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POTENTIAL IMPORTANCE OF METALLIC RESOURCES OF ORDINARY CHONDRITE PARENT BODIES

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Abstract: Demand for metallic resources constantly increases along with technological development. One of the factors that currently raises requests for resources is extensive space exploration. Especially, the exploration that involves space colonization creates the needs for resources not only on the Earth but also on other bodies in the Solar System. For instance, resources will be required for building bases and settlements or spare parts to machines, devices and space shuttles. The high transportation costs make launching them from our planet ineffective. New and attractive places for prospecting the resources in our Solar System are bodies located in the asteroid belt, namely parent bodies of ordinary chondrites. The goal of this paper is a review of scientific and economic aspects of extraterrestrial resources associated with such bodies. Studies of meteorites combined with scientific achievements of current space mission significantly improved our understanding of the origin, structure as well as chemical and mineral composition of these bodies and processes that affected them. This knowledge is used in XXI century to set up companies aiming at asteroid mining, or production of fuel and spare pieces in space. Additionally, owing to the fact that some asteroids are on collisional course with our planet, possibilities arise for resource utilization by deflection of hazardous asteroids and setting them on circumterrestrial or circummoon orbits.

Keywords: *extraterrestrial resources, metallic resources, asteroid mining, ordinary chondrite parent bodies*

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1. INTRODUCTION

All technical civilizations are based on the ability to utilize metals. However, deposits of terrestrial metallic resources are limited. On one hand, mining will develop in directions maximizing potential gain. On the other new sites will be prospected. Potential places for prospection of new deposits are mentioned by author in figure 1 (Łuszczek, 2011).

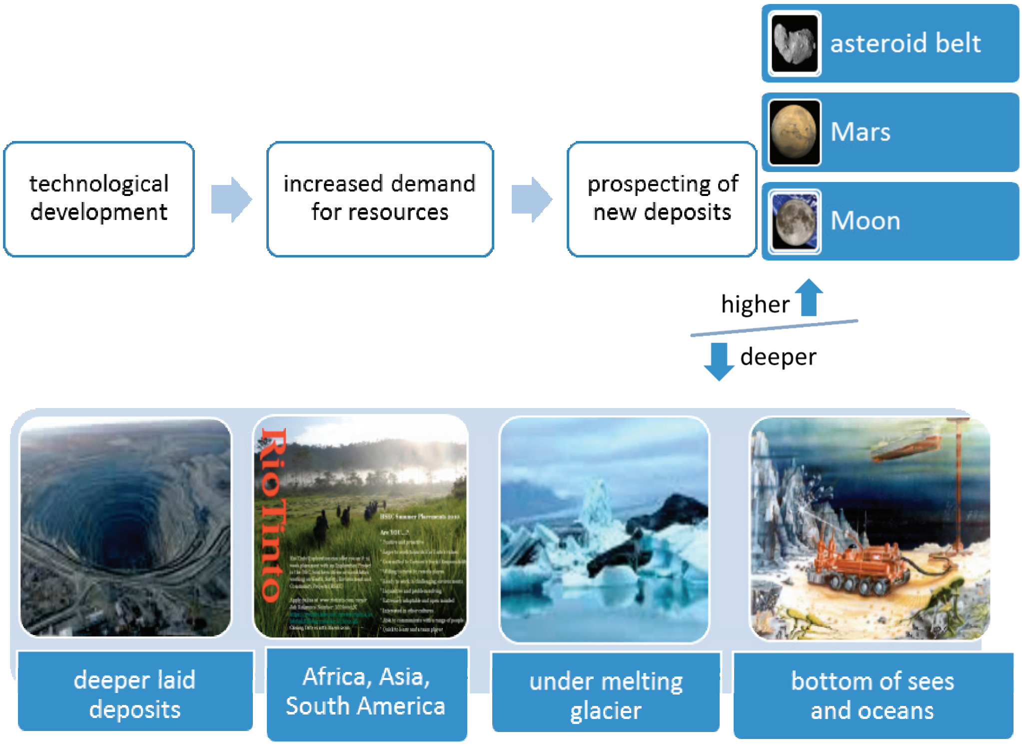

Fig. 1. Potential places of prospection of new deposits (deeper/higher according to Earth's crust)

From the economic point of view, metallic resources split into two categories. The abundant metals are these, whose content in the Earth's crust exceeds 0.1 wt. %, e.g., Si, Al, Fe, Mg, Ti, Mn). The scarce metals instead occur in the Earth's crust in an amount less than 0.1 wt. %. The scarce metals can be subdivided into several groups based upon properties in common and utilization. Among the categories are: the ferro-alloy metals (e.g., Ni, Cr), the base metals (e.g., Cu, Pb), the precious metals (Au, Ag, Ru, Rh, Pd, Os, Ir, Pt) and the special metals (e.g., Ga, Ge, REE, Sb, As, Li) (Craig et al., 2011).

