PTMSS

Planetary & Terrestrial Mining Sciences Symposium

&

Space Resources Roundtable

Hosted by the Canadian Minerals and Metals Plan Secretariat

The Canadian Minerals and Metals Plan | Le Plan canadien pour les minéraux et les métaux

Financé par Ressources naturelles Canada | Funded by Natural Resources Canada

Canada

Virtual 2021

Asteroids/Simulants

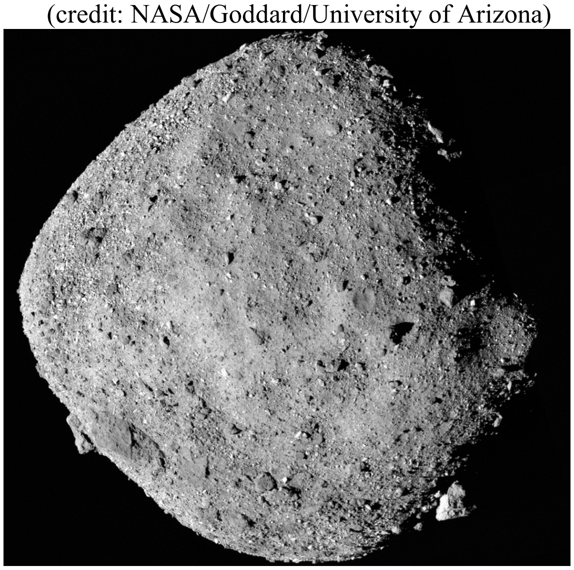
ASTEROID BENNU: THE FIRST AND BEST TARGET FOR AN ASTEROID MINING DEMONSTRATION MISSION. C. S. Dickinson[1], A. T. Polit[2] and D. S. Lauretta[3], [1]MDA 4700 Airport Rd., Brampton, Ontario, L6S 4J3, Canada, cameron.dickinson@mdacorporation.com. [2]University of Arizona, 1415 N 6th Ave, Tucson, AZ 85705, United States, anjani@orex.lpl.arizona.edu. [3]University of Arizona, 1415 N 6th Ave, Tucson, AZ 85705, United States, lauretta@orex.lpl.arizona.edu.

Introduction: With NASA's decision to return to the Moon by the mid-2020s, the need for supporting cis-lunar infrastructure (between Earth and the Moon) will move to the forefront — specifically, the need for low-cost, high-volume consumables, such as water and rocket propellant. Such infrastructure would unlock not only cis-lunar opportunities, but lower the cost of delivering essential supplies to Earth and lunar orbits, as well as facilitate future lunar and Martian surface opportunities. The opportunity to service cis-lunar space is not limited to governments, as private industries, such as SpaceX, have publically indicated their plans to provide interplanetary services.

Several recent developments indicate that such resources could be derived from near-Earth asteroids (NEAs) in an economically viable manner. These include existing asteroid missions, to upcoming resource-extraction demonstration missions. With over 20,000 NEAs available to be mined, the potential for growth could quickly exceed that of Earth's easily accessible minerals.

Initial efforts will almost certainly focus on the extraction of water, as it can be used for human consumption, rocket propellant, energy storage (fuel cells), radiation shielding, and more exotic applications like space agriculture.

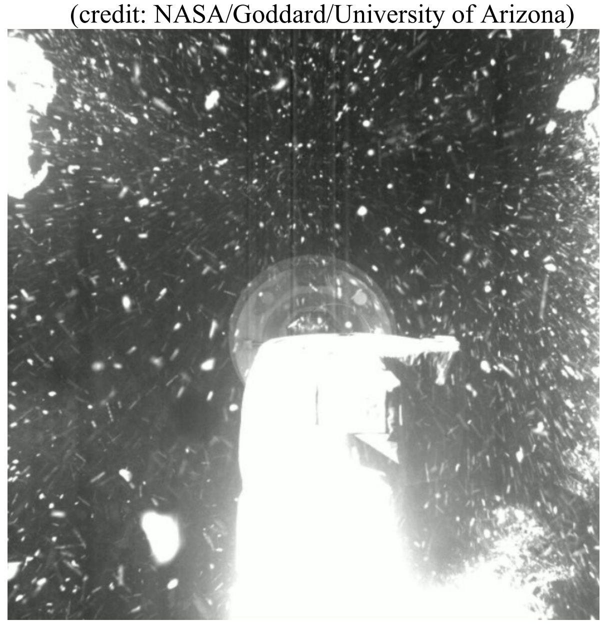
Figure 1. Asteroid Bennu, as observed by the OSIRIS-REx spacecraft
(credit: NASA/Goddard/University of Arizona)



The OSIRIS-REx Mission: NASA's Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx) spacecraft was launched in September of 2016 and rendezvoused with its target, the carbonaceous NEA (101955) Bennu (Figure 1), on December 3, 2018. A comprehensive survey campaign was undertaken for the following 22 months, culminating in the successful acquisition of ~400 g of sample [1]. Of the discoveries made by the mission, at least three are relevant to the extraction of space resources:

Water. The presence of hydrated minerals on Bennu was predicted [2] and later detected via spectrometers aboard the OSIRIS-REx spacecraft [3]. The presence of hydrated minerals will be confirmed when the sample is returned to Earth, but their spectral signatures were observed in the sampling area prior to acquisition [1]. Meteorites with similar spectroscopic features have been found to have compositions of hydrated minerals (silicates) of >55%.

Figure 2. The sample acquisition mechanism making contact with the surface of Bennu
(credit: NASA/Goddard/University of Arizona)



Regolith Physical Properties. Ultimately, the composition of the sample will be determined by Earth-based methods; however, what is known from the sample acquisition operation is that the surface of Bennu is composed of loose regolith that "responded like compliant, viscous fluid" to contact from the spacecraft [1]. The head of the sampling mechanism reached a depth of (more than) 50 cm [1] (owing to a combination of spacecraft inertia and the nitrogen-driven sample acquisition mechanism, shown in Figure 2), indicating little or no resistance. Spectral data show that much of Bennu has a similar composition [3], making materials easily extractable.

Surface Topography. Bennu was surveyed using a scanning laser altimeter [4], which globally surveyed the surface to resolutions of better than 10 cm. Bennu has a wide range of boulder sizes ranging from tens of meters down to less than a meter [5], and thus a variety of extraction strategies could be formulated and tested as part of a demonstration mission.

Economics of Bennu: When determining whether to collect water on asteroids or the Moon, plentiful hydrated asteroids with a large size are favorably accessible in terms of delta-v. It has been estimated, primarily on the basis of mass and spectral properties, that Bennu contains ~$670M worth of retrievable minerals, with an estimated profit of ~$185M [6].

