ENAA and SEM investigations of Carbonaceous Meteorites: Implications to the distribution of life and biospheres

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ABSTRACT

Epithermal Neutron Activation Analysis (ENAA) has provided data on the concentration of Rare Earth Elements (REE) and heat producing elements (HPEs: K, Th, U) in a variety of carbonaceous meteorites. Space missions and laboratory investigations have provided evidence for liquid water and a vast array of indigenous extraterrestrial organics and biomolecules in carbonaceous chondrites, interstellar dust particles, comets, moons and low density asteroids. SEM studies over the past few decades have provided evidence of indigenous microfossils in diverse groups of carbonaceous meteorites. The implications of these discoveries to the origin of life on Earth and distribution of water and biospheres throughout the Cosmos are discussed.

Key words: Epithermal Neutron Activation Analysis, REE, HPE’s, KREEP, microfossils, diatoms, low-density meteorites, Orgueil, comets, asteroids, origin of life, panspermia Polonnaruwa/Aralaganwila, Bennu, Itokawa, Ryugu.

ABBREVIATIONS

HPE’s; Heat-Producing Elements (140K, 232Th, 235U, 238U), REE; Rare Earth Elements, ENAA; Epithermal Neutron Activation Analysis, IBR-2; Pulsed Fast Reactor

INTRODUCTION

Recent discoveries of water and organics in comets, icy moons and low-density asteroids as well as evidence of abiogenic activity in ancient Achaean rocks combined with the recoveries of biomolecules and microfossils in carbonaceous meteorites are challenging widely accepted paradigms regarding the origin of life on Earth and the distribution of biospheres throughout the Cosmos. It has long been thought that life on Earth originated on Earth as a result of a long, slow, unproven process of abiogenesis – the abiotic formation of amino acids and other organics and biomolecules ultimately leading to the evolution of the first evolvable protocells in Earth’s primordial oceans. The long held hypothesis that the atmosphere and oceans of Earth formed by volcanic activity and degassing of the planetary interior is now being re-examined (Deming, 2002). Studies of H, O and N indicate the CI and CM carbonaceous chondrites formed not far beyond the orbit of Saturn (3-7 AU) and along with comets, asteroids and icy planetesimals may have been responsible for the delivery of surface water oceans and other of the volatiles of the terrestrial planets (Chyba, 1987; Alexander, 2017; Piani et al., 2020). Dating of Calcium-Aluminum-rich-Inclusions (CAI’s) in carbonaceous meteorites using 207Pb–206Pb radioisotopes indicates our Solar System formed 4.4682 billion years ago (Ga) (Bouvier and Wadhwa, 2010). Oxygen isotopes (δ18Osmow up to 9‰) in the 4.40 Gaddertral Zircons from the Jack Hills of Western Australia provides evidence of differentiation and the possibility of the formation of liquid water oceans by
delivery of volatiles via carbonaceous meteorites, comets, asteroids and icy planetesimals during the intense bombardment in the Hadean eon of early Earth (Wilde et al., 2001; Peck et al., 2001). The delivery of water and other volatiles to Earth by carbonaceous chondrites, comets and asteroids may not have been restricted to the Hadean epoch and may even continue to the present day.