This paper aims at reviewing the economic and exploration potential of parent bodies of ordinary chondrites. Ordinary chondrites are the most common and the best-known group of meteorites. Based on differences in chemical composition they are divided into three groups named on the basis of iron content: H (high-Fe), L (low-Fe) and LL (low-Fe, low-metal) (Hutchison, 2006). Chondrites are rocks that escaped any internal geological reprocessing such as differentiation (McSween and Huss, 2010). For this reason, it may be assumed that the metallic grains are distributed homogeneously in chondritic parent bodies. Although asteroids may have experienced some processes that led to minor reprocessing and redeposition of metal grains (e.g., impact and shock, Friedrich et al., 2013; Tomkins et al., 2013; Krzesińska, 2017), such processes were not capable to change the amount nor chemical composition of metals in chondritic parent bodies. Therefore, it is valid that the metal abundances in ordinary chondrites are an adequate measure of the metal abundances in their parent bodies.

In consequence, it may be expected that parent bodies of ordinary chondrites will play a key role in future resource supply to the mankind. The resources mined on asteroids can be transported to the Earth as well as, together with space exploration and colonization, may be a crucial component to supply permanent bases and settlements on the Moon, circumterrestrial or circummoon orbit. Other scenarios forecast bases and settlements on Mars or one of the dwarf planets in the asteroid belt supplies (Przylibski, 2015).

2. RESEARCH ON EXTRATERRESTRIAL METALLIC RESOURCES

2.1. BEFORE SPACE MISSIONS AGE

Even in XX century topic of extraterrestrial mining was known mainly from the science fiction books and movies. However, end of the previous century brought increasingly courageous scientific discussion on deposits in the space.

First scientific statements about prospection and future extraction of extraterrestrial resources are known from nineties of XX century. At this time the books *Space resources* (McKay et al., 1992), *Resources of the Near Earth Space* (Lewis et al., 1993) and *Mining the sky* (Lewis, 1997) were first published. In the book *Case of Mars*, Zubrin and Wagner (1997) communicated the need for extraction of extraterrestrial resources according to large scale of space exploration. Simultaneously, Kargel (1994) and Lewis (1997) made an attempt to estimate the value of metallic resources for a couple of asteroids. Based on literature data, Kargel (1994) found LL chondrites and iron meteorites to contain the largest bulk amount of precious metals (LL chondrites contain 50–220 ppm of them, while H chondrites only 29 ppm). Above mentioned authors also estimated potential profit from exploration of those resources.

Kargel (1994) and Lewis (1997) assumed that the mean content of precious metals in meteorites is adequate to average precious metal content in the whole parent body. Based on these assumptions they (Karger, 1994; Lewis, 1997) calculated how much would metallic resources on individual asteroid be worth. However, the volume of the deposits themselves was not provided. This causes calculation to be highly risky of getting outdated, because even the small change of prices at metal market triggers significant changes of the value of the deposits. Moreover, neither correlation in metal abundance nor mineral phases were mentioned by Kargel (1994) and Lewis (1997). Now, scientifically more accurate data allow us to address the issue and to verify the calculations.

The other field of research about extraterrestrial resources that emerged in the late 90s was focused on technical aspects of exploitation e.g., mining in low gravity conditions or mineral processing of these resources (Prado, 2009; Zubrin and Wagner, 1997; McKay et al., 1992; Sonter, 1998). Moreover, production of fuel from asteroid is also described (Hsu, 2009; Moskowitz, 2010). Yet other papers describe economic factors of resource utilization (Kargel, 1996; Sonter, 1998, 2006). In spite of many aspects being addressed, geology of extraterrestrial resources was not studied.

2.2. IN SPACE MISSIONS AGE

The remote sensing observations conducted by various space missions revolutionized our knowledge and geological understanding of physical features of asteroids (Michel, 2014). As best shown by Lang in his book *The Cambridge guide to the Solar System* (2011), "asteroids may be mined for minerals or water".

Space missions proved to significantly advance our knowledge on asteroids. JAXA mission Hayabusa collected samples from the surface of asteroid 25143 Itokawa and successfully delivered them to the Earth. This allows us to examine small fragments of rocks, which are unchanged during space travelling before they reached the Earth and moreover unchanged by terrestrial conditions. The images collected during missions provide more data on morphology and structures of small Solar System bodies (Sullivan et al., 2002; Clark et al., 2002; Tsuchiyama, 2014). Consequently, the topic of extraterrestrial resources advances from the field of science fiction to the level of science. NASA has in 2016 launched mission OSIRIS-REx (Origins-Spectral Interpretations-Resources Identification Security-Regolith Explorer) to the asteroid 101955 Bennu, which is expected to arrive there in August 2018. The aim of the mission is to sample the regolith and bring the sample back to the Earth in order to conduct research on origin of the Solar System, the life's beginning and also determination of resources.