Conclusion: Bennu offers an attractive target for a demonstration mission and/or technology demonstration for water extraction from a carbonaceous asteroid. The asteroid has a favorable delta-v, it has been well characterized, and the returned sample will provide a wealth of information on the mineral composition and physical properties. The fact that the surface of the asteroid has been extremely well surveyed provides an excellent reference for the development of a mineral extraction concept of operations, as well as the follow-on technological development.

Acknowledgments: We are grateful to the entire OSIRIS-REx Team for making the encounter with Bennu possible. OLA and funding for the Canadian authors were provided by the Canadian Space Agency. This material is based upon work supported by NASA under Contract NNM10AA11C issued through the New Frontiers Program.

References:

[1] D. S. Lauretta et al. (2021) *52nd Lunar and Planetary Science Conference,* #2097

[2] B. E. Clark et al. (2011) *Icarus, 216*, 462–475.

[3] V. E. Hamilton et al. (2019) *Nature Astronomy, 3*, 332–340.

[4] M. G. Daly (2020) *Science Advances*, Vol. 6, no. 41, eabd3649.

[5] D. N. DellaGiustina et al. (2019) *Nature Astronomy, 3*, 341-351.

[6] http://www.asterank.com/

An Asteroid Regolith Database for ISRU. Amara L. Graps [1,2,3] , Karlis Slumba[2], and Marta Vaivode[2], [1]amara@balticsinspace.eu [2]karlis.slumba@gmail.com [1]Baltics in Space, A. Caka iela, 96-31, Riga, Latvia LV-1011; [2]University of Latvia, Jelgavas 3, Riga, Latvia LV-1004; [3]Planetary Science Institute, 1700 East Fort Lowell, Suite 106, Tucson, Arizona, USA.

Abstract: We have developed the first database of asteroid regolith properties: "ARD": one hundred asteroids so far, to aid space resource utilisation workers. The physical parameters: grain density, grain size, near surface bulk density and porosity are provided of a collection of the asteroids. The strength of our method is that it combines three types of information: 1) spacecraft-based, in-situ data, 2) laboratory-based meteorite samples, and 3) telescopic, remote data, such as from polarization-- the joint usage which amplifies the success and the probability of gaining new information. The database is also uniquely robust, due to its large number of crosschecks for the database's regolith parameters. Theoretical and laboratory studies provide additional crosschecks. See Figure 1.

Introduction: In-space resource utilization will provide an extension of our SpaceShip Earth to include space infrastructures for, and of, our robots that are orbiting the Earth and traveling beyond. With such space resources, we can service, recycle, or build anew, without the limitations of carrying the resources from the Earth. Telecommunications, Earth observations, planetary research, extraterrestrial life explorations, are just a few examples, which can be implemented cheaper and more efficiently using resources in space.

Despite the asteroid mining industry's shift to smaller companies since 2018, it is no longer a question of 'if' but of 'when'. The endeavor of the in-space utilization of asteroid resources have several attractive features over their lunar and Martian counterparts, in that their low gravity, large quantities, and tiny sizes lead to different legal regimes [1] for their utilization. The continuing spacecraft miniaturization and drop in the cost of rocket launches support a variety of low-cost asteroid mission philosophies (pg. 56-60 of [2]). The asteroid mining community continues to build successes [3] and there is an active, engaged, international community [2, 4, 5].

Database Strategy: The information detail for each asteroid is uneven. The most detailed-information is acquired from 1) spacecraft measurements –least number of asteroids, 2) laboratory meteorite measurements and 3) regolith simulations. The fewest details – and largest asteroid numbers, are acquired from surveys: radar and optical light curve. If a parameter is deemed necessary for a calculation for a regolith physical property, it is included. This strategy is the reason for the approximately 40 information fields available for each asteroid. We expect that the database format will be more sophisticated, as we grow the database and learn what is needed in the community. In the interest of open, scientific reproducibility and verification, the data format for ARD version 1.0 is a spreadsheet that includes the calculation, for example to derive solid (rock) density from radar albedo. Other notes about the database strategy:

- Most of the ARD information is manually extracted from tables in published research journal articles (and less from official archives). As the asteroid research progress moves quickly, scientific conference attendance with tracking the research through public social media platforms is mandatory.

- With asteroid regolith-related measurements dependent on other factors, we've adopted a strategy of including multiple rows, for each asteroid, to aid future processing and filtering and for determining errors. We provide an identical reference spreadsheet to look up that data source in the [row,column] cell.

- We track the spatial scales where the bulk density and porosity [6] of an asteroid is related to the average density and porosity of its constituent rocks, which is further distinguished from the average density of the mineral assemblages within the rocks.

Regolith Porosity: Due to planned and executed surface operations on the asteroid and the electrostatic risks to equipment, asteroid regolith *porosity* is one of the most important parameters that must be known as precisely as possible. The Hayabusa2 and OSIRIS-Rex sample return space missions are pointing to, not only a very loose, porous regolith, but to *regolith layers of different porosities*, as envisioned in Fig. 5 of [7]. See, e.g. [8] of the regolith before and after the sampling operation on asteroid Bennu. A new view of dust charging since 2016 is the particles' charge buildup in the regolith's porous cavities. The Patched Charge Model [9] shifts our view from the regolith surface to electrostatic charging *within* microstructures inside the regolith, where a negative charge buildup results in strong repulsive forces between the regolith particles, to cause their lofting or mobilization.

Meteorites as Proxies: Measurements of meteorite densities, porosities, thermal inertia, thermal conductivity, heat capacity, and light scattering can act as 'bridge' of ground truth between remote asteroid thermal, radar, and polarimetry measurements, thermal heat conduction models, and first guesses of the multilayered [7] (or not) regolith physical properties. Meteorites acquired in fresh falls and in measurement conditions near vacuum pressures and at low temperatures are particularly helpful. The ARD v. 1 uses recent compilations by [10, 11] to bridge remote thermal inertia measurements [12,13], radar measurements [14, 15, 16], polarimetry measurements [17]. Empirical, laboratory-based thermal conductivity measurements that can indicate particle sizes [18] are rough, compared to particle sizes derived from theoretical heat conduction modeling [19]. Functional forms to fill in gaps in the data are used whenever possible. For example, upon rearranging the thermal inertia equation, $\rho = \Gamma^2 / (kc_p)$ and keeping track of scales (ρ_{rock}, ρ_{grain}, φ_{rock}, etc., for example: $\rho_{rock} = (1-\varphi_{rock})\rho_{grain}$ we can proceed with the sizes derived from the empirical fits in [20], and cross-check theoretical particle sizes from [19]. See the TREX website for the asteroid regolith database: https://trex.psi.edu/

Methodology: The derived products for the asteroid regolith properties are currently following this flowchart.

