



## Apollo 11 Revisited

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Dr Grenville Holland is a noted geochemist who has worked on the geology of the Scottish Highlands and Tertiary igneous province as well as that of the West Indies, South Africa, Sri Lanka, Kashmir, Turkey and Canada. Grenville moved to Durham in 1965 where he joined a friendly and supportive Department led by Professor Sir Kingsley Dunham FRS. The arrival of Professor Sir Malcolm Brown FRS in 1967 ushered in the Apollo research programme and Grenville was chosen to be part of the team to provide his geochemical and analytical expertise with X-Ray fluorescence spectrometry (XRF). At the time Durham University did not even have a computer and even Oxford’s computer was a temperamental colossus built with valves. However, due to the work of researchers within the department Durham was retained as a reserch centre for the entire duration of the Apollo programme, ending in 1977 with the production of 21 publications. Dr Holland spoke to the Institute in February 2020 about the role of the Durham group in the Apollo research programme and how many obstacles were overcome. He also recounted some of the lighter moments that have since passed into departmental myth.

### We choose to go to the Moon

On September 12<sup>th</sup>, 1962, I was working on the Lewisian gneisses at the start of my D.Phil at the University of Oxford. That same day, at Rice University in Houston, Texas, President John F. Kennedy was telling the students that: “We choose to go to the Moon.” It was a remarkable challenge and one that would, by approbation and choice, draw in high quality analytical support from around the world (Fig. 1).



*“We choose to go to the Moon in this decade and do the other things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one which we intend to win, and the others, too.”<sup>[1]</sup>*

Figure 1: JFK’s Address at Rice University on the Nation’s Space Effort, 12<sup>th</sup> September 1962.





Figure 2: Apollo 11 analysis team, September 1969. (L-R) Dr J.G. Holland, Dr C.H. Emeleus, Prof G.M. Brown, Mr R. Phillips

Exactly three years later I had moved to the University of Durham and joined the Department of Geology, at that time led by Professor Kingsley Dunham. It was a happy association which lasted 40 years. In 1967 Kingsley Dunham moved to London to become Director of the British Geological Survey. He was replaced by Professor Malcolm Brown who had just spent a year at the Geophysical Laboratory of the Smithsonian Institution, Washington DC, pursuing a research programme devoted to experiments on the melting of granite. The Americans were highly impressed by the outstanding ability of their English research colleague and NASA offered him the position of Principal Investigator in their forthcoming Apollo project.

The arrival of Malcolm Brown in Durham marked a prolific period of research not only on terrestrial igneous rocks but also on the rocks recovered by the Apollo Moon expeditions. Malcolm led a research team (Fig. 2) which included myself (Geochemistry), Henry Emeleus (Petrology), Roy Phillips (Mineralogy), and, later, Andrew Peckett (Microprobe). These studies led to the publication of 31 original papers, representing about one quarter of Malcolm's lifetime output. In addition, Malcolm was still able to find time to initiate major research into the petrology, geochemistry and evolution of the volcanic rocks of the Lesser Antilles and to extend

his interest in the Tertiary Igneous rocks of west Scotland. The decade that followed Malcolm Brown's arrival probably represented the high point in the Department's 100-year history. Malcolm proved to be an exceptional leader: quiet, thoughtful, supportive of his colleagues, generous in sharing any credit for this research, and always prepared to lead from the front. By the autumn of 1967 we already knew that we would be fully engaged once samples from Apollo 11 arrived and NASA were confident that this would be sometime in 1969, keeping Kennedy's promise of "in this decade". We therefore began getting ready to achieve a level of excellence well beyond what, at the time, was considered more than adequate.

Our main analytical tool was X-Ray Fluorescence (XRF) which had been an established laboratory technique for about 10 years, initially using a Philips PW1540 manual instrument, replaced at Durham in 1967 with the PW1212 semi-automatic spectrometer. The principle of the techniques was straightforward (Fig. 3), but interpreting the data less so. The sample for analysis, Fig. 4, is bombarded with a powerful (2-3 Kw) beam of monochromatic X-rays (normally from a W or Cr anode) which generates secondary or fluorescent X-rays in the sample whose character and composition is determined by its chemistry, each element producing an X-ray with a distinct wavelength.



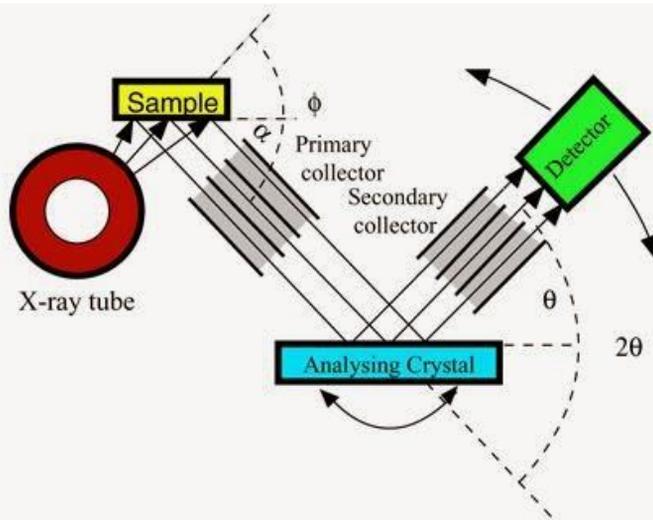


Figure 3: Schematic of the setup of an XRF analysis.