The time of the appearance of life on Earth has frequently been revised to earlier and earlier dates. Awramik (1997) provided evidence from 3.5 Ga stromatolites of microfossils consistent in size and morphology with morphotypes of coccoidal and filamentous phototrophic cyanobacteria. Carbon isotope signatures of the 3.5 Ga rocks of the Warrawoona group, Western Australia ($\delta^{13}$C = $-34\%$ to $-36\%$) and the Swaziland super group, South Africa ($\delta^{13}$C = $-26\%$ to $-36\%$) provide clear evidence of protoautrophic microorganisms. Isotopically light biogenic carbon was detected in the $\geq$3.85 Ga Isua banded iron formation of Akilia Island, Western Greenland (Mojzsis et al., 1996). Bell et al. (2015) discovered ancient graphite grains completely encased in crackfree, undisturbed 4.1 Ga Jack Hills zircons (U-Pb dating 4.10 ± 0.01). Carbon isotope signatures ($\delta^{13}$C$_{PDB}$ = $-24 \pm 5\%$) of these grains are consistent with biological activity suggesting life and biospheres appeared almost simultaneously with surface water oceans on Earth. This leaves virtually no time for the long, slow process of chemical and pre-biological evolution required by the current hypothesis of the endogenous origin of life on Earth. These discoveries are supported by the lack of success in any of the laboratory experiments directed at simulating the putative processes of abiogenesis (Deamer, 2011). Recent sampling missions have revealed the existence of extraterrestrial water and organic matter on the S-type asteroid 25143 Itokawa (Chan et al., 2020) and the low-density C-type carbonaceous asteroid 101955 Bennu (Simon et al., 2020, Nuth et al., 2020). The Mascot Lander of the Hayabusa 2 spacecraft made in-situ thermal infrared observations of a dark boulder with characteristics of CI carbonaceous meteorites on the C asteroid 162173 Ryugu. However, Ryugu has turned out to be dramatically different from all known meteorites possessing an exceptionally low thermal conductivity, low density (0.8 - 1.29 g/cm$^3$), high porosity (possibly 41%-55%) and extremely low tensile strength (200-280 kPa) (Grott et al., 2019). These investigators further concluded that the boulder would be too frail to survive atmospheric entry “and would thus be absent in our meteorite collections.”

It would appear to be a remarkable coincidence that the reported density of the Ryugu boulder is not significantly different from the extremely low-density (0.6 - 1.2 g/cm$^3$) stones that fell in North Central Sri Lanka on Dec. 29, 2012. Theoretical calculations show fragile vesicular meteoroids such as the Polonnaruwa/Aralaganwila stones and the low density Ryugu boulders could survive transit through Earth’s atmosphere (Wi±wramasinghe et al., 2013a). The delivery of microbial life forms to Earth by carbonaceous meteorites, comets, low-density carbonaceous asteroids, similar to Ryugu, Bennu and other small-solar system bodies may be a continuing phenomenon (Hoyle and Wickramasinghe, 1982, 1985; Hoover, 2004, 2011). Recent studies of short-lived isotopes of uranium and thorium carbonaceous chondrites by Turner et al. (2021) revealed an excess of $^{234}$U (246 Ka) over $^{230}$U (4.5 Ga) and $^{232}$U (4.5 Ga) over $^{230}$Th (75.6 Ka). Hence, it is concluded that the fluid mobile U$^{6+}$ ion migrated within the past few hundred thousand years (much less than the cosmic ray exposure age) providing evidence that liquid water was recently present in the parent bodies of these meteorites. The heating during this time could have resulted from isolated events such as recent energetic asteroidal impact collisions or alternatively the liquid water could have been produced episodically by solar heating of the low-albedo, jet-black carbonaceous crust melting subcrustal ices during perihelion passage of the parent body comet. An extremely intriguing possibility is that the liquid water may have been resulted from radiogenic heating by the decay of long-lived neutron-rich radioisotopes of Heat Producing Elements HPE’s 40K (1.2 Ga); 232Th (14 Ga); 238U (4.5 Ga) in the parent body interior (Hoyle and Wickramasinghe, 1985). The HPE’s are highly incompatible elements - K is a volatile lithophile while U and Th are refractory lithophile elements and their crystal/melt partition coefficients are much less than unity. Their radioactivity contributes ~99% of the total radiogenic heat power of the Earth (Huang et al., 2013). This mechanism would allow liquid water to be continuously present on the interior of planets, moons or planetesimals over astronomical and geological time scales even in interstellar space far away from radiative heat from a nearby star or tidal heating by massive Jupiter like planets.

MATERIALS AND METHODS

Samples

Orgueil C11- MHNP6 - Fall (43° 53’N, 01° 23’E) 5/14/1864 Muse´um Nationale d’Histoire Naturelle de Paris (Courtesy Dr. Martine Rossignol-Strick). Low-density, fragile micro-regolith breccia composed of mineral grains and insoluble organic matter 1OM particulates cemented together by water soluble salts. Abundant microfossils detected.


