (Tab. 1). The observed abundance distribution was partly caused by the lesser solubility of unsaturated chondritic matter in comparison with aliphatic compounds.

Within the aromatic section of chemical shift, chemical shift-based-discrimination of molecules was feasible because of electronic substituent effects. Electron-withdrawing substituents such as carbonyl derivatives COX caused downfield chemical shifts (δ_{H} > 7.3 ppm) for aromatic ortho and para positions; electroneutral substituents such as alkyls and hydrogen caused intermediate chemical shifts ($\delta_{\rm H}$ ~7.0... 7.3 ppm), whereas electron-donating groups caused upfield chemical shifts ($\delta_{\rm H}$ > 7.0 ppm; the electrondonating effect of electronegative substituents results from resonance interactions; Perdue et al., 2007). In Soltmany extract, the ratio of electron-withdrawing, electroneutral, and electron-donating aromatic substitution was 48/23/29 (Fig. 6), indicating considerable carboxylation of aromatic units. One single compound with strong NMR resonances produces almost one third of the total aromatic NMR integral (Fig. 6). Three positions of chemical shifts with characteristic splitting ($\delta_{\rm H}$ = 7.150 ppm, 2H, $J_{\rm HH}$ = 7.5 and 8.2 Hz; $\delta_{\rm H}$ = 6.785 ppm, 1H, t, $J_{\rm HH}$ = 7.3 Hz; $\delta_{\rm H}$ = 6.747 ppm, 2H, d, $J_{\rm HH}$ = 8.0) indicated a C₆H₅OZ unit with a yet-unidentified substituent Z (Z is not H as shown by comparison with ¹H NMR of methanolic phenol; data not shown). This C₆H₅OZ unit was also confirmed by two-dimensional ¹H,¹H TOCSY NMR spectra (Fig. 7).

Two-dimensional NMR spectra in general indicate pairs of atoms rather than individual atoms; the NMR experiment determines the interaction shown [e.g. spatial proximity (¹H,¹H NOESY NMR spectra), homonuclear J couplings (^{2,3}J_{HH}: COSY NMR spectra; ${}^{n}J_{HH}$: TOCSY NMR spectra, commonly *n* \leq 5–6), and heteronuclear J couplings (¹J_{CH}: HSQC NMR spectra; ⁿJ_{CH}: HMBC NMR spectra, commonly $n \le 2-3$]. Homonuclear 2D NMR spectra relate two identical NMR spectra and initially show socalled diagonal peaks, in essence reflecting 1D NMR spectra with low resolution and negligible information content. The useful information is derived from the off-diagonal cross peaks, which indicate connectivities of atom pairs defined by respective NMR experiments (Macomber, 1998).

¹H, ¹H TOCSY NMR spectra allow a sensitive depiction of proton-proton couplings ⁿJ_{HH} within proton NMR spin systems. According to sections of chemical shift, purely aliphatic spin systems (HC-C_n-C<u>H</u>; n: 0-4) resonate below $\delta_{\text{H}} < 3$ ppm (Fig. 7, panel A, box a). Spin systems with one heteroatom (-O-<u>H</u>C- C_n -C<u>H</u>; n: 0-4) show one participating proton in the aliphatic section ($\delta_{\rm H}$ < 3 ppm) and one participating proton in the heteroatom section ($\delta_H > 3$ ppm; Fig. 7, panel A, box b). Note the relative scarcity of double-heteroatom-containing aliphatic spin systems (X-O-<u>H</u>C-C_n-C<u>H</u>-O-Y; n: 0-4, X,Y: any substitution) in Soltmany methanolic extract: only very minor TOCSY cross peaks were found with chemical shifts δ_{H} : 3.0... 5.0 ppm (Fig. 7, panel A). Intra-aliphatic spin systems in Soltmany extract were numerous (Fig. 7) and likely represented a superposition of several common chemical environments. Pure aliphatics are terminated by methyls; here, the ratio of methyl/total aliphatics was close to one-third (Fig. 6). Given that the H/C ratio of methyl is 3 and that of the other aliphatics is near 1.3 (in analogy to common chondritic organic matter), about every seventh carbon of Soltmany aliphatics is methyl. Methyl-terminating aliphatics show a lesser chemical diversity than do other aliphatics, because variance in substitution extends solely in one direc-