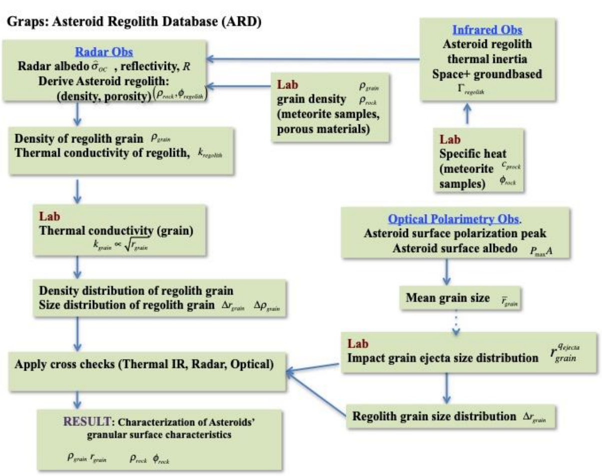


Figure 1: Flowchart of the methodology of the Asteroid Regolith Database.

References: **[1]** The Hague International Space Resources Governance Working Group 'Building Blocks' https://isn.page.link/3UqH **[2]** Graps, A. + 43 co-authors: ASIME 2018 White Paper @ ArXiV https://isn.page.link/bNWN **[3]** Graps, A. Ten Asteroid Mining Milestones 2018-2019 https://bit.ly/33w35yr, 2019-2020 https://bit.ly/2RqYkAP **[4]** Graps, A. + 30 Co-Authors. ASIME 2016 White Paper @ ArXiV https://ishort.ink/LS1Fk/LS1F **[5]** Lewicki, C.; Graps, A.; Elvis, M.; Metzger, P.; Rivkin, A. (2020) Decadal Survey White Paper. https://ishort.ink/uY6T **[6]** Carry, B. (2012). *PSS*, 73, 98-118. **[7]** Vernazza P.; Delbo M.; King P.L.; Izawa M.R.M.; Olofsson J.; Lamy P.; Cipriani F., et al., (2012), *Icar*, 221, 1162–1172. **[8]** NASA Press Release 15 April 2021. "NASA's OSIRIS-REx Leaves its Mark on Asteroid Bennu" https://ishort.ink/iu4i **[9]** Wang, X.; Schwan, J.; Hsu, H.-W; Grün, E. and Horányi, M. (2016), *Geophys. Res. Lett.*, 43, 6103–6110. **[10]** Flynn, G.; Consolmagno, G.; Brown, P.; Macke, R. (2018), *Geochem*, 78, 269–298. **[11]** Soini, A.J.; Kukkonen, I.T.; Kohout, T. and Luttinen, A. (2020). *Meteorit Planet Sci*, 55: 402-425. [**12**] Delbo, M., Mueller, M., Emery, etal (2015). In P. Michel, F. E. DeMeo, & W. F. Botke (Eds.), *Asteroids IV* (pp. 107-128). UA Press. [**13**] Harris, A.W. and Drube, L. (2016) *ApJ* 832, 127. **[14]** Magri, C.; Consolmagno, G.J.; Ostro, S.J., Benner, L.A.M. and Beeney, B.R. (2001), *Meteorit Planet Sci*, 36: 1697-1709. **[15]** Magri, C.; Nolan, M.C.; Ostro, S. J.; Giorgini, J. D. (2007). *Icar*, 186, 126-151. **[16]** Neese, C., Benner, L.A.M., and Ostro, S.J., Eds., Asteroid Radar V18.0. NASA Planetary Data System, 2012. **[17]** Lupishko, D., Ed., Asteroid Polarimetric Database V1.0. NASA Planetary Data System, 2019. **[18]** Krause, M.; Blum, J.; Skorov, Yu.V.; Trieloff, M. (2011). *Icar*, 214, 286-296. **[19]** Gundlach, B. and Blum, J. (2013). *Icar*, 223, 479-492. **[20]** Kiuchi, M.; Nakamura, A.M. (2014). *Icar*, 239, 291-293.

Acknowledgements: The ARD has been supported, in part, by several funding organizations: (Slumba, Vaivode): the University of Latvia Institute of Astronomy small research projects funding, and (Graps): the NASA Toolbox for Research and Exploration (TREX) project, which is a node of NASA's Solar System Exploration Research Virtual Institute 2016 (SSERVI16) Cooperative Agreement (NNH16ZDA001N).

SPACE RESOURCES IN CHONDRITIC ASTEROIDS: INSIGHTS FROM CHONDRITE METEORITES.

C. M. Gilmour[1] and C. D. K. Herd[2], [1]Centre for Research in Earth and Space Science, York University, Toronto, ON, Canada. E-mail: cgilmour@yorku.ca, [2]Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, AB, Canada.

Introduction: There is an abundance of precious resources contained within chondritic asteroids. Chondritic asteroids are thought to be the parent bodies of carbonaceous chondrites (carbonaceous 'C-type' asteroids) and ordinary chondrites (stony 'S-type' asteroids) [1]. Due to the aqueously altered nature of C-type asteroids, these bodies are rich in water and volatiles. In contrast, as ordinary chondrites contain Fe-Ni metal, their asteroid parent bodies are suitable for metal extraction. These three resources—water, volatiles, and metal—are essential to the future of space exploration. To assess the quantity of resources within chondritic asteroids, we have completed two comprehensive chondrite meteorite studies: 1) an evaluation of water abundances in pristine samples of the Tagish Lake carbonaceous chondrite via Thermogravimetric Analysis (TGA) [2] and 2) an investigation of Platinum Group Element (PGE) concentrations in ordinary chondrite metal with laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) [3]. Here, we summarize our findings to provide insight into the resources that can potentially be mined from chondritic asteroids.

Water: Water is considered the most precious resource as it is essential for life support and is also fundamental for transportation (i.e., rocket fuel and radiation shielding) [4,5]. C-type asteroids are good targets for water extraction. Specifically, water in C-type asteroids is structurally bound in hydrous minerals (i.e., phyllosilicates) in the form of hydroxyl (-OH); the most aqueously altered carbonaceous chondrites contain up to 85 vol.% phyllosilicates [6-8]. Based on carbonaceous chondrite investigations, the most altered carbonaceous asteroid compositions (i.e., CI, CM, and Tagish Lake-like) could potentially yield between 8 and 23 wt.% water (-OH) [2, 9-11]. TGA of the Tagish Lake carbonaceous chondrite has revealed two temperature regions where water is released upon heating: 1) <200°C and 2) 400 to 700°C (Fig. 1). Included in Fig. 1 is the derivative thermogravimetric (DTG) curve which corresponds to the peak temperatures at which the decomposition reaction of minerals and organics occur (refer to [2] for more information). At temperatures <200°C, adsorbed water is released (Fig. 1); however, this water is terrestrial in origin and therefore has no significance for space resource utilization.