Sutter’s Mill CM2 - SM65 - Fall(38° 48’36.7”N, 120° 54’58.7”W) 4/22/2012 collected by Philippe de Riemer(CourtesyMichael Farmer Meteorites).(Microfossils
Sri Lanka immediately

intriguing new information about the orth Central Sri Lanka; cal properties, oxygen isotopic
ich CO3.5
y (Brunfelt and Steinnes, 

yeva and

0.6 to 0.8 g/cm 

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ICP
S,

Federation
Institute fo
(PIN/RAS)
Rozanov
Samaranayake, sent a 10
them and
pathogenicity. Di
microbiological tests to evaluate possible
Research Institute
observed the
Fall
Polonnaruwa/Aralaganwila C Ung.

141
Collected by R
Polonnaruwa/Aralaganwila C Ung.

carbonaceous meteorites.

Hoover et al., 2020) and the
yielded i
fossilized remains of filame
high velocity asteroidal impacts
provide clear evidence the Polonnaruwa/Aralaganwila
composition,
basalts of the
near
meteorites.

roads and rooftops.

undisturbed sandy soil in well cultivated rice fields and on
recovered
Sri Lanka
the Ratkinda reservoir and the village of Girandurukotte,
extended from
large region of N
Earth asteroid
's in these stones as compared with other groups of
Other fragments
were examined
-7 min the
in a NE to SW trajectory
Low
KREEP terrain
un
any

is
these stones as compared with other groups of
carbonaceous meteorites.

Polonnaruwa/Aralaganwila C Ung. POL_RBH_141Fall. Collected by Richard B, Hoover 1/29/2013 @ Waypoint 141 (7° 52' 58.8" N, 81° 09' 16.2" E).

Polonnaruwa/Aralaganwila C Ung. POL_Banda_CuPIN2a Fall. (Courtesy Dr. Anil Samarmayake, Medical Research Institute, Colombo, Sri Lanka). Fragment of stone collected on Dec. 29, 2012 by farmer Tikiri Banda in his rice paddy field in Aralaganwila, Sri Lanka immediately after he observed the fall of this stone. It was sent to the Medical Research Institute in Colombo, Sri Lanka for chemical and microbiological tests to evaluate possible toxicity or pathogenicity. Diatoms were observed, embedded within them and the Director of the Institute Dr. Anil Samaranyake, sent a 10 g interior fragment of the Banda stone to RBH for Scanning Electron Microscopy studies at NASA/MSFC. Other fragments were examined by SEM at Cardiff University (NCW and Dr. Jamie Wallis). Studies were also carried out by RBH and Academician Alexei Yu. Rozanov and students at the Paleontological Institute (PIN/RAS) in Moscow and Astrobiology Laboratory, Joint Institute for Nuclear Research (JINR) in Dubna Russian Federation. Other fragments of this stone were studied by Triple Oxygen Isotope in Germany and Japan and prepared at PIN/RAS to polished thin sections for petrology and mineralogy analysis by transmission and polarized light optical microscopy, Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES); Fourier Transmission Spectroscopy (FTIR) and X-ray Diffraction (XRD) at Cardiff University.

POL_RBH_162 - (7° 52' 59.5" N; 81° 09' 15.7" E) Fall Interior fragment (0.5 g) of stone collected at 4:00 PM Jan. 29, 2013 in Aralaganwila, Sri Lanka at Garmin GPS Waypoint 162by RBH with Banda in rice paddy field. NWA 5515 - CK4-Find Algeria, Nov., 2007 - (Courtesy Dr. Paul Sipiera, Planetary Studies Foundation).

NWA 6136 - CO3- Find Morocco, 2008 - (Courtesy Dr. Paul Sipiera, Planetary Studies Foundation).

NWA 2086 - CV3 - Find (Purchase) Rissani, 2003 - (Courtesy Dr. Paul Sipiera, Planetary Studies Foundation).

NWA 4540CO3.5Find Erfoud, Morocco, 2006; (Courtesy Dr. Paul Sipiera, Planetary Studies Foundation).

Methods

Neutron activation analysis (NAA) was selected as the most appropriate technique for the determination of the relatively low abundance levels for trace elements in carbonaceous chondrites, and a method was devised to determine these elemental abundances simultaneously. Additional possibilities became apparent by the introduction of activation with epithermal neutrons (ENAA) (Morrison et al., 1970; Brunfelt and Steiness, 1971; Nakamura, 1974; Frontasyeva and Pavlov, 2005; Frontasyeva, 2011). This allows better determination of rare earth elements due to their large resonance integrals in the epithermal interval of neutron energies. The purpose of this study was to utilize ENAA to obtain precise data concerning the distribution and ratios of REE and HPE’s in representatives of major carbonaceous chondrite groups for comparison those of the low-density Polonnaruwa/Aralaganwila stones. The ENAA studies were carried out at the IBR-2M reactor at the Joint Institute of Nuclear Research in Dubna, Russian Federation. The analytical procedures and characteristics of the employed pneumatic system at the IBR-2M reactor are described in detail elsewhere (Frontasyeva and Pavlov, 2005; Frontasyeva, 2011).