JAXA space mission Hayabusa2 will arrive at C-type asteroid 162173 Ryugu in June-July 2018. The aim of this mission is to study the origin and evolution of the Solar System as well as materials for life by analyzing samples acquired from a primordial celestial body such as a C-type asteroid (http://global.jaxa.jp, 2018).

Additionally, two NASA missions Lucy and Psyche have been recently approved. Lucy will study the Trojans and is expected to revolutionize our knowledge of the planetary origin and the formation of the Solar System. The Psyche mission will explore a unique metal-rich asteroid, which will help us understand the formation of iron cores of planets (https://www.nasa.gov, 2018).

In 2010 Barack Obama proposed a crew-mission to an asteroid ca. 2025, which would aim at the testing feasibility of mining metallic resources and fuel from asteroids. If successful, such mission can serve as a forerunner for man-mission to Mars. Such mission would also advance our abilities in terms of changing orbit of potentially hazardous asteroids (Lang, 2011).

Sanchez and McInnes (2011) created a map of extraterrestrial resources which is designed to show a mass of resources close to our planet in function of energy needed for resources extraction. The map allows estimating changes of velocity necessary for catching an asteroid or launching from it resources to the Earth as a function of the object's size.

Furthermore, Asterank – a catalogue of the value of the Solar System has recently arisen (www.asterank.com, 2015). The catalogue splits all the objects in the Solar System into four groups (kosmonauta.net, 2012), based on factors such as:

- the highest profit,
- the highest value,
- the highest profit to cost ratio,
- accessibility.

There are theoretical values calculated by Ian Webster, who used scientific databases (www.asterank.com, 2018). An example large asteroid in the Solar System, such as 253 Mathilde shows high value (estimated for 100 billion $) but reaching it is difficult. Small asteroids instead, especially NEAs, offer better profit to cost ratio or accessibility. In the category of the best profit to cost ratio, the asteroid 2000 BM_{19} seems to be the most interesting. After launching raw materials out of this asteroid to the Earth, the profit generated could be even 7 billion $, assuming prices as for the year 2012. The most accessible asteroid appears to be 2009 WY_7, which belongs to NEAs and will make an approach to the Earth eleven times between 2032 and 2066. A supplement to the catalogue, Asterank 3D, displays the details of asteroids' orbits, and their positions in relation to orbits of planets in our Solar System (http://www.asterank.com, 2015). As compared to Sanchez and McInnes (2011), the Asterank catalogue is a step forward to obtain a map of resources in the Solar System. Most important, Asterank took into consideration not only the energy that is demanded for exploitation of the resources from space but also the profit from mining these resources. However, prices of resources vary depending on many factors, one of which is resource accessibility and demand on a market. Considering these facts, a value of resources from asteroid may fluctuate.

The book *Asteroid. Prospective Energy and Material Resources* was published in 2013 under edition of Viorel Badescu (2013). The book presents the basic information about asteroids and plans of future crew-mission to NEAs, thoughts about machine's work in low-gravity conditions, the way of their power supplying, as well as schemas of robots for extraterrestrial mining. It also addresses a point of asteroid capturing, trajectory (deflection) of an asteroid changing, creation of artificial gravity on an asteroid, colonization of asteroids, and usage of asteroids for building and launches spaceship. Generally, this book deals with different technical and economic aspects but the geological aspect of asteroid prospecting was beyond the scope of this book.

2. THE INCREASE OF COMMERCIAL IMPORTANCE OF EXTRATERRESTRIAL RESOURCES

Currently, we can observe increasing social interest in prospection and mining of extraterrestrial resources. Especially, many sessions at conferences are dedicated to this aspect (e.g. Off Earth Mining Forum, University of New South Wales, Australia).

The new companies such as Deep Space Industries, Planetary Resources, and Moon Express, which are set up for asteroid mining, are a proof that exploitation of resources in space is a serious and approachable task. In their activity, they included not only mining of the space resources but also fuel production on the orbit or spare parts to satellites or space vehicles constructions.

Cognitive aspects raise also a question of the property rights on space resources. Prof. Piotr Wolański, the president of Space and Satellite Research Committee of Polish Academy of Science, expects that the extraterrestrial resources may be the matter of dispute in the future, similar to today's disputes around the terrains exposed after continental glaciers melted on Antarctica or Arctic (Rybicka, 2007).