The water that has the greatest economic significance is released between 400 and 700°C. Our TGA

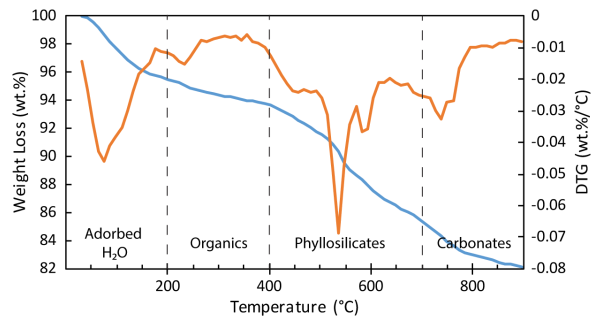


Fig. 1. TGA (blue line) and DTG (orange line) for one Tagish Lake specimen (TL11i). Adapted from [2].

results reveal that dehydroxylation of phyllosilicates occurs within this temperature range (Fig. 1); however other TGA studies of carbonaceous chondrites suggest phyllosilicate dehydroxylation occurs between 300 and 800°C [11,12]. Based on these investigations, heating the carbonaceous material up to 800°C is necessary for extraction of water (-OH).

It is important to note that dehydroxylation of hydroxide minerals has been reported to occur between 200 and 400°C [11,12]; however, the pristine samples of Tagish Lake do not contain hydroxides [2,13]. As hydroxides are believed to be terrestrial weathering products [14], the weight loss between 200 and 400°C is believed to be due to the decomposition of organics (see below), at least in the case of Tagish Lake [2].

Volatiles: C-type asteroids are also potentially rich sources of volatiles, including those essential for life (C, H, N, O, P, and S), as well as NH_3, CO_2, and hydrocarbons [4,5]. However, the amount of volatiles that could be extracted is not well defined. Due to the high abundance of carbon in C-type asteroids, heating the carbonaceous material can result in the autoreduction of magnetite (Fe_3O_4) to Fe-Ni metal [5,15]. It has been stated by [5] and [15] that the autoreduction process can produce ~40 to 45 wt.% of volatiles. However, carbonaceous chondrite TGA results suggest otherwise. Heating carbonaceous chondrites between 200 and 1000°C results in a total weight loss up to 22 wt.%, with the majority of weight loss occurring between 300 and 800°C [2,11,12] (Fig. 1). TGA of Murchison (CM2) insoluble organic matter (IOM) reveals decomposition between 200 and 420°C [2]. Therefore, any weight loss between 200 and ~400°C corresponds to the breakdown of organic material. The amount of weight lost due to the release of organic matter in

Tagish Lake corresponds to ~2 wt.% [2].

It is also important to consider that decomposition of Fe-sulphide minerals can occur between 200 and 700°C [e.g., 11]; however, weight loss related to the release of sulphur is expected to be minor given the relatively low abundance of sulphides in carbonaceous chondrites [6-8]. Furthermore, decarbonation of carbonates releasing CO_2 occurs between 700 and 900°C constituting a weight loss of ~2 to 4 wt.% (Fig. 1, [2], [11]) although [12] suggest that carbonates begin to break down at 600°C.

Based on the observations from TGA investigations [2,11,12], only ~6 wt.% of volatiles from C-type asteroids is expected. However, it is important to note that the TGA analytical conditions are likely not sufficient to properly induce autoreduction. Therefore, a thorough investigation of the autoreduction process in carbonaceous chondrites is needed to confirm the amount of volatiles that could be extracted from C-type asteroids.

Metal: Fe-Ni metal is a fundamental resource for construction material in space [5] and the processing of Fe-Ni metal can provide valuable byproducts such as PGEs. Metallic asteroids are a potentially rich source for metal resources; however, the material processing of these bodies will be difficult given that iron meteorites typically have a crushing strength of 3600 bars [5,16]. Instead, we should consider mining the metal from stony asteroids. Ordinary chondrites have material crushing strengths between 60 and 2600 bars [16], and therefore their parent bodies should be more cost effective and energy efficient to process than metallic asteroids. Furthermore, since ordinary chondrite parent bodies are undifferentiated, they are expected to contain PGE concentrations greater than what is found in the richest deposits on Earth (e.g., Bushveld Complex).

Our study involved the analysis of the main metal phases (kamacite and taenite) in 14 ordinary chondrites via LA-ICP-MS in order to determine the concentrations of PGEs in the metal of chondritic asteroids [3]. Despite the differences in metal abundances among the ordinary chondrite groups (H > L > LL), we found that average PGE concentrations in ordinary chondrite metal are similar among the different groups, within uncertainty (Table 1). Additionally, we have discovered that the variability of PGEs decreases with increasing petrologic type (degree of secondary heating) due to intragrain homogenization during metamorphism [3].

To put into perspective the value of PGEs in ordinary chondrite metal, we can compare these concentrations to terrestrial PGE concentrations in Southern Africa where PGE production is greatest. PGE head grades for 6E PGEs (Pt + Pd + Rh + Ru + Ir + Au) from all South African mines (2010 to 2015) averaged between 3.17 and 3.75 g/t (ppm) [17]. Taking into consideration the metal abundance in ordinary chondrites defined by [18] and the fractions of taenite and kamacite in each ordinary chondrite group from [3], we have found that the average 6E PGE grades in ordinary chondrite metal are 3.56 ppm, 3.26 ppm, and 1.45 ppm for H, L, and LL chondrites, respectively. Therefore, it is apparent that the PGE concentrations in H and L ordinary chondrite metal is comparable—not greater as originally predicted—to the richest terrestrial deposits.

	H		L		LL	
ppm	**Km**	**Tn**	**Km**	**Tn***	**Km**	**Tn**
Ru	3.3 (0.9)	n.d.	2.9 (1.4)	8.3 [0.9]	n.d.	12.1 (3.9)
Rh	0.95 (0.26)	n.d.	0.93 (0.44)	2.0 [0.2]	n.d.	3.3 (1.2)
Pd	2.7 (0.4)	n.d.	2.8 (0.6)	13 [0.8]	n.d.	15 (1.9)
Os	2.4 (0.7)	n.d.	2.2 (1.4)	6.0 [0.4]	n.d.	6.9 (3.0)
Ir	2.2 (0.7)	n.d.	2.0 (1.4)	4.8 [0.3]	n.d.	6.6 (2.7)
Pt	4.3 (1.2)	n.d.	4.0 (2.3)	9.4 [0.9]	n.d.	15.1 (5.9)
Au	1.0 (0.1)	n.d.	1.1 (0.4)	3.9 [0.5]	n.d.	4.5 (1.0)

Table 1. Average PGE + Au concentrations (ppm) in ordinary chondrite kamacite (Km) and taenite (Tn) from [3]. SD = parenthesis and SE = square brackets. *From a single measurement (BhT-1). n.d. = no data.