Two types of irradiation were carried out. One is a short irradiation for 30 s to determine short-lived isotopes (Al, Ca, Cl, I, Mg, Mn, and V). After a decay-period of 5-7 min the irradiated samples were measured twice, first for 3-5 min and then for 10-15 min. A long irradiation of 4-5 days was used to analyze for long lived radionuclides. After irradiation the samples were re-packed and measured twice: first after 4-5 days for 40-50 min to determine As, Br, K, La, Na, Mo, Sm, U, and W and after 20 days for 2.5-3 hours to determine Ba, Ce, Co, Cr, Cs, Fe, Hf, Ni, Rb, Sb, Sc,
Figure 1: Rare Earth Elements, oxygen isotopes, shock fractured grains and fossils in the low-density Polonnaruwa/Aralaganwila (C-Ung.) and Orgueil (C1) meteorites. 

a. Polonnaruwa Rare Earth Element is plotted with data from Stannern eucrite and H-Al and VHK basalts of Apollo 14 breccia; b. Oxygen Isotopes plots show Polonnaruwa is far away from Terrestrial Fractionation Line but near the CV carbonaceous meteorites; c. SEM image shows K-rich SiO$_2$ glass, fractured ilmenite & olivine grains and the high pressure mineral Maskeynite indicative of a high velocity asteroidal impacts. d. SEM images of fossils diatoms *(Pinnularia segariana* Foged 1979) in Orgueil and f., g.Polonnaruwa fossils of the diatom *Aulacoseira ambigu* (Grunow) Simonsen 1979; e.astonishingly well-preserved hystrichosphaere and h. wrinkled acritarch. The extremely porous, low-density (0.8 g/cm$^3$) black Polonnaruwa stonei with complete fusion crust is shown in-situ in rice paddy field in Aralaganwila, Sri Lanka prior to recovery by RBH Jan. 29, 2013 (Hoover et al., 2013).

**Images Courtesy:** a. and c. Jamie Wallis and Anthony Oldroyd, Univ. Cardiff; b. Andreas Pack; Univ. Grotingen; d. M. Kapralov LRB/JINR; e-h. J. Wallis, NCW Univ. of Cardiff and e.-i. Richard B. Hoover, Univ. Buckingham, UK.
Table 1: Bulk Density (g/cm$^3$), Porosity (%) and ENAA measurement (accuracy in %) of concentrations (ppm) of Re; Rare Earth Elements (REE); Heat-Producing Elements HPE’s (K, Th, U) and Rb; Re (Half-Life in Ga) in Carbonaceous Meteorites compared with Earth Rocks, Lunar Basalt, Comet 67P/C-G & Near Earth Asteroids