This bundle of secondary X-rays that emits from the sample is then collimated onto an analysing crystal whose 2D spacing, by diffraction, conveniently separates this bundle into discrete lines, characteristic of the elements in the sample. These lines are then further collimated into a detector that determines the intensity of the characteristic X-rays at the appropriate angular locations where they emerge (Fig. 3). There are two detectors: a gas flow proportional counter close to the crystal enclosed within a vacuum chamber to detect the long wavelength, soft X-rays from the light elements (e.g. Si); and a scintillation counter outside the vacuum chamber which can capture the hard X-rays from the heavier elements (e.g. Sr). The data is refined electronically and displayed either numerically or as a trace. For example, Fig. 5 shows a trace for a sample that clearly contains the elements Fe, Cr, and Ni. An examination of the peaks indicates that this sample contains more Fe than Cr and more Cr than Ni, using the primary X-ray signals which are referred to as  $K\alpha$  lines. It is the conversion of that observation into absolute values of element concentration in the sample that represents the real challenge in XRF.

In 1967 that question of accuracy lay at the heart of a long-standing concern for those who used XRF as their daily analytical tool. NASA demanded high accuracy from limited and very precious samples. In essence, XRF is a comparative technique: the X-Ray spectrum from the unknown is compared with the spectrum emerging from accurate standards. At that time accurate rock standards were few and far between: W-1 (basalt), G-1 (granite), AGV-1 (andesite), DTS-1 (dunite), PCC-1 (peridotite) and S-1 (syenite) were reasonably well known and had been analysed individually around the world with the data being compiled and optimised by the USGS. Even so, there were uncertainties about the accuracy of these data. Furthermore, NASA was indicating, from all their preliminary observations of the Moon, that the first samples returned would generally have a basaltic composition. In essence this left W-1 as the only primary reference point. In Durham I asked Pilkingtons Glass Co. in St. Helens to build me a whole set of basaltic glasses accurately spiked with 'specpure' traces of the elements of interest. Pilkingtons were delighted with this opportunity to contribute to our research and, with their samples, I was confident that we could analyse the first returns accurately (a confidence shown much later to have been justified).

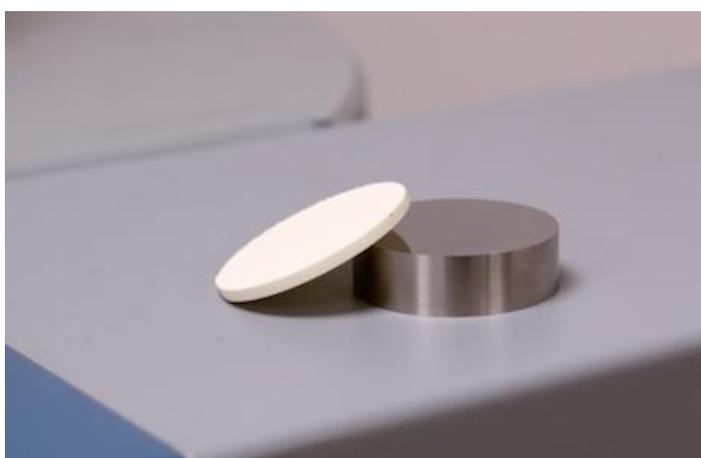


Figure 4: Example pressed pellet used in XRF (approx. 4 cm across).

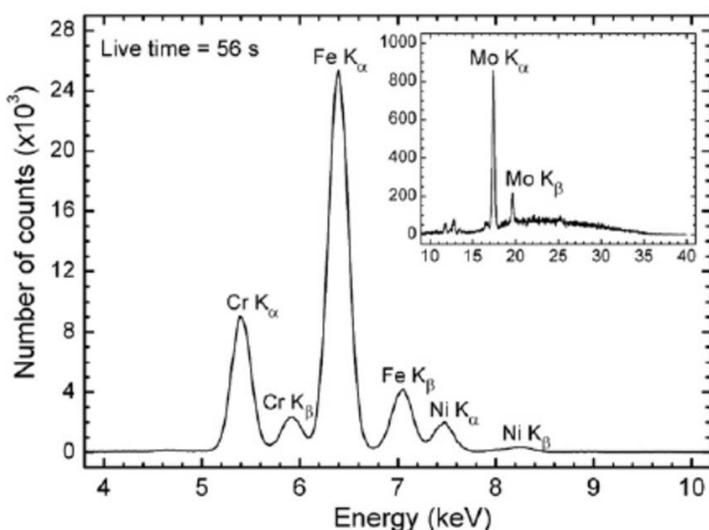


Figure 5: Example XRF element trace spectra of a stainless steel lid<sup>[2]</sup> x-ray fluorescence lines of Chromium (Cr), Iron (Fe), Nickel (Ni) and Molybdenum (Mo).





Standards were not our only problem. Fig. 5 shows peaks for Fe, Cr and Ni, and those peaks can automatically be read as numbers, counts per seconds, on the digital display. In turn that number can be converted into a concentration as a % or ppm by reference to a set of relevant standards. However, that simple, linear translation is not so easy and does not lead to accuracy. As part of the calculation the inter-element effects have to be calculated as well. For, within the sample, the elements interfere with each other either absorbing or enhancing the emission of a characteristic X-Ray depending both upon the location of the absorption edges of every element in the sample and also depending on the quantity of each element present in the sample. Mathematically this can be resolved but this resolution is made more difficult if the chemistry of the sample being analysed is unknown, an ignorance that obstructs the very calculation you wish to make. Using an iterative technique this problem had been overcome in 1966 by Holland & Brindle<sup>[3]</sup>. But it needed a good computer.

In 1967 Durham University did not have a computer. It did not get one until 1971 and this was shared with Newcastle University linked by a telephone line. In converting XRF data to chemical analyses we therefore had to use the National Computing Laboratory at Harwell. Data was loaded onto paper tapes that were then entrusted to the Royal Mail. The printed results arrived back a few days later.