Asteroids are rich in strategically important materials e.g., iron, nickel or water. Low-gravity conditions make these materials easy to be mined from the surface of Near Earth Asteroids. This will be advantageous for in case resources are required directly in space. However, increased availability and supply of these materials may result in demand increase. In such case transport to our planet will need to be considered. One solution for transporting the materials could be utilizing mass-driver – a device which can excavate the pieces of asteroids and eject them to space in the opposite direction to the planned movement direction according to the principle of conservation of momentum, propelling the asteroid like a rocket.

NASA invented the RASSOR rover (Fig. 2) with a goal to mine extraterrestrial resources (RASSOR – Regolith Advanced Surface System Operations Robot). Production of water and fuel from lunar dust will allow saving a lot of money. According to NASA, the RASSOR could extract both the resources and lunar dust regolith with an aim of production of fuel (http://nt.interia.pl, 2015).

NASA experts have developed the strategy to deflect the resources-rich asteroids to lunar orbit. They anticipate they will manage with an object 7 m in diameter with a mass of 500 tones. Manipulation of an asteroid will be done by a probe launched by the Atlas rocket. The intent is to catch an asteroid in a container with a diameter of 10–15 meters, connect it by a rope with the probe and haul in the direction of the Moon (http://www.rp.pl, 2015).

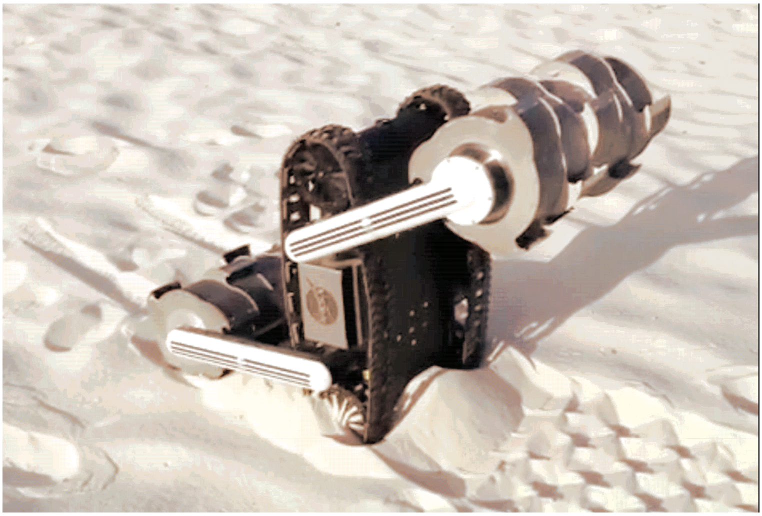

Fig. 2. NASA RASSOR rover designed for regolith exploration (www.nasa.gov, 2015)

Deep Space Industries (DSI) aims at mining the extraterrestrial resources and producing fuel on the orbit, spare pieces to satellites and space vehicles. DSI invented 3D laser printer, which can work in weightlessness (MicroGravity Foundry) and produce nickel components with density and strength higher than of components produced on the Earth. From this point, it is only small step towards construction of mining machines on asteroids (http://pierwszymilion.forbes.pl, 2015).

Eric Anderson, the cofounder of Planetary Resources, expounds that an asteroid with a diameter of 30 – 40 meters may contain more than 370 tons of platinum (http://tech.money.pl, 2015), which equals to more than 5 years of commercial sales of this raw material. Platinum from one asteroid can be acquired with a cost of 300 $/oz and this cost will be gradually decreasing with the development of new technologies (http://tech.money.pl, 2015). Current price of platinum oscillates around 900 $/oz (http://www.kitco.com/market, 2018).

Planetary Resources has developed out a few steps plan. The first stage is an identification of small Solar System bodies based on size, structure and resources, which they comprise. To achieve this goal the company plans to put a telescope on terrestrial orbit in order to estimate profitability of mining of particular asteroids. After identifying an asteroid with precious minerals, it may be captured by a dedicated spaceship. The last stage would be the transportation of asteroids to manufactures, where mineral processing would take place (http://tech.money.pl, 2015). Another possibility is asteroid deflection i.e., change of its orbit into a preferred course. Planetary Resources and

Deep Space Industries both work in collaboration with NASA with a goal to assess how their technology can be modified in order to participate in asteroids deflection (http://tech.money.pl, 2015).

Deep Space Industries makes one step further. This company announces chances to place a factory on the orbit. Extraction of resources and their processing in space will cut down transportation costs of resources from the Earth to the orbit. A factor that currently inhibits space exploration the most is high transport cost (http://tech.money.pl, 2015).