References: [1] Gaffey M. J. et al. (1993) *Meteoritics, 28,* 161-187. [2] Gilmour C. M. et al. (2019) *MAPS, 54,* 1951-1972. [3] Gilmour C. M. and Herd C. D. K. (2020) *MAPS,* https://doi.org/10.1111/maps.13436. [4] Nichols C. R. (1993) In *Resources of Near-Earth Space,* pp. 543-568. [5] Lewis J. S. (2015) *Asteroid Mining 101,* 183 pp. [6] Howard K. T. et al. (2009) *GCA, 73,* 4576-4589. [7] Howard K. T. et al. (2011) *GCA, 75,* 2735-2751. [8] King A. J. et al. (2015) *GCA, 165*, 148-160. [9] Alexander C. M. O'D. et al. (2012) *Science, 337,* 721-723. [10] Alexander C. M. O'D. et al. (2013) *GCA, 123,* 244-260. [11] Garenne A. et al. (2014) *GCA, 137,* 93-112. [12] King A. J. et al. (2015) *EPS, 67,* 12 pp. [13] Blinova A. I. et al. (2014) *MAPS, 49,* 473-502. [14] Bland P. A. et al. (2006) In *Meteorites and the early solar system II,* pp. 853-867. [14] Lewis J. S. and Hutson M. L. (1993) In *Resources of Near-Earth Space,* pp. 523-542. [16] Lewis J. S. (1992) In *Space Resources Materials,* NASA-SP-509, pp. 59-78. [17] Thormann L. et al. (2017) *Minerals, 7,* 224. [18] Gattacceca J. et al. (2014) *MAPS, 49,* 652-676.

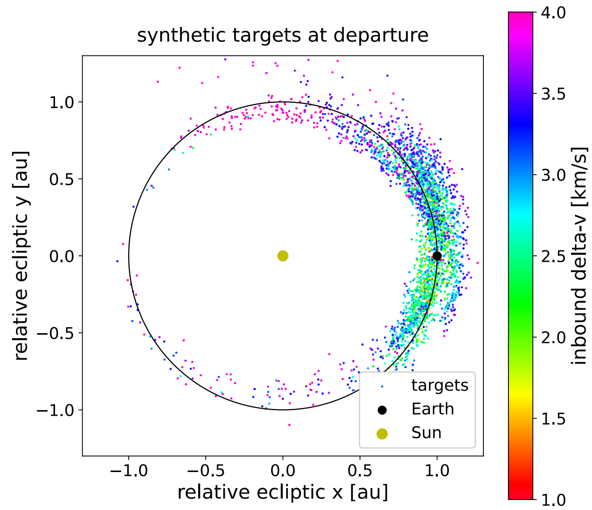
OPTIMISED LOW-THRUST ROUND-TRIP TRAJECTORIES TO THOUSANDS OF ULTRA-LOW DELTA-V ISRU TARGETS.

R. Jedicke[1], P. Hermosin[2], J. Sercel[3], S. Centuori[2], M. Sciarra[2], Á. Cano[2] and C. Peterson[3], [1]Institute for Astronomy, University of Hawai`i, 2680 Woodlawn Drive, Honolulu, HI 96822, USA (jedicke@hawaii.edu), [2]Deimos elecnor group, Ronda de Poniente 19, 28760 Tres Cantos, Madrid, Spain (pablo.hermosin@deimos-space.com, simone.centuori@deimos-space.com, marcello.sciarra@deimos-space.com, alvaro.canot@deimos-space.com) , [3]TransAstra Corporation, 11404 Camaloa Avenue, Lake View Terrace, CA, 91342, USA (sercel@transastracorp.com, craig@transastracorp.com).

Introduction: In recent years asteroids have become increasingly interesting due to a heightened awareness of their scientific, commercial, and hazardous properties. Scientifically, they continue to unveil precious details about the solar system's origin and ongoing evolution due to 1) technological advances that have improved their discovery and characterization rates by orders of magnitude and 2) the many spacecraft missions that have visited a growing list of these diverse objects. They are commercially valued at trillions of dollars once the technology has evolved to the point where mining is economically viable. Finally, the danger of asteroid impacts on Earth has become fully appreciated only in the past half century and dedicated efforts to identify the most dangerous km-scale asteroids have already reduced the risk of an unknown impact by more than 90%. Even so, the residual risk remains significant and justifies continued investment in identifying smaller, but still hazardous, objects.

The Problem: Irrespective of whether the motivation is scientific investigation, deflection for planetary defense, or the profit margin of an asteroid mining company, there is a growing need for rapid cost evaluation of asteroid mission scenarios that requires novel optimisation tools and techniques. The identification of the most interesting or profitable targets may require screening trajectories for thousands of objects over long time scales of up to a hundred years to identify optimal candidates. Potentially millions of trajectories may need to be calculated to provide a consistent comparison, especially for round-trip sample return or mining missions. The problem's complexity is reduced with the use of high-thrust, pseudo-impulsive chemical propulsion but explodes in the case of more realistic continuous, low-thrust missions that e.g. use less fuel and are therefore more profitable.

The Solution: We describe our method to solve the problem based on combining a fast but low fidelity optimiser (SESWIC; an in-house tool developed by Deimos) with a high-fidelity trajectory design [1] to provide quick and robust trajectories. We applied our algorithm to optimise round-trip low-thrust missions to a catalogue of more than 4,000 synthetic but realistic ultra-low Δv near Earth objects [2] over the course of the next 100 years. In this case, the customer, TransAstra Corporation, plans to extract water from the asteroids, use some of the extracted water as fuel for the return trip to the Earth-Moon system, and then sell the remaining water to customers in high Earth orbit or e.g. at NASA's Lunar Gateway [3]. Our tools allow the company to maximize their profit margin by minimizing the use of fuel/water over multiple launch, rendezvous time spans, and return opportunities to each target over the course of the century.



References: [1] Ranieri C. L. and Ocampo C. A. (2006) JGCD, 29, 1360. [2] Jedicke R. et al. (2018) P&SS, 159, 28. [3] Sercel, J.C. (2016) NIAC Phase I Final Report.