### From the Lunar Surface to Country Durham

Having landed at 20:17 on July 20<sup>th</sup> 1969 the following morning Neil Armstrong first set foot on the Moon at 02:56. Buzz Aldrin joined him 19 minutes later. The two astronauts spent over 2 hours together outside the spacecraft, and collected 21.5 kg of lunar material to bring back to Earth. These samples were then quarantined before a small portion of them were distributed in September to chosen laboratories around the world. Many are still held back in store even today awaiting analysis at some time in the future when our skills have been better honed.

In Durham we were ready and Malcolm Brown collected his foil wrapped and plastic bottled 2-gram sample of lunar regolith at State House in London. Following a short interview with Tyne Tees TV on the steps of this building Malcolm set off on his return journey.

Because the sample had been valued at £2 million, with dire warnings about any loss or misadventure, it was placed carefully in his briefcase and he was taken by the Metropolitan Police to Kings Cross and seen safely on the train to Durham as it departed for the north. Here he would be met by the local police for transport to the Department of Geology. Ever mindful of the popular film at the time, "The Ipcress File", nothing had been left to chance.

Malcolm did not reach Durham Station. He got as far as Darlington where the train halted overlong. Concerned, Malcolm stepped from the train with his briefcase to find the cause for this delay. The train then departed. From his own account to me the following morning, now concerned and seeking advice, he approached a porter and said "My name is Professor Malcolm Brown and, in my briefcase, I have a sample of the Moon". The porter had, of course, come across people like this before and responded "Oh, ay, and my name's Harold Wilson and I've got the crown jewels in my pocket".



Figure 6: First sample of lunar regolith.





Eventually he called the Railway Police and then the Darlington constabulary were involved before the identity of this quietly spoken, lunar carrying gentleman had been confirmed. The Darlington Police obligingly transferred Malcolm to our Department in one of their squad cars so that this precious cargo could be secured in the safe.

His problems did not end there. As Malcolm opened the safe the attending sergeant mentioned that he knew a couple of lads back in Darlington who could break into this safe “using a tin opener”. Alarmed, the very next morning Malcolm had a quality Chubb safe installed whose cunning codes were known only to him, safe and secure from lads with tin openers.

The official opening of the sample with photography was set for the following morning. We all wore suits for the occasion. However, when I met Malcolm outside his office he was in a state of agitation. “What’s wrong” I asked. “I can’t open the safe” he muttered. “I’ll go and get Roger Long” I offered, for Roger was our resident seismologist licensed to handle gelignite. “That’s not funny” grumbled Malcolm. I went into his office with him and we sat in front of the safe where you rotated a dial clockwise and anti-clockwise. Given the code (his wife’s birthday!) and calm, precise fingers there was a reassuring click and our sample bottle stood looking at us.

It was placed in front of the four of us, with a lunar globe set to the left. The photographer took a few shots of the group. No one smiled. The sample was then opened onto a large sheet of polished white paper (Fig. 6). We stared in wonder at this display of powder, fragments, individual minerals and the odd molten droplet. My first instinct was to sneeze, which I avoided by grabbing my nose and moving away, to the concern of my colleagues. The sample was carefully sorted into coarse and fines. The coarse material went to my colleagues; the fine residue was left to me for chemical analysis.

### The First Analyses of the Regolith

In September and October, we were busy analysing this sample of regolith and the fines were further ground down in agate to a homogenous powder and then carefully pressed into a disc using an organic liquid cement (e.g. Fig 4). This pellet was analysed for major



Figure 7: The first gathering in Houston.

and some trace elements using the standards that had been prepared beforehand. In those early months we had few points of chemical references. We had not seen the results of our colleagues around the world for we were working in isolation. We had to trust our analyses and, for petrogenetic purposes, compare them with similar terrestrial rock types, in this case basalts. Yet some things stood out immediately in making those early comparisons and those are highlighted in bold in Tables 1 & 2. In terms of its major element composition the regolith fines, which probably made up a reasonable cross sample of the local lithology at the landing site, compared to their terrestrial “equivalents” (listed in 1969 as ‘Average Basalt’, with the average MORB value added in this paper from Gale et al.<sup>[4]</sup> recommended mean composition) were relatively rich in FeO and Cr<sub>2</sub>O<sub>3</sub> and exceptionally rich in TiO<sub>2</sub>.





	Apollo-11 10085	Average Basalt	MORB
SiO <sub>2</sub>	42.13	49.2	50.47
Al <sub>2</sub> O <sub>3</sub>	13.64	15.8	14.70
Fe <sub>2</sub> O <sub>3</sub>	0.06	0.06	
FeO	<b>15.26</b>	<b>10.7</b>	<b>10.43</b>
MnO	0.21	0.17	0.18
MgO	7.38	6.6	7.58
CaO	11.32	10.0	11.39
Na <sub>2</sub> O	<b>0.54</b>	<b>2.7</b>	<b>2.79</b>
K <sub>2</sub> O	<b>0.16</b>	<b>1.0</b>	<b>0.16</b>
TiO <sub>2</sub>	<b>7.69</b>	<b>1.9</b>	<b>1.68</b>
P <sub>2</sub> O <sub>5</sub>	0.10	0.33	0.18
Cr <sub>2</sub> O <sub>3</sub>	<b>0.33</b>	<b>0.03</b>	<b>0.03</b>
S	0.31	0.03	
<b>Total</b>	<b>99.16</b>	<b>98.52</b>	<b>99.87</b>