Extraction and processing of resources in space would allow limiting costs of extraterrestrial infrastructure development, and in consequence, would amplify space research. David Grump, vice-president of Deep Space Industries, estimates current transportation cost of one tone of any resources to the orbit to be about 17 million $. According to his statements, if the company was able to extract the resources from an asteroid with a cost lower than the cost of their transportation from the Earth by the year 2022, the whole space mining market would arise (http://tech.money.pl, 2015).

Even when NASA points out that the main goal of the program is a development of technology to allow the future human mission to Mars, the elaborated results allow also for identification of potential hazards which asteroids pose for our planet. The possibility of catching these bodies and placing them on the orbit before they hit the Earth will be a huge innovation (http://tech.money.pl, 2015).

Space mining will be focused on elements necessary for technology advancing. It is estimated that the demand for dysprosium will increase by ca. 2600% and for neodymium ca. 700% in next years. According to Peter Diamandis, the co-founder of Planetary Resources, terrestrial resources are insufficient for such a demand, solution for this may be space mining (http://www.rp.pl, 2015).

In 2015, Deep Space Industries has planned to launch small probes (Fireflies with a mass of 25 kg), the main goal of which was meant to be an identification of asteroid rich in resources. In 2016, the launch of 32-kg probe Dragonflies should start (Fig. 3) which would be able to conduct asteroid sampling and deliver samples back to the Earth. The third stage is hauling the chosen asteroid to lunar orbit, extraction of precious metals and delivering them to lunar bases, space stations or terrestrial factories (http://www.rp.pl, 2015).

Experts from Deep Space Industries estimated that an asteroid with a diameter of 50 m may provide water, that can be extracted and used in space for production of rocket fuel. Water comprises 5% mass of asteroid and has a value of about 65 billion US dollars. Iron, nickel and other metals compose another 10% mass of the asteroid and assuming that these metals can be mined, their values was estimated for 130 billion of $ (in 2015). Scientists from Deep Space Industries presume that even if the future prices of resources will decrease significantly (by several times) a 50 m large asteroid would still be worthy of several dozen of million $, while cost of equipment needed to reach it and cost of mining machines, which allow extraction in space will be much lower (http://www.nettg.pl, 2015).