<table>
<thead>
<tr>
<th>Group - Sample</th>
<th>Density (g/cm$^3$)</th>
<th>Porosity (%)</th>
<th>La(10%)</th>
<th>Ce(10%)</th>
<th>Nd(10%)</th>
<th>Eu(20%)</th>
<th>Sm(7%)</th>
<th>Tb(2%)</th>
<th>Yb(25%)</th>
<th>Tm(20%)</th>
<th>$^{40}$K (5%)</th>
<th>$^{212}$Th (7%)</th>
<th>$^{238}$U (10%)</th>
<th>K/U</th>
<th>Th/U</th>
<th>$^{87}$Rb (20%)</th>
<th>$^{187}$Re (12%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orgueil - CI1 - MHN P6</td>
<td>1.6</td>
<td>35%</td>
<td>0.25</td>
<td>&lt;2.86</td>
<td>&lt;2.08</td>
<td>&lt;0.19</td>
<td>0.16</td>
<td>0.036</td>
<td>0.22</td>
<td>0.07</td>
<td>&lt;600</td>
<td>0.049</td>
<td>0.09</td>
<td>12,245</td>
<td>5.4</td>
<td>3.14</td>
<td>0.28</td>
</tr>
<tr>
<td>Murchison - CM2 - E12393</td>
<td>2.25</td>
<td>23.1%</td>
<td>0.35</td>
<td>&lt;2.49</td>
<td>&lt;1.76</td>
<td>&lt;0.11</td>
<td>0.20</td>
<td>0.055</td>
<td>0.24</td>
<td>0.09</td>
<td>&lt;600</td>
<td>0.042</td>
<td>0.008</td>
<td>75,000</td>
<td>5.25</td>
<td>3.57</td>
<td>0.29</td>
</tr>
<tr>
<td>Sutter’s Mill - CM2 - Farmer</td>
<td>2.25</td>
<td>23%</td>
<td>0.36</td>
<td>&lt;4.47</td>
<td>&lt;3.06</td>
<td>0.36</td>
<td>0.22</td>
<td>0.067</td>
<td>&lt;0.4</td>
<td>&lt;0.1</td>
<td>&lt;600</td>
<td>0.073</td>
<td>0.031</td>
<td>19,354</td>
<td>5.21</td>
<td>3.33</td>
<td>0.48</td>
</tr>
<tr>
<td>NWA 5515 - CK4 - Sipiera</td>
<td>2.85</td>
<td>21.8%</td>
<td>0.59</td>
<td>2.46</td>
<td>&lt;0.96</td>
<td>0.11</td>
<td>0.24</td>
<td>0.053</td>
<td>0.23</td>
<td>0.05</td>
<td>&lt;600</td>
<td>0.065</td>
<td>0.11</td>
<td>5,455</td>
<td>4.75</td>
<td>0.98</td>
<td>0.18</td>
</tr>
<tr>
<td>NWA 6136 - C03 - Sipiera</td>
<td>2.58</td>
<td>22%</td>
<td>0.39</td>
<td>4.33</td>
<td>1.56</td>
<td>0.46</td>
<td>0.24</td>
<td>0.069</td>
<td>0.28</td>
<td>0.09</td>
<td>&lt;600</td>
<td>0.045</td>
<td>0.018</td>
<td>33,333</td>
<td>7.5</td>
<td>&lt;0.5</td>
<td>0.082</td>
</tr>
<tr>
<td>NWA 4540 - C03.5 - Sipiera</td>
<td>2.85</td>
<td>22%</td>
<td>0.57</td>
<td>&lt;2.11</td>
<td>1.16</td>
<td>&lt;0.13</td>
<td>0.28</td>
<td>0.015</td>
<td>0.19</td>
<td>0.05</td>
<td>&lt;600</td>
<td>0.033</td>
<td>0.10</td>
<td>6,000</td>
<td>4.0</td>
<td>&lt;0.5</td>
<td>0.42</td>
</tr>
<tr>
<td>NWA 2086 - CV3 - Sipiera</td>
<td>2.95</td>
<td>21.8%</td>
<td>0.55</td>
<td>3.20</td>
<td>1.22</td>
<td>0.10</td>
<td>0.26</td>
<td>0.074</td>
<td>0.38</td>
<td>0.05</td>
<td>&lt;600</td>
<td>0.038</td>
<td>0.49</td>
<td>1,224</td>
<td>2.75</td>
<td>1.86</td>
<td>0.17</td>
</tr>
<tr>
<td>Polonnaruwa/Aralaganwila C-Ung</td>
<td>~0.6-0.8</td>
<td>60-80%</td>
<td>0.47</td>
<td>&lt;3.47</td>
<td>&lt;3.44</td>
<td>&lt;0.27</td>
<td>0.11</td>
<td>0.024</td>
<td>&lt;0.2</td>
<td>&lt;0.1</td>
<td>138,000</td>
<td>0.143</td>