Table 1: Average (Wt.%) major element analysis of Regolith fines sample 10085 (average of 32 determinations), c.f. with average Basalt calculated in 1969 (n = 1996 samples) and average Mid Oceanic Ridge Basalt (MORB) calculated by Gale et al.<sup>[4]</sup>. Initial key differences highlighted in bold. New Minerals identified: Armalcolite (MgFe<sup>2+</sup>)Ti<sub>2</sub>O<sub>5</sub>; Pyroxferroite (Fe<sup>2+</sup>Ca)SiO<sub>3</sub>

	Apollo-11 10085	Average Basalt	MORB
Ni	117	120	90
Cu	<b>16</b>	<b>100</b>	<b>75</b>
Zn	<b>19</b>	<b>100</b>	<b>91</b>
Rb	<b>3</b>	<b>30</b>	<b>3</b>
Sr	159	430	132
Y	<b>124</b>	<b>25</b>	<b>36</b>
Zr	<b>351</b>	<b>130</b>	<b>114</b>
Nb	15	20	5
Ba	257	260	32
Cr	<b>3000</b>	<b>300</b>	<b>249</b>

Table 2: Average trace element analysis (ppm) of Regolith fines sample 10085 (average of 32 determinations), c.f. average Basalt calculated in 1969 (n = 1996 samples) and average Mid Oceanic Ridge Basalt (MORB) calculated by Gale et al.<sup>[4]</sup>. Initial key differences highlighted in bold. New Mineral identified: Tranquillityite (Fe<sup>2+</sup>)<sub>8</sub>Ti<sub>3</sub>Zr<sub>2</sub>Si<sub>3</sub>O<sub>24</sub>

In contrast the lunar sample was low in the alkalis Na<sub>2</sub>O and K<sub>2</sub>O. Furthermore, two new minerals, Armalcolite (a name that thoughtfully combines **Armstrong**, **Aldrin** and **Collins**) and Pyroxferroite had been identified, reflecting the different chemistry and petrogenetic conditions of formation.

The trace elements also revealed what appeared to be significant differences, for the regolith was noticeably enriched in Y, Zr and Ba and impoverished in Cu, Zn and Rb. Indeed, the Zr was sufficiently enriched to yield a new mineral, Tranquillityite (collected from the Sea of Tranquillity). The question was: why?

In December 1969 we prepared all our information in readiness for the first Apollo 11 Lunar Science Conference at NASA's Headquarters in Houston early in January 1970. The abstract, summarising our findings, was assembled and mailed to Houston a few days after Christmas. Indeed, such was the pressure to get everything in good order, we even worked on Christmas Day, led inevitably by Malcolm Brown.

NASA's chosen team of Principal Investigators gathered together in Houston on January 5<sup>th</sup> 1970. Their abstract booklet, Fig. 7, often with hand written corrections, had been hurriedly Xeroxed, and stapled together. Yet it was the beginning of a great surge of internationally driven research. Those initial days were taken up with the presentation of facts and of observations with relatively little petrogenetic interpretation. The PIs were exchanging ideas and testing the water. The main body of papers were published a month later in the Proceedings of the Apollo 11 Lunar Science Conference<sup>[5]</sup> and the first cautious interpretations were contained there for everyone realised that the data base was small and the sample area tiny.

How close were those early analyses to identifying the origin of the Moon? With the benefit of hind sight they were close from the outset. As the data from Apollo 12 to Apollo 17 accumulated, as the data base and the scientific contributors expanded dramatically, the interpretation of the Moon's origin and evolution became more assured (Fig. 8).



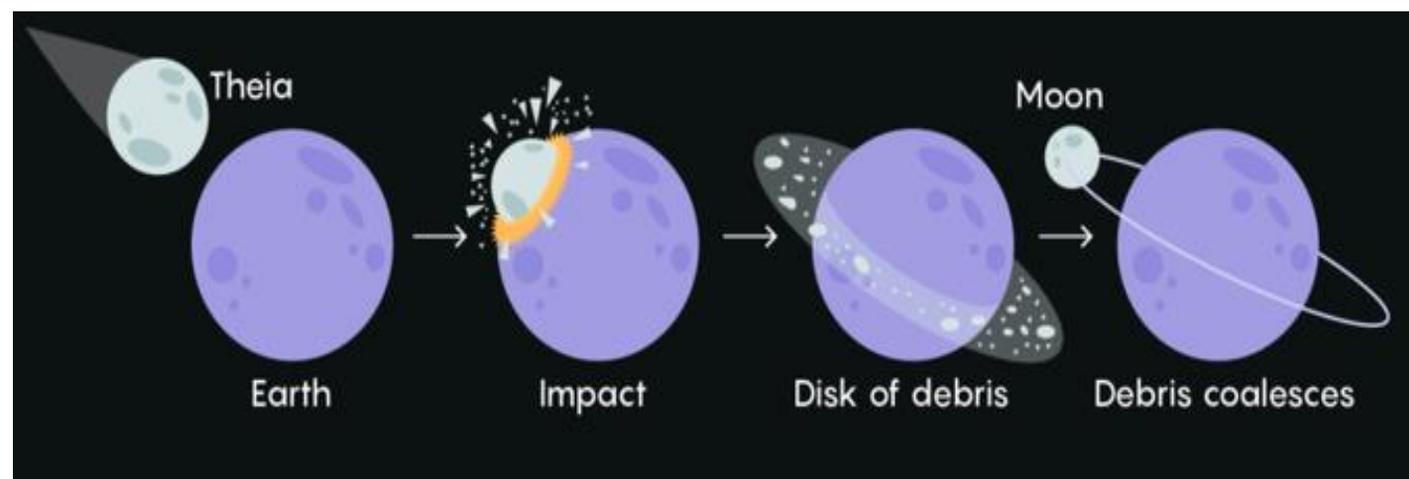


Figure 8<sup>[6]</sup>: The first 100,000 years of the formation of the moon. (L-R): initial impact of between the Earth and 'Theia' with debris heated to 4000°K; blending of material in a disc at 2000°K; the disc coalesces with crystallisation of material at 1200°K. During this process 'refractory' elements were retained (Y, Nb, Zr, Ba, Cr, Ti, Fe) and volatile elements were lost to space (Cu, Zn, Rb, K, Na).