Fig. 7. 800 MHz ¹H, ¹H TOCSY NMR spectra of methanolic extract of Sołtmany meteorite. Panel A: section of aliphatic cross peaks with purely intra-aliphatic cross peaks, section a: (C-C**H**-C**H**-C cross peaks) as well as oxygenated aliphatic units, section b: (C-C**H**-C**H**-O cross peaks) indicated. Panel B: enlarged section (panel A, section a) of intra-aliphatic cross peaks with a plausible spin system indicated. H_a resonates downfield of $\delta_{\rm H} \sim 2.14$ ppm and likely denotes protons in δ -position to carbonyl groups. With increasing distance, protons show progressively lower values of chemical shift [$\delta({\rm H}_{\beta}) \sim 1.59$ ppm; $\delta({\rm H}_{\gamma}) \sim 1.31$ ppm]. Polymethylene, i.e. long aliphatic chains, resonate near $\delta_{\rm H} \sim 1.28$ ppm, depending on proximate and remote substitution. This resonance produce a rather expansive consolidated cross peaks of many similar chemical environments. Chain-terminating methyl groups resonate below $\delta_{\rm H} < 1.0$ ppm. Panel C: section of aromatic TOCSY cross peaks (X-C_{ar}**H**-C_{ar}**H**-Z; with two main spin-systems denoted according to characteristic patterns of chemical shift and spin-spin coupling ($\delta_{\rm H} = 7.15$ ppm, 2H, dd, J = 8.3, 7.5 Hz; $\delta_{\rm H} = 6.79$ ppm, 1H, t, J = 7.3 Hz; $\delta_{\rm H} = 6.75$ ppm, 2H, d, J = 8.0 Hz) very likely indicates an oxygen-substituted benzene H₅C₆OZ (Z: R, SO_nR with n = 0-3). The two downfield spin systems from $\delta_{\rm H} ~ 7.38 \dots 7.78$ ppm most probably denote carbonyl derivatives of benzene rings with vicinal proton pairs (i.e. protons bound to adjacent carbon positions)

tion. In contrast, methine carbon $(C_3 \underline{C}H)$ allows for freedom in substitution in three directions. Hence, aliphatic methyl resonates at a rather narrow chemical shift range (here: $\delta_{H} \sim 0.7...1.2$ ppm). Carbonyl derivatives COX were likely substituents in Soltmany organic matter, imposing downfield chemical shifts for adjacent protons (δ_H > 2.1 ppm; Fig. 6), and common chemical shifts for typical aliphatic chemical environments (Fig. 7; Panel B). With respect to distance from carbonyl, (α -, β -, γ -, Fig. 7, panel B) aliphatic positions resonated at certain proton NMR chemical shifts. Similarly, pure aliphatic (e.g. linear and branched) hydrocarbons resonated within this chemical shift range (commonly $\delta_{\rm H}$ < 1.6 ppm; alicyclic rings more often resonated downfield from $\delta^{}_{\rm H}$ – 1.2 ppm than open chain aliphatics). Polymethylene units, abundant in common biomolecules (like fatty acids, plant waxes) resonate at $\delta_{\rm H}$ ~1.2 ppm but were not preferred in meteoritic organic matter, in which a near statistical distribution of aliphatic branching motifs was found. Hence, the rather large ¹H NMR resonance at δ_{H} ~1.32 ppm observed in Soltmany methanolic extract probably resulted from the superposition of many purely aliphatic chemical environments; this was corroborated by the large number (> 10) of ${}^{1}H$, ${}^{1}H$ TOCSY cross peaks related to this NMR resonance (Fig. 7; Panel B). In conclusion, Soltmany aliphatics were composed of abundant branched hydrocarbons with ~ 7% of protons adjacent to carbonyl derivatives (likely carboxylic acids) and similar amounts bound to oxygen; substantial aliphatic branching was deduced from the $CH_3/C_{aliphatic}$ ratio in the range of 1:7.

The ¹H, ¹H TOCSY NMR spectrum showed the characteristic cross peaks of a C₆H₅OZ unit; i.e. the spin system is composed of a single (para, 1H) proton and both ortho and meta positions (2H each because of magnetic equivalence) exhibit TOCSY cross peaks (Fig. 7, Panel C). In addition, several carboxylated aromatic rings show downfield ($\delta_{\rm H} < 7.4$ ppm) cross peaks, indicating multiple carboxylations.