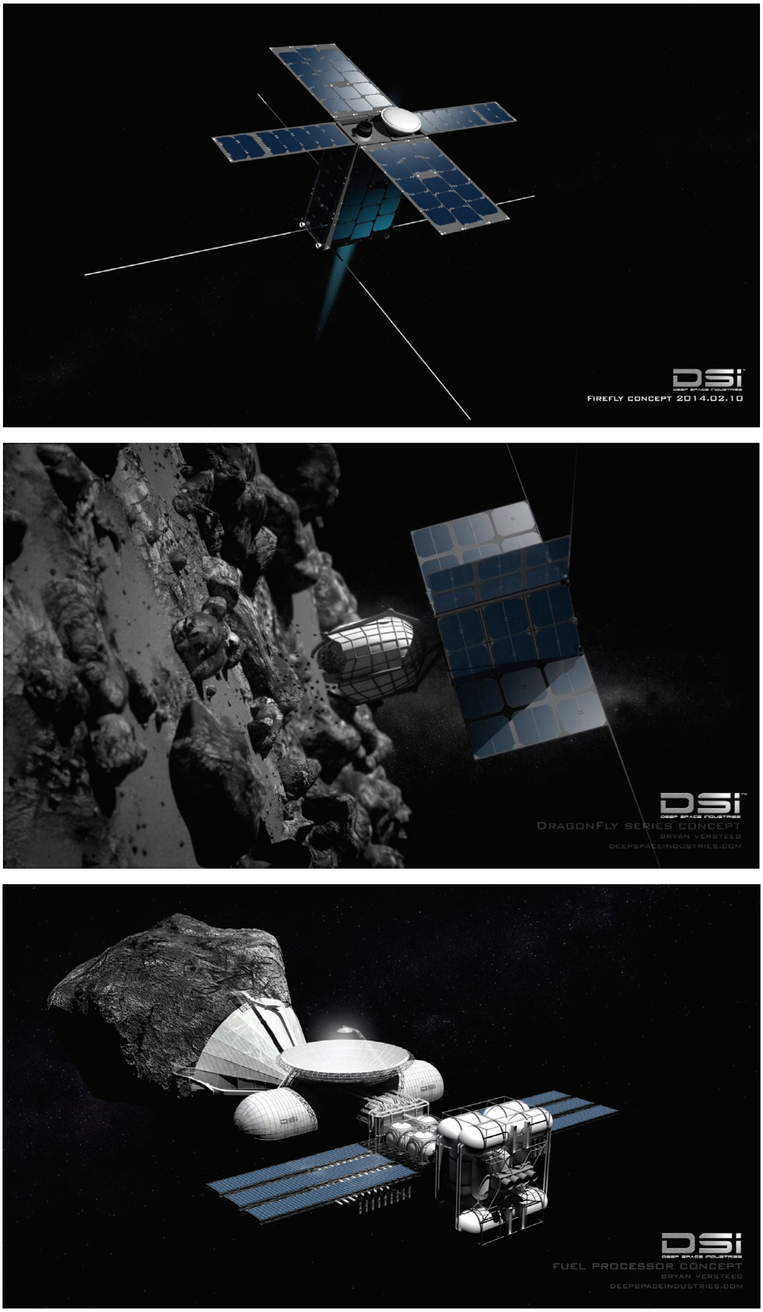

Fig. 3. Industrial robots for the prospection (top figure), sampling (middle), extraction and mineral processing of extraterrestrial resources (bottom) designed by Deep Space Industries (Bryan Versteeg/Deep Space Industries from http://deepspaceindustries.com, 2015)

Establishing the companies like Deep Space Industries or Planetary Resources shows that we deal with combination of advanced mining knowledge with the knowledge how to deflect the course of small Solar System body and development of methods to reach Mars (http://mining.com, 2015).

As for the beginning of 2013, no international policy existed that would regulate property rights to space resources (http://www.nettg.pl, 2015). This situation changed in November 2015, along with *US Commercial Space Launch Competitiveness Act*. This act about mining of the extraterrestrial resources postulates that every material, which any US citizen or any American company would find on asteroids or Moon would belong to a finder and can be used in any way. This act gives up with the conception that space is a common wealth of all Earth's citizens and, according to American legislation, grants discoverers and investors a right for private exploration of space resources (http://kopalniawiedzy.pl, 2016). This breaking-through act is an important regulation, especially having taken into account that most companies working on extraterrestrial mining are based in the US.

3. RESEARCH ON METALS IN CHONDRITES AND IMPLICATION FOR AN UNDERSTANDING OF RESOURCES

The research concerning on the metal content in ordinary chondrites has been carried out since '60 of XX century (Fouche and Smales, 1967; Ahrens, 1970; Chou and Cohen, 1972; Rambaldi, 1977; Rambalidi et al., 1978; Kallemeyn et al., 1989; Wolf and Lipschutz, 1998; Horan et al., 2003; Fischer-Gödde et al., 2010). The aim of these studies was, however, completely different than the goal of this paper. Metallic minerals in ordinary chondrites have never been viewed as metallic resources. Based on the metal content in different mineral phases and their volatility, the former authors concluded about the processes associated to origin of parent bodies of ordinary chondrites (Dodd, 1976; Morgan et al., 1985; Kong and Ebihara, 1997), and also later processes transforming their structure, physical properties and chemical and mineralogical composition (Linger et al., 1987; Friedrich, 2006; Tagle and Berlin, 2008). These works will be a reference point and could give an estimate of expected metal abundances in meteorites and in their parent bodies.

During literature review, author did not manage to find any references about a geological understanding of resources of ordinary chondrite parent bodies. As for author knowledge, there was no data interpretation done previously on metal abundances in ordinary chondrites in this way. It is likely that such work has been undertaken by private companies but the results have not been published yet (in order to keep them confidential for internal use of companies).

The closest approach to geological aspects of metallic resources of ordinary chondrite parent bodies is the work of Blair (2000), who emphasizes that LL chondrites are a source of precious metals. Blair (2000) presents mean abundance of elements such as Ge, Au, Re, Ru, Rh, Pd, Os, Ir, Pt in LL chondrites based on the work of Kargel (1996). Since parent bodies of ordinary chondrites are undifferentiated objects and assuming the amount of platinum in parent bodies of ordinary chondrites being equal to Pt content in ordinary chondrites Blair (2000) performed a theoretical calculation of the content of those elements in asteroids which are parent bodies of them. Blair (2000) assumes that those asteroids are spheres 10, 20, 50, 100, 200, 500 and 1000 m in diameter. Adopting the price of Pt as for 2000 he estimated the value of asteroids with before mentioned sizes. Identification of mineral phases in which precious metals are concentrated was beyond the scope of paper by Blair (2000).

4. SUMMARY

Ordinary chondrite parent bodies are asteroids orbiting in the asteroid belt or as the Near Earth Asteroids. These objects are rich in Fe, Ni, Co and precious metals. Metallic resources extracted from ordinary chondrite parent bodies may be used in space because utilization of resources in-situ facilitates space colonization and exploration. Alternatively, the resources may be delivered to Earth and support Earth's economy.