### Building a Model of Lunar Formation

Today it is believed that the Moon formed about 4.51 billion years ago, 67 million years after the Solar System began to develop, as the result of a collision between the Earth and a small planet about the size of Mars, named Theia (Fig. 8). In astronomical terms, the impact would have been of moderate velocity. Theia is thought to have struck the Earth at an oblique angle when the Earth was nearly fully formed. A significant portion of the mantle material from both Theia and the Earth would have been ejected into orbit around the Earth. The material retained in orbit around the Earth, as fragments, liquid and gas, quickly coalesced into the Moon, possibly within 10s to 100s of years<sup>[7]</sup>.

How does this model relate to the chemical data that we gathered at Durham in the autumn of 1969? Fig. 8 provides a model of lunar accretion beginning with an accumulation of debris at about 4000 K which coalesced at about 2000 K and crystallised at 1200 K. The chemical response to this process would be to boil off the volatile elements (e.g. Cu, Zn, Rb, K, and Na) and retain the refractory elements (e.g. Y, Nb, Zr, Ba, Cr, Ti and Fe). Fig. 8 gives a tantalising glimpse of this process and suggests that my comment to Malcolm Brown in the very first weeks of our research together that "the zinc and copper looks too low" had some relevance. This separation of volatile elements (V) from refractory elements (R) (Table 3), received attention rather later in the lunar research programme.

The lowest V/R ratios are found in angrites, considered as possible fragments from Mercury (ADOR), (Fig. 9). The Howardite-Eucrite-Diogenite meteorites (HED) formed in a differentiated parent body which experienced extensive igneous processing similar to the Earth and it is believed that they originated from the crust of the asteroid Vesta, located in the asteroid belt between Mars and Jupiter. The different V/R ratios of the Moon, the Earth (BSE) and Mars, although linked on a common plot, show that the Moon is depleted in volatile elements (K and Rb) compared to the Earth whereas Mars is relatively enriched in these two elements. The interpretation is based on a thermal history in which the Moon passed through a period of transient high temperature coalescence that influenced its V/R ratios, whereas Mars, more distant from the Sun during its primary formation, retained its more volatile components with greater success. The same argument can be applied to the chondrites whose even higher V/R ratios reflect their origin at an even greater distance from their solar hub.

The radio-active character of both K and U allowed a more widespread study their ratios using gamma-ray spectrometry (Figs. 9, 10; Table 4). These results underpinned the earlier work of Ross Taylor<sup>[8,9]</sup> on the thermal history of the solar system.

The stable isotopes, such as <sup>18</sup>O/<sup>16</sup>O, have long been used for tracing climatic temperature variations both in the recent past and also in earlier periods of Earth





Category	Condensation temperatures	Elements
Super-refractory	higher than 1700 K	Re, Os, W, Zr and Hf
Refractory	1500 K to 1700 K	Al, Sc, Ca, Ti, Th, Lu, Tb, Dy, Ho, Er, Tm, Ir, Ru, Mo, U, Sm, Nd and La
Moderately refractory	1300 to 1500 K	Nb, Be, V, Ce, Yb, Pt, Fe, Co, Ni, Pd, Mg, Eu, Si, Cr
Moderately volatile	1100 K to 1300 K	Au, P, Li, Sr, Mn, Cu, Zn and Ba
Volatile	700 K to 1100 K	Rb, Cs, K, Ag, Na, B, Ga, Sn, Se and S
Very volatile	less than 700 K	Pb, In, Bi and Tl

Table 3<sup>[8]</sup>: Volatile and refractory elements. The condensation temperatures are the temperatures at which 50% of the element will be in the form of a solid (rock) under a pressure of  $10^{-4}$  bar.

history. The general convention was that this naturally occurring isotopic variation occurs only in light elements where the mass differences between the isotopes are significant and can respond to relatively modest temperature fluctuations with time.

However, because it was believed that during the development of the Moon temperatures reached 4000 K before the cooling and recrystallisation processes began it begged the question: at such temperatures would the heavier volatile elements also fractionate during this episode of lunar formation; and would their isotopic ratios differ significantly from the Earth, informing yet further the model for the formation of the Moon?

As discussed above, research had already demonstrated the volatile-depleted patterns that developed during the initial formation of the Moon and the subsequent, and variable, evaporative loss of these volatile elements which also occurred during later lunar formation and differentiation. Perhaps these processes caused their stable isotopes to fractionate too. To test this concept Wang & Jacobson<sup>[10]</sup> measured the value of  $^{41}\text{K}/^{39}\text{K}$  ratios in lunar rocks set against those found on the Earth and in chondrites. The significantly higher  $^{41}\text{K}/^{39}\text{K}$  values that they found in the lunar samples implied a preferential loss of  $^{39}\text{K}$  during the formation of the Moon and they concluded that this supported a model that involved a high-energy, high-angular-momentum giant impact for the origin of the Moon.