Considering the strong thermal alteration of Sołtmany L6 chondrite, the provision of extensive EOM chemical diversity suggests that investigating organic chemical diversity in any pristine or thermally altered meteorite will offer encouraging clues about its

formation and evolution. It is still too early for us to understand the intimate processes involved in the formation of these compounds, and we will need to systematically investigate fresh meteoritic falls of different classes and petrologic types to assess the significance of the chemical complexity and diversity we unexpectedly discovered with this study. Intimate organomineral interactions (Kleber et al., 2007; Schoonen et al., 2004), which are known to protect terrestrial (e.g. soil and sedimentary) organic matter from rapid degradation, might have provided additional means of EOM generation and conservation. A rich diversity of minerals acting as sorbents, catalysts, and templates all offer the capacity to initiate crucial transformations of primordial volatile precursor molecules (CO, CO₂, H₂, CS, H₂O, HCN, NH₃, H₂S, HCHO) into simple organic molecules (~10 atoms) and the consecutive assembly of ever larger compounds. The minerals' chemical compositions, morphologies, distributions of impurities, and presence of structural and/or electronic defects as abundantly found in chondrites will decisively affect the specificity of these organo-mineral interactions (Schoonen et al., 2004) responsible for the generation and decomposition of organic molecules throughout the history of EOM formation. Here, an extensive and largely unknown organic molecular complexity meets an appreciable and passably understood mineral heterogeneity ranging from nanoscales (e.g. electronic and structural defects; shape selectivity) to microscales (crystal symmetry and surface properties), of which a limited fraction has been explored in more than 50 years of industrial catalysis (Pérez-Ramírez et al., 2008; Smit and Maesen, 2008).

It is conceivable that (formerly hot) mineral surfaces within porous parent bodies might have catalyzed bond formation in-between small and possibly vaporized organic molecules, contributing to the assembly of those precursors into larger compounds. These smaller molecules were then subject to preferential deposition in narrow cavities of abundantly available large interior mineral surfaces (Le Guillou et al., 2012). Furthermore, active organo-mineral interactions will likely limit the solubility of OM in organic solvents; i.e. the proportions of soluble and insoluble organic matter (IOM) could then shift towards IOM.

CONCLUSION

We first made an inventory of the polar solvent extractable organic matter from the L6 ordinary chondrite that fell in Soltmany and showed the presence of thousands of different CHNOS-type of molecules. More studies are needed to describe the chemical footprints of extracts from various petrologic types of chondrites on a molecular level, involving a parallel characterization of the insoluble organic matter (IOM) in order to describe the various chemical diversities and better understand the structural origin of the present organic matter. On-going studies will employ additional extraction procedures with protic/ aprotic solvents to extract molecules of various polarities. The known limitations of electrospray ionization in ionizing non-polar molecules will require the use of alternative ionization techniques such as photoionization or chemical ionization to generate a more significant assessment of organic molecular diversity. The molecular characterization of CH, CHN of CHS type of compounds will contribute to a better understanding of the processes leading to the formation and stabilization of particular organic chemistry discovered in ordinary chondrites.

This study also demonstrated the yet-untapped opportunities that arise from the collection of structural information of organic compounds extracted from a pristine, freshly fallen sample. Our investigations underline the importance of protecting freshly fallen meteorites from terrestrial contamination or weathering

that could occur over time, modifying their pristine organic compositions, thereby, interfering in later global organic analyses. The sooner after a fall an analysis can be performed, the better the odds that (chemical and biological) contaminations can be limited. It would be perfectly adequate to avoid direct handling with skin contact and to eliminate the potential for terrestrial corruption by cooling the sample with liquid nitrogen directly after the fall; this might be more feasible with meteorites that have fallen in Antarctica. Even if inconvenient, the insights derived from the organic analysis of pristine meteorite samples will provide invaluable clues about meteorites' histories and their pathways of chemical evolution in general. Studies currently being performed with other fresh falls such as the carbonaceous chondrite Sutter's Mill and Shergottite Tissint confirm the presence of specific organic signatures changing as a function of the petrologic type (Schmitt-Kopplin et al., 2012a, 2012b).

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APPENDIX 1. PRINCIPLES OF FT-ICR-MS

Ion cyclotron resonance mass spectrometry refers to the measurement of the cyclotron frequency of ions trapped inside a confined cylindrical geometry located inside a magnet (Marshall et al. 1998). Fig. A shows the ICR cell with an orbiting ion inside. Ions can be



Fig. A. A cylindrical geometry of an ICR cell with two bored end cap electrodes. The blue spiral indicates a trajectory of an ion during radial (XY) ion excitation prior to detection. The central electrode is segmented four-fold with both counterpart segments representing either detector pairs or transmitter pairs

detected by their energy absorption from an external waveform generator that causes expansion of their cyclotron radius so that their orbits range in proximity to two detector plates located in the central ring electrode of the cell. Each ion m/z corresponds to a specific cyclotron frequency (Eq. 1). A mass spectrum (MS) represents a histogram, which shows different ion abundances as a function of m/z ratios. Mass spectra result from the detection of the cyclotron frequencies of all confined ions. This is achieved by performing a mathematical Fourier transform of the detected transient induced charge, collected as a function of time (Fig. B).

$$\omega_c = \frac{q B}{m} \tag{1}$$

The cyclotron frequency ω_c is given by Eq. 1, in which m is the ion mass in amu, q is the charge state, and B is the magnetic field strength in Tesla. It is obvious from Eq. 1 that higher magnetic field strength causes larger confined ion cyclotron frequencies, translating into higher mass resolving power.