<td>0.023</td>
<td>6,000</td>
<td>0</td>
<td>2.04</td>
<td>439</td>
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<tr>
<td>Polonnaruwa/Aralaganwila C-Ung</td>
<td>~0.6-0.8</td>
<td>60-80%</td>
<td>1.38</td>
<td>3.15</td>
<td>24.1</td>
<td>&lt;0.07</td>
<td>0.17</td>
<td>0.018</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>130,000</td>
<td>0.135</td>
<td>0.043</td>
<td>960,000</td>
<td>6.25</td>
<td>323</td>
<td>4.41</td>
</tr>
<tr>
<td>Polonnaruwa/Aralaganwila C-Ung</td>
<td>~0.6-0.8</td>
<td>60-80%</td>
<td>8.65</td>
<td>23.2</td>
<td>31.8</td>
<td>0.09</td>
<td>0.85</td>
<td>0.087</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>132,000</td>
<td>2.33</td>
<td>0.39</td>
<td>3,384,61</td>
<td>5.97</td>
<td>378</td>
<td>4.02</td>
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<tr>
<td>Continental Crust Abundance</td>
<td>2.7-3.0</td>
<td>~22%</td>
<td>39.0</td>
<td>66.5</td>
<td>41.5</td>
<td>2.0</td>
<td>7.05</td>
<td>1.2</td>
<td>3.2</td>
<td>0.52</td>
<td>20,000</td>
<td>9.6</td>
<td>2.7</td>
<td>7,407</td>
<td>3.8</td>
<td>90</td>
<td>0.000</td>
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<tr>
<td>Jack Hills Zircon 4.4 Gy W74/2-36</td>
<td>2.80</td>
<td>~25%</td>
<td>4.6</td>
<td>112</td>
<td>46.2</td>
<td>5.3</td>
<td>34.5</td>
<td>28.2</td>
<td>555</td>
<td>-</td>
<td>40-665</td>
<td>48-600</td>
<td>-</td>
<td>3.5</td>
<td>12.40</td>
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<tr>
<td>North Pacific Micronodules</td>
<td>~1.5</td>
<td>~45%</td>
<td>18.0</td>
<td>11.6</td>
<td>12.0</td>
<td>4.16</td>
<td>-</td>
<td>5.52</td>
<td>3.39</td>
<td>-</td>
<td>20,70</td>
<td>22.2</td>
<td>6.50</td>
<td>3,185</td>
<td>3.42</td>
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<td>MOON ROCKS</td>
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<tr>
<td>Apollo 15 Kreep Basalt</td>
<td>3.15</td>
<td>19.7%</td>
<td>5.3</td>
<td>14.4</td>
<td>9.6</td>
<td>0.87</td>
<td>3.4</td>
<td>0.72</td>
<td>2.42</td>
<td>0.4</td>
<td>-</td>
<td>0.5</td>
<td>0.12</td>
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<td>COMETS</td>
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<tr>
<td>67P/C-G</td>
<td>0.5</td>
<td>80%</td>
<td>-</td>
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</table>
Sr, Ta, Tb, Th, Yb, and Zn. The gamma spectra of induced activity were measured with HPGe detector with a resolution of 1.9 keV for the $^{60}$Co 1332 keV line. The processing of spectra data and calculation of elemental concentrations were performed using software developed in FLNP, JINR (Pavlov et al., 2014). Certified reference materials and flux comparators were used to determine the concentrations of elements by relative method of calculations.