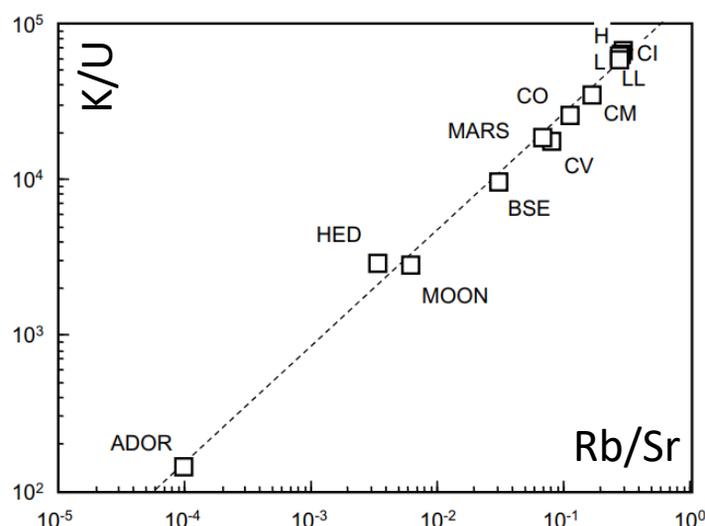


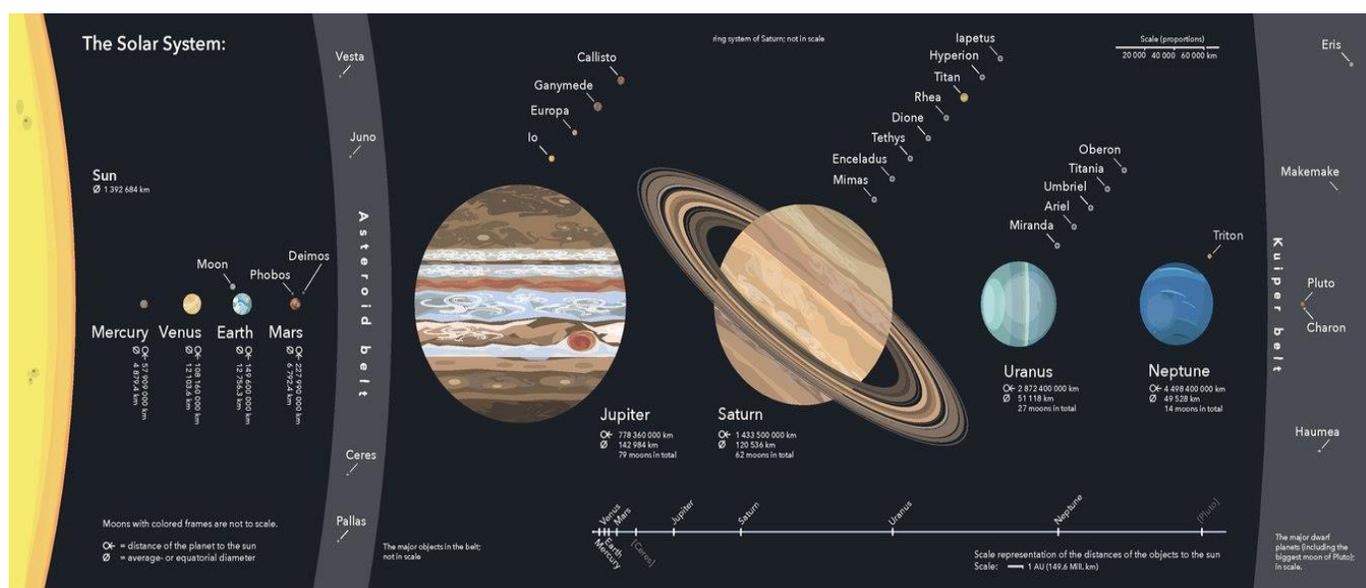
Figure 9: Plot of  $\text{K}/\text{U}$  vs  $\text{Rb}/\text{Sr}$  for a variety of chondritic meteorites (C-, H, L- types – top right), Mars, the Earth (BSE), as well as smaller differentiated bodies such as the Eucrite (HED) Parent Body (believed to be Asteroid 4 Vesta) and the Moon. Data for the volatile element depleted meteorite Angra dos Reis are shown as well. The data define a very tight trend. However,  $\text{Rb}/\text{Sr}$  is more variable than  $\text{K}/\text{U}$  despite Rb having a higher half mass condensation temperature than K. From Halliday et al. (2001)<sup>[11]</sup>.





Component	K/U ratios
Mercury	Uncertain
Venus	7,000
Earth	12,000
Moon	2,500
Mars	18,000
Ordinary chondrite meteorites	63,000
Carbonaceous chondrite meteorites	70,000

Table 4: K/U ratios using Gamma-Ray Spectrometry<sup>[8]</sup>.



Mercury: 1000  
Venus: 7000  
Earth: 12000  
Moon: 2500

Saturn: 63000

Neptune: 70000

Figure 10<sup>[8,12]</sup>: K/U ratios of solar system bodies increase away from the Sun.

Age of the Solar System:	4.571 billion years
Age of the Earth:	4.54 billion years
Age of the Moon:	4.51 billion years
Earth's Crust:	4.05 By (Archaean) to the Present Day
Moon's Crust:	4.44 By (Highlands), to 3.16 By (Mare)

Table 5<sup>[8]</sup>: Radiometric age dates for the Earth and the Moon.





**Figure 11:** 4.44 billion year old Highland rocks (Tracy's Rock Apollo-17).

Day & Moinier<sup>[13]</sup> recognised a similar pattern with  $^{87}\text{Rb}/^{85}\text{Rb}$ . They noted that the Moon and volatile depleted asteroids, compared to the Earth and chondrites, also show enhanced  $^{87}\text{Rb}/^{85}\text{Rb}$  ratios through progressive loss of the lighter isotope  $^{85}\text{Rb}$  during their formation.