ASTEROID PROVIDED IN-SITU SUPPLIES (APIS ™) MISSION ARCHITECTURE AND PROGRESS

Joel C. Sercel[1] , Philip Wahl, and Craig Peterson, [1]TransAstronautica Corporation, 10276 Foothill Blvd. Lake View Terrace, CA 91342, sercel@transastracorp.com, philip@transastracorp.com, craig@transastracorp.com

Introduction: In 2015 the first Phase 1 NIAC proposal for the Apis™ architecture quoted the NASA Advisory Council Committee on Human Exploration and Operations, "The mismatch between NASA's aspirations for human spaceflight and its budget for human spaceflight is the most serious problem facing the Agency". This is still the key problem facing NASA. NASA has not yet embraced the innovations needed to enable its great mission ambitions. Apis™ (Asteroid provided in-situ supplies) is a breakthrough mission and flight system architecture that solves this problem by providing all major consumable materials including rocket propellant, radiation shielding, consumable water, and oxygen, thereby collapsing the cost of NASA human exploration of deep space and later the industrialization and human settlement beyond Earth. NIAC was created to solve exactly this type of major strategic problem.

The Patent Pending Apis™ spacecraft concept and mission architecture with Optical Mining™ was invented by the PI in 2013 and advanced to TRL 3-4. Current work has been funded for a ground demonstration model of the Mini Bee™ (The initial version of Apis™ for validation and demonstration in LEO) which will advance key technologies to TRL 4-5.

Key Apis™ innovations and inventions include:

- **Optical Mining™ to extract resources from asteroids using highly concentrated sunlight**. An Optical Mining™ Test Bed (OMTB) has been developed and is currently targeting various test materials including heat resistant bricks and CI type asteroid simulants. Simulants have been developed replicating a range of

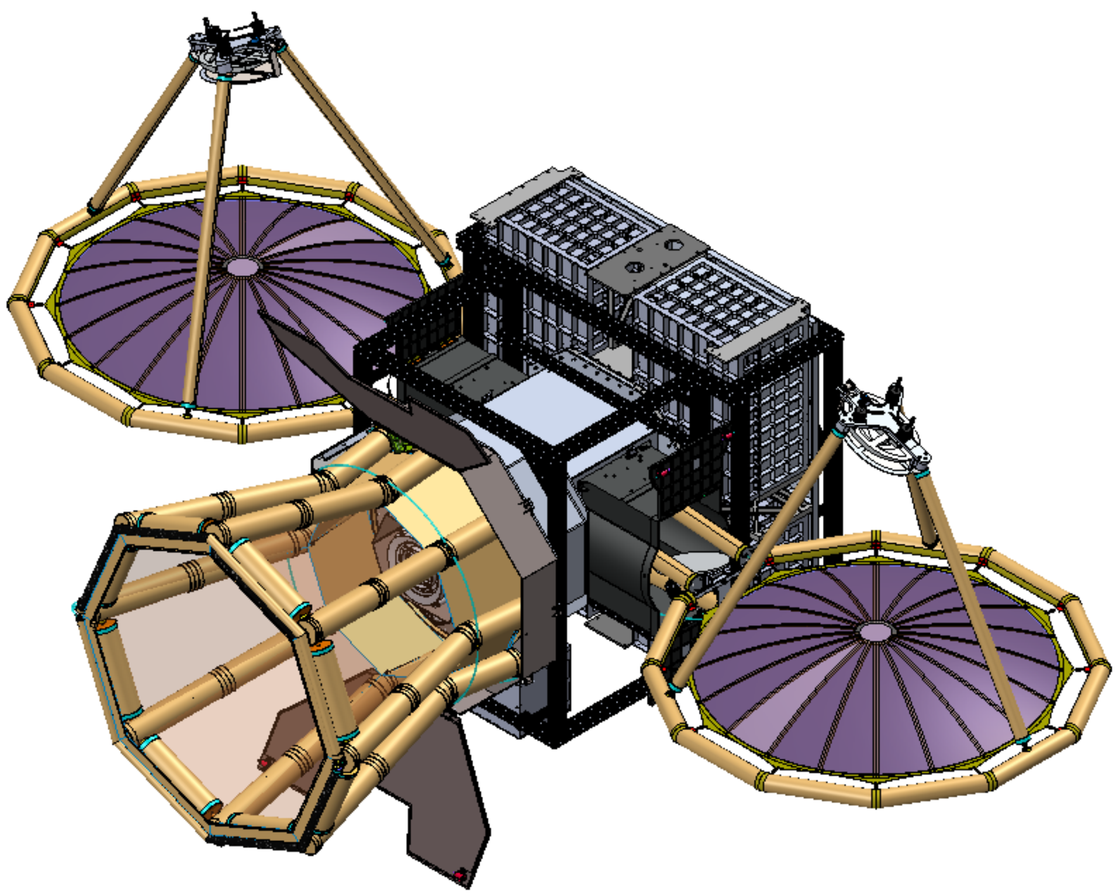


Figure 1= Mini Bee™ Spacecraft

solid form asteroid and regolith types including representatives of both CM and CI materials.

- **The Omnivore™ thruster** is a breakthrough technology which uses asteroid-extracted volatile liquids such as unprocessed water as a propellant.

- **The Apis™ spacecraft architecture** based on Optical Mining, thin film solar reflectors, asteroid capture systems, and water based propulsion is core to the Mini Bee technology demonstrator, the Honey Bee 100 MT ice return system, Worker Bee™ Orbital Transfer Vehicles (OTVs), and the Queen Bee multi thousand ton ice return system.

- **The Apis™ commercial transportation network design** which includes a combination of cargo vehicles and chemically propelled spacecraft for crewed transport with all consumables supplied by Optical Mining™.

Mission and business analysis funded by a combination of private, NIAC, Office of Emerging Space, and NASA SBIR sources has been peer reviewed and published, clearly showing that a Public Private Partnership (PPP) can be applied with the Apis™ architecture promising ~$300B in savings for a NASA HEOMD program over 20 years with human missions to the Moon, asteroids, and Mars. This savings enables affordable cis-lunar tourism and commercial infrastructure for space industrialization and settlement.

CURRENT RESEARCH IN SOIL SEALS, WATER STABILITY, AND SIMULANT BEHAVIOR. Diane L. Linne[1], Fransua Thomas[1], John E. Gruener[2], Douglas L. Rickman[3], and Beau M. Compton[1], [1]NASA Glenn Research Center, 21000 Brookpark Road, Cleveland, OH 44135 (diane.l.linne@nasa.gov, fransua.thomas-1@nasa.gov, beau.m.compton@nasa.gov), [2]NASA Johnson Space Center, 2101 NASA Parkway, Houston, TX 77058 (john.e.gruener@nasa.gov), [3]Jacobs Space Exploration Group, 620 Discovery Drive Northwest, Huntsville, AL 35806 (douglas.l.rickman@nasa.gov)

Introduction: The past few years have seen an exciting increase in visibility for the use of in-situ resources to achieve sustainability at the Moon and Mars. This visibility and inclusion in the mission architectures has led to an explosion in the research and development of mining and processing of regolith at the Moon. However, there are still many fundamental issues regarding digging, transporting, and processing of lunar and Mars regolith that may slow the progress by multiple teams who need to undertand these issues before proceeding with hardware development. The objective of this project is to utilize the same team of soil and thermal experts and unique facilities to allow for efficient and fast generation of fundamental data and dissemination of critical results to the larger community. The capability gaps being addressed include how to dig up hard, frozen resources, transport to the processing site, lifting/depositing into a hopper or reactor, and extracting the water, all without losing the primary product to the environment.