RESULTS AND DISCUSSION

A detailed description of the carbonaceous meteorites investigated and the results of the multi-element Epithermal Neutron Activation Analysis (ENAA) of these stones have previously been provided (Hoover et al., 2020). The results for the total of 41 elements were determined at the REGATA Neutron Activation Analysis facility of the IBR-2 pulsed reactor of the Frank Laboratory of Neutron Physics (FLNP) of the Joint Institute for Nuclear Research in Dubna, Russian Federation. These Neutron activation analysis studies are helping resolve the mystery of the very low-density Polonnaruwa/Aralaganwila stones. These studies have revealed very dramatic differences in the density, porosity and element composition of the ungrouped Polonnaruwa/Aralaganwila stones as compared with CI, CM, CO, CK and CV meteorites, and zircons, pacific micro-nodules and rocks from the continental crust of Earth and Moon (Table 1). Some of the Lanthanide rare earth elements (REE) are notably higher (La, Ce, Nd, Sm) while the Europium level is lower than that of other carbonaceous meteorites. The Polonnaruwa stones are seen to exhibit astonishing high levels of the group 1 alkali metal Rubidium and the group 7 transition metal Rhenium, which have radioisotopes with extremely long half-lives (>40 Ga). Rhenium is one of the rarest elements in the Earth's crust with an average concentration <1 part per billion. Of particular note is data on the concentrations of the incompatible heat-producing elements (HPE's) Potassium (K), Thorium (Th) and Uranium (U) in the Polonnaruwa stones as compared with the other carbonaceous meteorites. Radioactive decay of the four long-lived radioisotopes ($^{40}$K, $^{232}$Th, $^{235}$U and $^{238}$U) of these elements is responsible for more than 90% of the heat flow through the Earth's surface (Bea, 1998, 2012). The chemical composition of the host matrix varies between different Polonnaruwa/Aralaganwila samples, but they all exhibit an SiO$_2$-rich melt that displays a heterogeneous enrichment in potassium-rich glass (K$_2$O of 2 - 10%) as compared to crystalline forms as was also characteristic of the lunar granites and KREEP basalts collected during the Apollo missions (Papike et al., 1998; Neal et al, 1988). Wallis et al. (2013) have shown that the Polonnaruwa/Aralaganwila stones exhibit non-terrestrial oxygen isotopes; physical properties unlike all known meteorites and terrestrial rocks; fractured/shocked grains, high pressure minerals and REE and HPE’s characteristic of some asteroids, meteorites and the lunar KREEP basalts and are rich in well preserved microfossils (Hoover et al. (2013) (Figure 1).

While they have properties very different from all known groups of meteorites, these stones are also very different from all known Earth rocks. No known meteorites have density ~0.6 to 0.8gm/cm$^3$ and only two Earth rocks (pumice and diatomite) can float in water. However, recent observations indicate Comet 67P and the dark boulders on Near Earth Asteroid Bennu also have densities < 1 gm/cm$^3$ (Davidson et al., 2016; Rozitis et al., 2013).

CONCLUSIONS

The physical properties and ENAA data shown in Table 1 clearly demonstrate the dramatic differences in density, porosity and element composition of the Polonnaruwa/Aralaganwila stones as compared to major Carbonaceous Chondrite, Apollo 14 KREEP basalt, Continental crust rocks and Pacific micronodules. The density and porosity of the Polonnaruwa/Aralaganwila stones is similar only to that of the Comet 67P/Churyumov-Gerasimenko and the dark boulders of the Near Earth Asteroid 101855 Bennu. The Polonnaruwa stones are obviously very different from the measured representatives of major groups of carbonaceous meteorites. The Rhenium excess is very interesting. Rhenium is a heavy, third-row transition metal in group 7 of the

Table 1: Cont

<table>
<thead>
<tr>
<th>Code</th>
<th>Name</th>
<th>Density (gm/cm$^3$)</th>
<th>Porosity (%)</th>
<th>REE</th>
<th>HPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>25143Ito</td>
<td>Dark Boulder</td>
<td>0.8</td>
<td>60-70%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>60313I</td>
<td>Dark Boulder</td>
<td>1.9-1.95</td>
<td>~40%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>162173Ryugu</td>
<td>Dark Boulder</td>
<td>1.19</td>
<td>~50%</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
periodic table with atomic number 75. It is one of the rarest elements in the Earth’s crust with an estimated average concentration of 1 part per billion (ppb). The unusual concentrations of Rhenium, REE’s and HPE’s provides additional support to prior Oxygen Isotope and mineralogy data establishing that the Polonnaruwa/Aralaganwila stones are not terrestrial rocks. While the Th/U ratios of the Polonnaruwa/Aralaganwila stones are not dramatically different from the other carbonaceous chondrites studied, their excess of K is astonishingly high. Planned future ENAA investigations of different samples of the Polonnaruwa/Aralaganwila, Ratkinda and Girandurukotte samples along with a variety of other carbonaceous, lunar and SNC meteorites and Terrestrial rocks may provide additional information to resolve these intriguing mysteries. The long held paradigm that Earth life originated on Earth after a long slow period of chemical and biological evolution resulting in the appearance of protocells in Earth’s primordial Oceans is severely challenged by the recent discoveries of evidence for water in the ancient zircons from the Jack Hills of Australia (Wilde et al., 2001) and isotopic evidence for extraterrestrial life (δ13C = -28 to -22‰) as biogenic carbon in primordial xenolithic clasts in the ancient Zag H5 meteorite (Kebukawa et al., 2019). Virtually no time is left for abiogenesis in liquid water oceans of Earth after the condensation of the protosolar nebula as is required by the hypothesis of endogenous origin of Earth life.