Planned space missions, such as OSIRIS-REx, will advance our knowledge on asteroids and give to companies dealing with extraterrestrial resources hints about the design of metallic resources extraction. Along with developing technical aspects of extraterrestrial mining, understanding of the geological aspects of metallic resources has to be improved.

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REFERENCES

AHRENS L.H., 1970, *The composition of stony meteorites (VII) observations on fractionation between the L and H chondrites*, Earth and Planetary Science Letters, 9, 345–347.

BADESCU V. (ed.) 2013, *Asteroids. Prospective Energy and Material Resources,* Springer, 689 p.

BLAIR B.R., 2000, *The Role of Near-Earth Asteroids in Long-Term Platinum Supply. Talk presented during Second Space Resources Roundtable*, Colorado School of Mines, 8–10.11.2000, Boulder, CO, USA, http://www.nss.org/settlement/asteroids/RoleOfNearEarthAsteroidsInLongTermPlatinumSupply.pdf

CHOU Ch.L., COHEN A.J., 1972, *Gallium and germanium in the metal and silicates of L- and LL-chondrites*, Geochimica et Cosmochimica Acta, 37, 315–327.

CLARK B.E., HAPKE B., PIETERS C., BRITT D., 2002, *Asteroid Space Weathering and Regolith Evolution*, [In:] W.F. Bottke, Jr., A. Cellino, P. Paolicchi, R.P. Binzel, *Asteroids III*, University of Arizona Press, Tucson, pp. 585–599.

CRAIG J.R., VAUGHAN D.J., SKINNER B.J., 2011, *Earth resources and the environment*, 4th ed., Person Education, 508 p.

DODD R.T., 1976, *Iron-silicate fractionation within ordinary chondrite groups*, Earth and Planetary Science Letters, 28, 479–484.

FISCHER-GÖDDE M., BECKER H., WOMBACHER F., 2010, *Rhodium, gold and other highly siderophile element abundances in chondritic meteorites*, Geochimica et Cosmochimica Acta, 74, 356–379.

FOUCHE K.F., SMALES A.A., 1967, *The distribution of trace elements in chondritic meteorites. 2. Antimony, arsenic, gold, palladium and rhenium*, Chemical Geology, 2, 105–134.

FRIEDRICH J.M., 2006, *Limit on the scale of impact-related metal/silicate segregation on L chondrite parent(s)*, Geochemical Journal, 40, 501–512.

FRIEDRICH J.M., RUZICKA A., RIVERS M.L., EBEL D.S., THOSTENSON J.O., RUDOLPH R.A., 2013, *Metal veins in Keronuvé (H6 S1) chondrite: Evidence for pre- or syn-metamorphic shear deformation*, Geochimica et Cosmochimica Acta, 116, 71–83.

HUTCHISON R., 2006, *Meteorites. A Petrologic, Chemical and Isotopic Synthesis*, Cambrigde Univeristy Press, Cambrigde.

HORAN M.F., WALKER R.J., MORGAN J.W., GROSSMAN J.N., RUBIN A.E., 2003, *Highly siderophile elements in chondrites*, Chemical Geology, 196, 5–20.

HSU J., 2009, *New Rocket Fuel Mixes Ice and Metal*, http://space.com (5.05.2010).

KALLEMEYN G.W., RUBIN A.E., WANG D., WASSON J.T., 1989, *Ordinary chondrites: bulk compositions, classification, lithophile-element fractionations, and composition-petrographic type relationships*, Geochimica et Cosmochimica Acta, 53, 2747–2767.

KARGEL J.S., 1994, *Metalliferous asteroids as potential sources of precious metals*, Journal of Geophysical Research, 99, 2114–2129.

KARGEL J.S., 1996, *Market Value of Asteroidal Precious Metals in an Age of Diminishing Terrestrial Resources*, Engineering, Construction, and Operations in Space, 5, 821–829.

KONG P., EBIHARA M., 1997, *The origin and nebular history of the metal phase of ordinary chondrites*, Geochimica et Cosmochimica Acta, 61, 2317–2329.

KRZESIŃSKA A.M., 2017, *Contribution of early impact events to metal-silicate separation, thermal annealing, and volatile redistribution: Evidence in the Pułtusk H chondrite*, Meteoritics and Planetary Science, 52 (11), 2305–2317.

LANG K.R., 2011, The Cambridge Guide to the Solar System, Second ed., Cambridge University Press, Cambridge.

LEWIS J.S., 1997, *Mining the sky: Untold Riches from the Asteroids, Comets, and Planets*, Addison-Wesley Publishing Company, 274 p.

LEWIS J.S., MATTHEWS M.S., GUERRIERI M.L., 1993, *Resources of Near Earth Space*, University of Arizona Press.