The three Zn isotopes  $^{68}\text{Zn}$ ,  $^{66}\text{Zn}$  and  $^{64}\text{Zn}$  also fit this pattern well<sup>[13]</sup>, and the values for  $^{68}\text{Zn}/^{64}\text{Zn}$  and  $^{66}\text{Zn}/^{64}\text{Zn}$  both show significantly higher values in lunar samples compared to the Earth and Mars reflecting the higher volatile loss of the lighter  $^{64}\text{Zn}$  compared to  $^{68}\text{Zn}$  and  $^{66}\text{Zn}$ , underpinning the model proposed by Wang and Jacobson.

Using data taken mainly from apatite crystals, Stephant et al.<sup>[14]</sup> analysed the very volatile chlorine isotopic pair  $^{37}\text{Cl}/^{35}\text{Cl}$  and recognised that the Moon exhibits a higher  $^{37}\text{Cl}/^{35}\text{Cl}$  ratio compared to the Earth. Barnes et al.<sup>[15]</sup> also reported that these isotopes are more highly fractionated in lunar samples compared to most other samples so far analysed from the solar system. These variable signatures have therefore been attributed to large scale degassing processes that occurred both during the early formation of both the Moon and the development of its magma oceans.

$^{71}\text{Ga}/^{69}\text{Ga}$  offers further isotopic evidence for extensive volatile loss during the formation of the Moon, Kato & Moynier<sup>[16]</sup>, whose results revealed a two-fold process. The difference in the Ga content as well as its isotopic



**Figure 12:** 4.05 billion years old Acasta tonalitic gneiss outcrop, NW Canada.

ratios between the Earth and the Moon confirm its volatile loss during the impact phase of its formation. Furthermore, isotopic differences between the anorthosites and the magma ocean samples, reflect a second phase of volatile loss during the initial crystallisation and crustal separation of the Moon.

However, these simple and consistent fractionation patterns revealed by K, Rb, Zn, Cl and Ga, in which the lighter isotope was preferentially lost during the formation of the Moon, is not found with every element. Other forces were clearly at play, other reactions were influencing processes of isotopic fractionation.

For example, analysing the  $^{53}\text{Cr}/^{52}\text{Cr}$  and  $^{54}\text{Cr}/^{52}\text{Cr}$  ratios on a range of lunar, terrestrial and enstatite chondrite samples, Mougél et al.<sup>[17]</sup> found that these ratios were lower in the lunar samples than in either the terrestrial or chondrite samples, in sharp contrast to the patterns seen in other more volatile elements. The authors propose that this observation is consistent with a process which involved Cr partitioning in an oxygen-rich vapor phase in equilibrium with the early proto-Moon, as a result of which the  $\text{CrO}_2$  species that is isotopically heavy is preferentially stabilised rather than CrO which is subsequently developed in a lunar melt. Sossi et al.<sup>[18]</sup> suggested that temperatures of 1,600 K to 1,800 K at an appropriate partial pressure of oxygen were required to explain the elemental and isotopic difference of Cr between the Earth's mantle and the Moon.



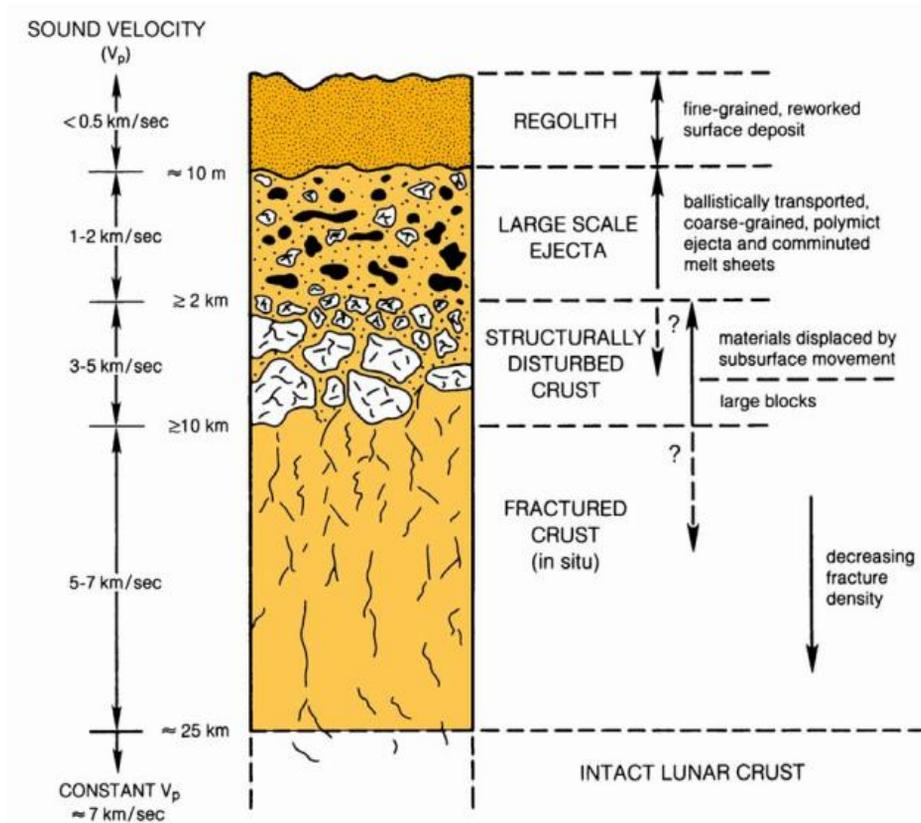


Figure 13: Inferred cross-section through the top 25 Km of the lunar crust. After Hörz et al.<sup>[19]</sup>.