Furthermore, no time is available for the origin of life anywhere else in our Solar System, pointing to the pre-existence of life across the universe distributed through the mechanism of cometary panspermia. The recent discovery of the interstellar comets such as 2I/Borisov (Jewitt and Luu, 2019) and Oumuamua (Jewitt et al., 2017) which traveled through our Solar System in a hyperbolic trajectory at very high velocities (26 to 32 km/s) support this hypothesis. At this speed it would require only 1.5 million years to travel from the ancient subgiant “Methuselah” star (14.3 Ga old and 190.1 light years away from to Earth and 250 million years from the ancient globular cluster M92 which contains over 330,000 stars with average age 11 Ga (27,000 light years distant). Scanning Electron Microscopy studies carried out at PIN/RAS, NASA/MSFC, Cardiff University and LRB/JINR since 1997 have resulted the discovery of a great diversity of diatoms, filamentous cyanobacteria, hystrichospheres, acritarchs, alveolata and many other aquatic microorganisms in the Orgueil C1, Murchison CM2, Polonnaruwa/Aralaganwila stones and many other meteorites (Zhmur et al., 1997; Hoover, 1997; Hoover et al., 2013; Wickramasinghe et al., 2013; Hoover et al., 2018; Rozanov et al., 2020). Energy-Dispersive X-ray Spectroscopy (EDS) data of life-critical bioelement ratios (C/N; C/O; C/S; C/P) provides direct observational evidence that these well-preserved biological remains are indigenous ancient microfossils rather than modern, post-arrival terrestrial bio-contaminants (Hoover, 2007). Therefore, there exists direct observation evidence for the existence of extraterrestrial life and support for the exogenous origin of life and the hypothesis of Panspermia. These results, combined with recent data from space missions, meteorites and ancient terrestrial zircons indicate life may have originated elsewhere in the Cosmos and delivered to Earth by the influx of carbonaceous chondrites, comets, planetesimals and water-bearing asteroids. This provides a hypothesis for a Panspermia mechanism in which life does not require long-term survival as spores or dormant in ancient salt crystals. Instead, living organisms grow, replicate and die within water-filled fractures in HPE-rich deep, hot rocks or the permafrost, icy crusts and sub-crustal oceans rogue planets, icy moons or comets. In this way, life continues as it has in the hot deep terrestrial biosphere of planet Earth and the deep oceans, polar ice caps which ancient zircons reveal apparently appeared shortly after the condensation of the protosolar nebula.

In this way, biology continues to spread and flourish on life-bearing bodies ejected from Star systems. Replication and growth allows life to continue as the comet or planet traverses’ vast reaches of the Cosmos to deliver water during transit organics and biospheres to newly formed Solar Systems virtually as soon as capture occurs and conditions suitable for life emerge. Multitudes of planetary systems in M92 or the Magellanic clouds would have all had billions of years for life to have developed and travel via cometary panspermia across vast distances of space as interstellar comets or water-bearing asteroids longbefore the formation of our own Solar System. The long-lived radiogenic HPE’s could maintain oceans in liquid state for billions of years beneath the rocky or icy crusts of ejected comets, planets or moons wherein living organisms could and biospheres might maintain active metabolism with growth and death re-cycling precious bioelements and biomolecules. Life on Earth thrives in the deep, hot crustal rocks, deep oceans and polar ice sheets. There is no reason to assume these principles do not apply throughout the Universe. Cosmic bodies may spread life far from their parent star with water, energy, bioelements and metabolism maintained by long-lived radiogenic HPE’s. Recent discoveries of exoplanets support this mechanism of life dispersal. Data from NASA’s Kepler mission suggests that there must exist in excess of 100 billion exoplanets orbiting dwarf stars within our own galaxy (Kopparapu, 2013). Therefore, the mean distance between habitable planets in our Milky Way galaxy is only a few light years (a distance that could be most easily bridged). There are exchanges of comets that can act as agencies to yield an interconnected web of galactic and cosmic life straddling the hundreds of millions of habitable exoplanetary systems in the Galaxy. Thus, the exchange of life-bearing cometary fragments, meteorites, planetesimals and biology appears
to be essentially unavoidable.

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