Soil Seals: Much attention has been focused on the challenges with regolith inlet/outlet valves that must seal in process gases after being repeatedly exposed to abrasive regolith and dust particles. One possible solution that has been proposed is to design the inlet hopper or duct such that the bulk of regolith provides sufficient sealing of the reactor. Tests are planned to parametrically measure the maximum delta-pressure that can be maintained across a column of soil before 'blow-out' occurs. Variables to be examined include column height and width, simulant type, and compaction.

Soil Transport: The water that has been identified in the permanently shadowed regions of the Moon's poles has spurred significant research for feasible and optimal methods of mining and extracting it for propellants and life support. Prospecting missions are planned to better determine the spatial and vertical distribution of the water. The current prevailing theory is that the top centimeters of regolith are desiccated due to impact gardening and long-term exposure to hard vacuum [1]. Several test campaigns conducted in the NASA Glenn Research Center vertical dirty thermal vacuum chamber has measured significant drying of the top centimeters of water-doped simulant in an 11-inch liquid-nitrogen chilled simulant bin after several days exposure to vacuum levels on the order of 1×10^{-6} Torr [2]. In addition, icy simulant brought to the surface in those tests on the flutes of an auger and brushed into a sample container experienced 50 percent or greater water loss after only a few minutes of exposure. All of this raises questions of how much water will be lost during excavation and transport of the raw resource before it can be processed in a controlled manner. Tests are being designed to parametrically measure the amount of water lost in various size transport bins as a function of transport time, agitation, etc.

Highland Simulant Behavior: During the past two decades of research in excavation and regolith processing it has been well-recognized that using appropriate simulants is critical to designing hardware and conducting tests that produce relevant results. The plans to explore near the polar regions has resulted in taking a new look at the mineral and chemical makeup of lunar highlands regolith and developing simulants that more closely mimic those properties. Recent tests with the new Greenspar highland simulant in a carbothermal reactor has highlighted the significant differences in melt viscosity which can have significant consequences on processing methods that have to-date been mostly tested with mare simulants. A brief discussion on the key composition differences that are driving this viscosity change will be discussed and demonstrated.

References:

[1] Cannon, K.M. and Britt, D.T. (2020) *Icarus 347*, 113778. [2] Kleinhenz, J.E., et al. (2018) Earth and Space 454.

THERMAL PROPERTIES OF LUNAR MATERIAL IN PERMANENTLY SHADOWED REGIONS

R. J. Macke[1], C. P. Opeil[2], D. T. Britt[3], and G. J. Consolmagno[1]; [1]Vatican Observatory, V-00120 Vatican City-State, rmacke@specola.va; [2]Boston College Dept of Physics, 140 Commonwealth Ave, Chestnut Hill MA 02467, opeil@bc.edu; [3]University of Central Florida Dept of Physics/ Center for Lunar and Asteroid Surface Science, 4111 Libra Dr., Orlando FL 32816, britt@physics.ucf.edu.

Introduction: Thermal emission data from the Lunar Reconnaissance Orbiter Diviner Lunar Radiometer Experiment indicate that permanently shadowed regions of the Lunar surface, such as those near crater rims in the extreme polar regions, may have temperatures as low as roughly 20 K [1,2]. Given that these regions are also candidates for reservoirs of permanently frozen water, understanding the thermal properties of Lunar materials at comparably low temperatures may be vital for Lunar resource utilization.

To date, thermal properties measurements on Lunar materials and analog Lunar materials has been mostly limited to the temperature range 100-350 K. Woods-Robinson et al. [3] have developed semiempirical theoretical models for Lunar thermal properties at lower temperatures, but there have not been any systematic studies of actual Lunar materials at temperatures below about 100 K.

We have measured heat capacity, thermal conductivity, the coefficient of thermal expansion, thermal inertia, and thermal diffusivity for six Lunar meteorites from Northwest Africa [NWA]. These include Lunar feldspathic breccias (NWA 5000, NWA 10678, NWA 11421, and NWA 11474), a gabbro (NWA 6950) and a troctolite (NWA 8687). Heat capacity data are supplemented by a further nine specimens collected from African desert regions.

Measurement: All thermal measurements were conducted using a Quantum Design Physical Properties Measurement System (QD-PPMS) at Boston College. The measurement procedure is described in detail in [4]. Meteorite specimens are cut to parallelapipeds a few mm per side (exact size varies depending on the particular measurement). The device uses liquid He coolant to precisely control the temperature over a range 5 - 300(+) K, enabling the measurement of thermal properties as a function of temperature.

Thermal diffusivity and thermal inertia were calculated from heat capacity, thermal conductivity, and meteorite bulk density. Thermal diffusivity is $D_T = \kappa\, \rho^{-1}\, c_p^{-1}$, where κ is the thermal conductivity, c_p is specific heat capacity, and ρ is bulk denity. Thermal inertia (Γ) is calculated $\Gamma = (\rho\, c_p\, \kappa)^{1/2}$.

Results and Discussion: Our results are summarized in Figures 1-5. Heat capacity is a strong function of temperature over the range 5 – 300 K. Thermal conductivity is a weak function of temperature above about 100 K, but in the range 5 - 100 K temperature becomes very important. This is consistent with what we have observed for other meteorites [4,5].

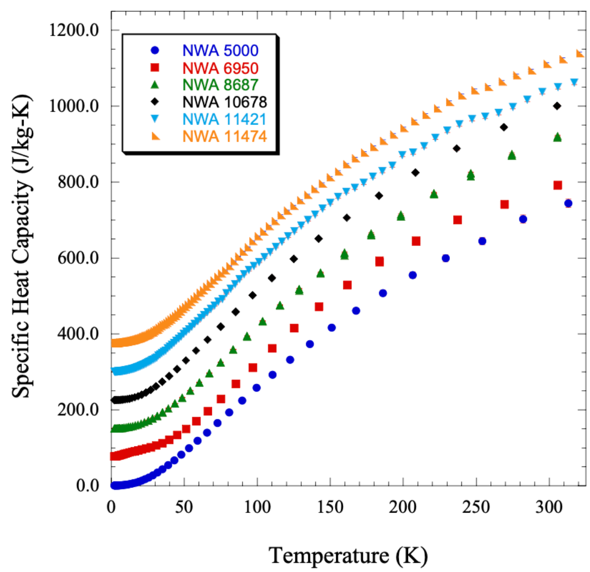


Figure 1: Heat Capacity as a function of temperature for the six specimens in this study. Plots are offset vertically by intervals of 75 J kg^{-1} K^{-1} to distinguish each meteorite.