LINGNER D.W., HUSTON T.J., HUTSON M., LIPSCHUTZ M.E., 1987, *Chemical studies of H chondrites. I: Mobile trace elements and gas retention ages*, Geochimica et Cosmochimica Acta, 51, 727–739.

ŁUSZCZEK K., 2011, *Poszukiwania nowych zasobów surowców w Układzie Słonecznym*. Prace Naukowe Instytutu Górnictwa Politechniki Wrocławskiej, Studia i Materiały 40, 85–94.

MCKAY M.F., MCKAY D.S., DUKE M.B., 1992, *Space resources*, U.S. Government Printing Office, Washington.

MCSWEEN H.Y, HUSS G.R., 2010, *Cosmochemistry*, Cambrigde Univeristy Press, Cambrigde.

MICHEL P., 2014, *Formation and Physical Properties of Asteroids*, Elements, 10, 19–24.

MORGAN J.W., JANSSENS M.J., TAKAHASHI H., HERTOGEN J., ANDERS E., 1985, *H-chondrite: Trace element clues to their origin*, Geochimica et Cosmochimica Acta, 49, 247–259.

MOSKOWITZ C., 2010, *"Wet" Asteroid Could Be a Space Gas Station*, http://space.com (10.05.2010).
PRADO M., 2009, *Permanent*. Chapter 1.6. *Mining and Processing an Asteroid*, www.permanent.com/a-mining.htm
PRZYLIBSKI T.A., 2015, *Pozaziemskie górnictwo*, Meteoryt, 3, 3–10.
RAMBALDI E.R., 1977, *Trace element content of metals from H- and LL-group chondrites*, Earth and Planetary Science Letters, 36, 347–358.
RAMBALDI E.R., CENDALES M., THACKER R., 1978, *Trace element distribution between magnetic and non-magnetic portions of ordinary chondrites*, Earth and Planetary Science Letters, 40, 175–186.
RYBICKA U., 2007, *50 lat temu rozpoczęła się era kosmiczna*, PAP – Nauka w Polsce, http://www.eduskrypt.pl/index.php?infoserw=1&view=9650 (02.10.2007).
SANCHEZ J.P., MCINNES C., 2011, *An Asteroid Resource Map for Near-Earth Space*, Journal of Spacecraft and Rockets, 48 (1), 153–165.
SONTER M.J., 1998, *The technical and economic feasibility of mining the Near-Earth Asteroids*. 49 IAF Congress, 28.09–2.10.1998, Melbourne, Australia.
SONTER M.J., 2006, *Asteroid Mining: Key to Space Economy*, http://space.com (10.05.2010).
SULLIVAN R.J., THOMAS P.C., MURCHIE S.L., ROBINSON N.S., 2002, *Asteroid Geology from Galileo and NEAR Shoemaker Data*, [In:] W.F. Bottke, Jr., A. Cellino, P. Paolicchi, R.P. Binzel (Eds.), *Asteroids III*, University of Arizona Press, Tucson, 331–350.
TAGLE R., BERLIN J., 2008, *A database of chondrite analyses including platinum group elements, Ni, Co, Au and Cr: Implication for the identification of chondritic projectiles*, Meteoritics and Planetary Science, 43 (3), 541–559.
TOMKINS A.G., WEINBERG R.F., SHEAFER B.F., LANGENDAM A., 2013, *Disequilibrium melting and melt migration driven by impacts: Implications for rapid planetesimal core formation*, Geochimica et Cosmochimica Acta, 100, 41–59.
TSUCHIYAMA A., 2014, *Asteroid Itokawa – A source of ordinary chondrites and a laboratory for surface processes*, Elements, 10, 45–50.
WOLF S.F., LIPSCHUTZ M.E., 1998, *Chemical studies of H chondrites 9: Volatile trace element composition and petrographic classification of equilibrated H chondrites*, Meteoritics and Planetary Science, 33, 303–312.
ZUBRIN R., WAGNER R., 1997, *Czas Marsa*, Prószyński i Spółka, Warszawa.
http://www.asterank.com (8.01.2015; 16.04.2018).
http://deepspaceindustries.com (8.01.2015).
http://global.jaxa.jp (10.04.2018).
http://www.kitco.com/market (15.06.2018).
http://kopalniawiedzy.pl (9.03.2015).
http://kosmonauta.net (17.06.2012).
http://mining.com (15.12.2015).
http://www.nettg.pl (8.01.2015).
www.nasa.gov (8.01.2015; 16.04.2018).
http://nt.interia.pl (8.01.2015).
http://pierwszymilion.forbes.pl (8.01.2015).
http://www.rp.pl (8.01.2015).
http://tech.money.pl (8.01.2015).