Fig. B. Acquisition of one a standard natural organic matter sample (Suwannee River surface water fulvic acid / FA, obtained from International Humic Substances Society – IHSS). The time domain detected transient is shown on the left, acquired with 4M data points within 1.6 seconds. Right: The mass spectrum is obtained as a result of Fourier transformation of the induced charge transient and application of Eq. 1. Here, the mass resolving power is 362,972 at m/z = 451

APPENDIX. 2. BASICS OF NMR SPECTROSCOPY FOR ELUCIDATION OF MOLECULAR STRUCTURES

NMR measures the precession frequencies of individual nuclear magnetic moments in an external magnetic field B_0 ; these depend on the nuclear properties (γ_N : gyromagnetic ratio), B_0 applied, and the local chemical environments. Hence, any atom within an organic molecule produces a unique NMR signature. This information-rich detection defines NMR spectroscopy as the most powerful method for the structural analysis of amorphous materials currently available. For instance distinguishing between isomers using this process is facile (Fig. C). Common isotopes used in the structural elucidation of organic compounds are the spin $\frac{1}{2}$ nuclei ¹H, ¹³C, ¹⁵N and ³¹P; note that the common nuclei ¹²C, ¹⁶O and ³²S do not exhibit a magnetic moment (nuclear spin I = 0) and therefore cannot be used for NMR spectroscopy (Macomber, 1998).

Tab. A. Three key	y NMR parame	ers useful for stru	ctural analysis of o	rganic molecules
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Parameter	Acronym	Appearance in NMR spectrum	Significance in structural analysis
Chemical shift	δ	position of NMR resonances on the horizontal (frequency) axis	defines chemical environment of all neighboring atoms. δ denotes the fractional change in precession frequency of a specific nucleus induced by the variance in chemical environments normalized to B ₀ , typically given in [ppm]
Spin-spin coupling	ⁿ J _{AB}	multiplicity of NMR resonances	spin-spin coupling constant for nuclei A and B through "n" bonds [Hz]; refers to count of adjacent nuclei
Integral	S	integrated signal intensity	signal intensity integrated across a full multiplet, denotes quantity of magnetically equivalent nuclei



Fig. C. ¹H NMR spectra (300 MHz, computed) of two isomers of C_3H_8O with assignments (asterisk denotes the exchangeable hydroxyl proton which is out of range in case of isopropanol). Red numbers denote NMR integrals; NMR signal splittings indicate J-couplings, which denote counts of adjacent nuclei according to the equation $2 \times n \times I + 1$ [*n*: number of magnetically equivalent neighbors, I: nuclear spin (¹H) = ¹/₂]. In isopropanol (bottom row), a single proton (H-2; integral 1H) and six magnetically equivalent protons (H-1,3; integral 6H) from two methyl groups define the overall spin system of non-exchangeable protons. H-2 is split into seven signals (septet, $2 \times 6 \times 1/2 + 1 = 7$, with intensity distribution according to Pascal's triangle) and H-1,3 into two signals (doublet, $2 \times 2 \times 1/2 + 1 = 2$). Similarly, three groups of magnetically nonequivalent protons define the spin system of non-exchangeable protons in n-propanol (top row). These three groups are the chain-terminating methyl group (H-3; integral 3H, 1:2:1 triplet splitting from two adjacent methylene protons), the central methylene (H-2; integral 2H, sextet splitting from five neighboring protons, with intensity distribution according to Pascal's triangle), and the hydroxymethylene group (H-1; integral 2H, 1:2:1 triplet splitting from two neighboring methylene protons). Note that proximate oxygen causes a chemical shift $\delta_H > 3.0$ ppm (yellow shade), while methyl groups resonate near $\delta_H < 1.2$ ppm (orange shade). Hydroxy protons are typically subject to fast chemical exchange in solution and therefore produce rather broad 1H NMR resonances.

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$$v > \sqrt{\frac{2MG}{r}} \tag{1}$$

where:

v – escape velocity, m·s⁻¹,

M – mass of body from which object is projected, kg, G – universal gravitational constant, N·m²·kg⁻²,

r – radius of body from which object is projected, m.

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