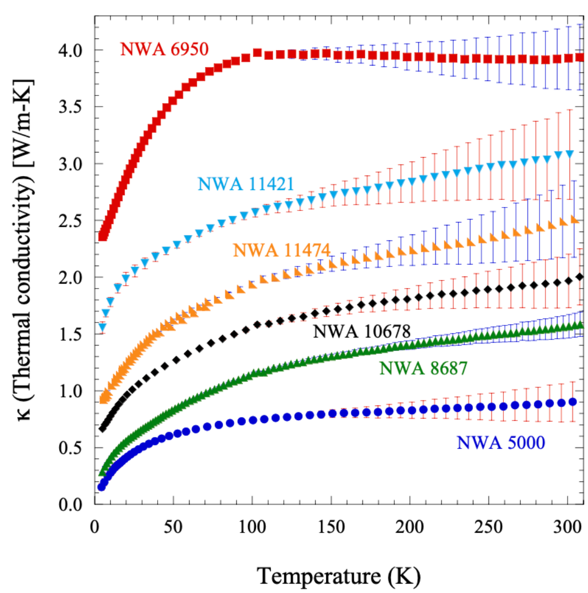


Figure 2: Thermal Conductivity as a function of temperature for the specimens in this study. Data are offset vertically by varying amounts to distinguish each meteorite. Note that κ varies lightly above 100 K but is a strong function of temperature below 100K.

In previous studies of CM2 carbonaceous chondrites, we observed a zone of negative thermal expansion centered at about 235 K, which we attribute to phyllosilicates [4]. Several of the lunar meteorites in this study also include a zone of negative thermal expansion centered at about 75-80 K. This negative thermal expansion (NTE) behavior in lunar samples differs from CM2, as it is caused by a different mineral component, most likely from the abundant lunar silicate mineralogy [6,7]. NTE in silicates has been observed by [8].

References: [1] Aye K.-M. et al. (2013) *LPSC XLIV* #3016. [2] Paige D. A., et al. (2010) *Science* 330, 479-482. [3] Woods-Robinson R. et al. (2019) *JGR Planets* 124, 1989-2011. [4] Opeil C. P. et al. (2020) *Meteoritics & Planet. Sci.* 55, E1-E20. [5] Opeil C. P. et al. (2012) *Meteoritics & Planet. Sci.47, 319-329.* [6] Lucey P. et al. (2006) *Rev. Mineral. & Geochem*. 60, 83-219. [7] Papike J. J. et al. (1998) "Lunar Samples" in *Planetary Materials*, chapter 5. [8] White G. K. (1973) *J. Phys. D: Appl. Phys.* 6, 2070-2078.

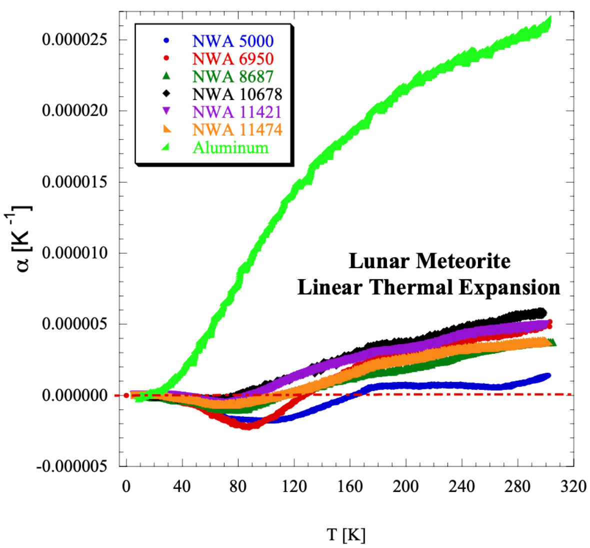


Figure 3: Coefficient of linear thermal expansion for the meteorites in this study. (Aluminum is included for comparison.) Note the range of negative thermal expansion for these specimens centered at about 80 K.

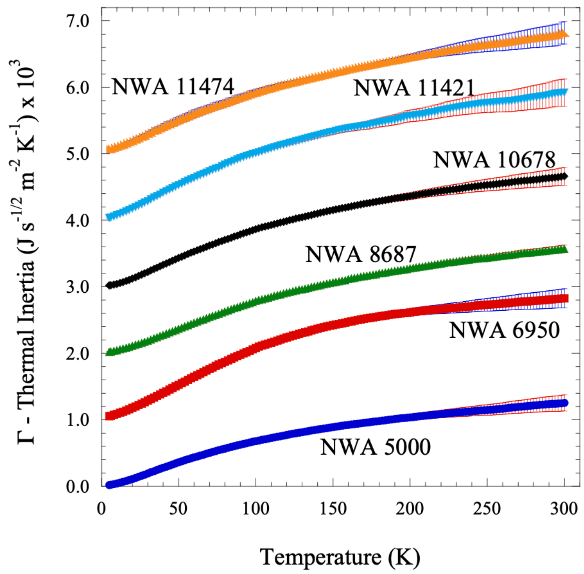


Figure 4: Thermal Inertia as a function of temperature for the specimens in this study. Data are offset vertically by intervals of 10^3 J $s^{-1/2}$ m^{-2} K^{-1} to distinguish the different meteorites.

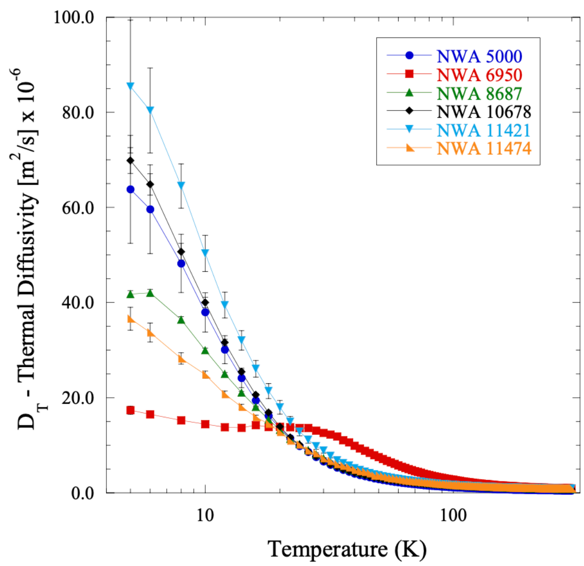


Figure 5: Thermal diffusivity as a function of temperature for the specimens in this study. Temperature is scaled logarithmically. Note the strong temperature dependence below 100K.