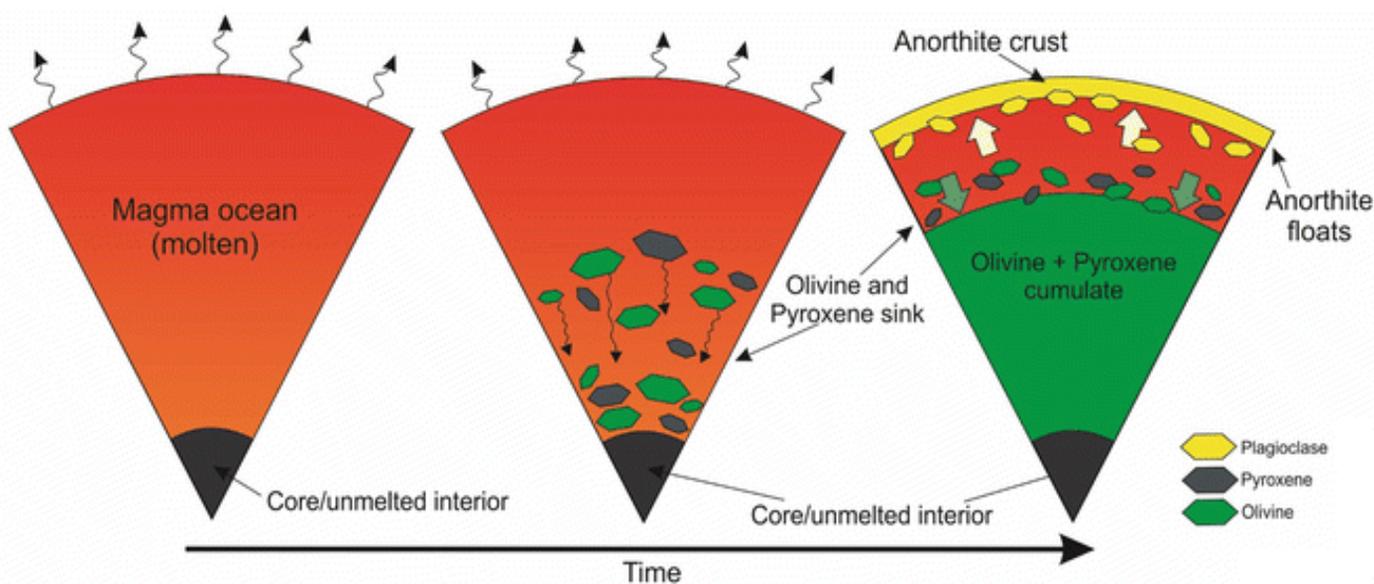


Figure 14<sup>[20]</sup>: Model of the early internal structure of the Moon.



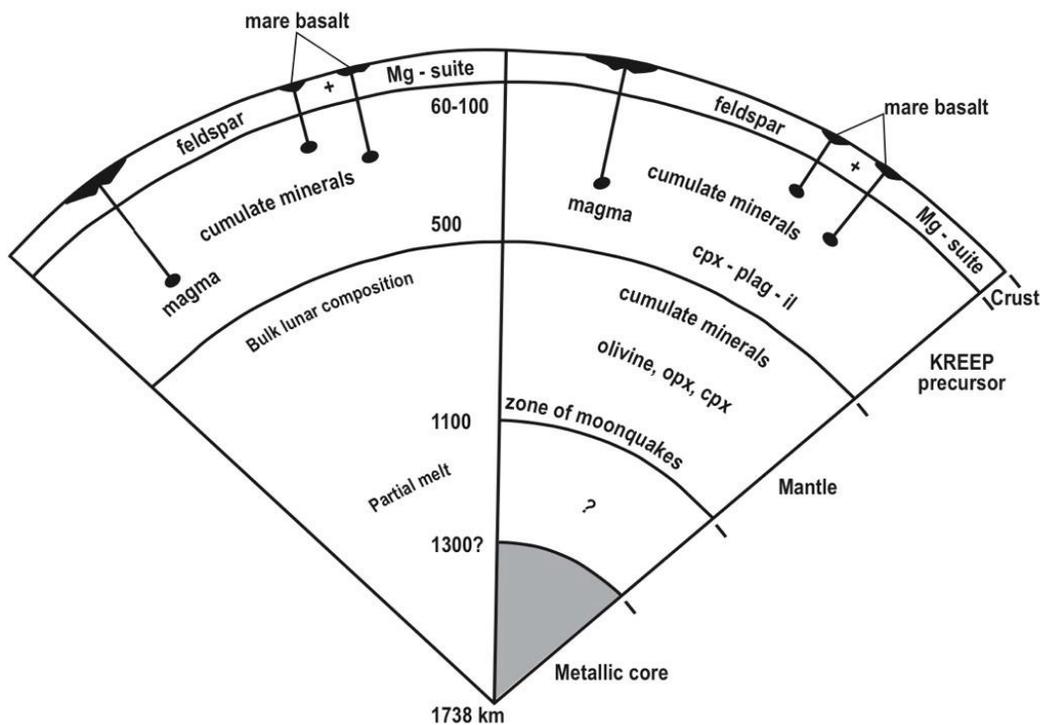


Figure 15: Two proposed views on the internal structure of the Moon<sup>[21]</sup>, note lack of tectonic activity.

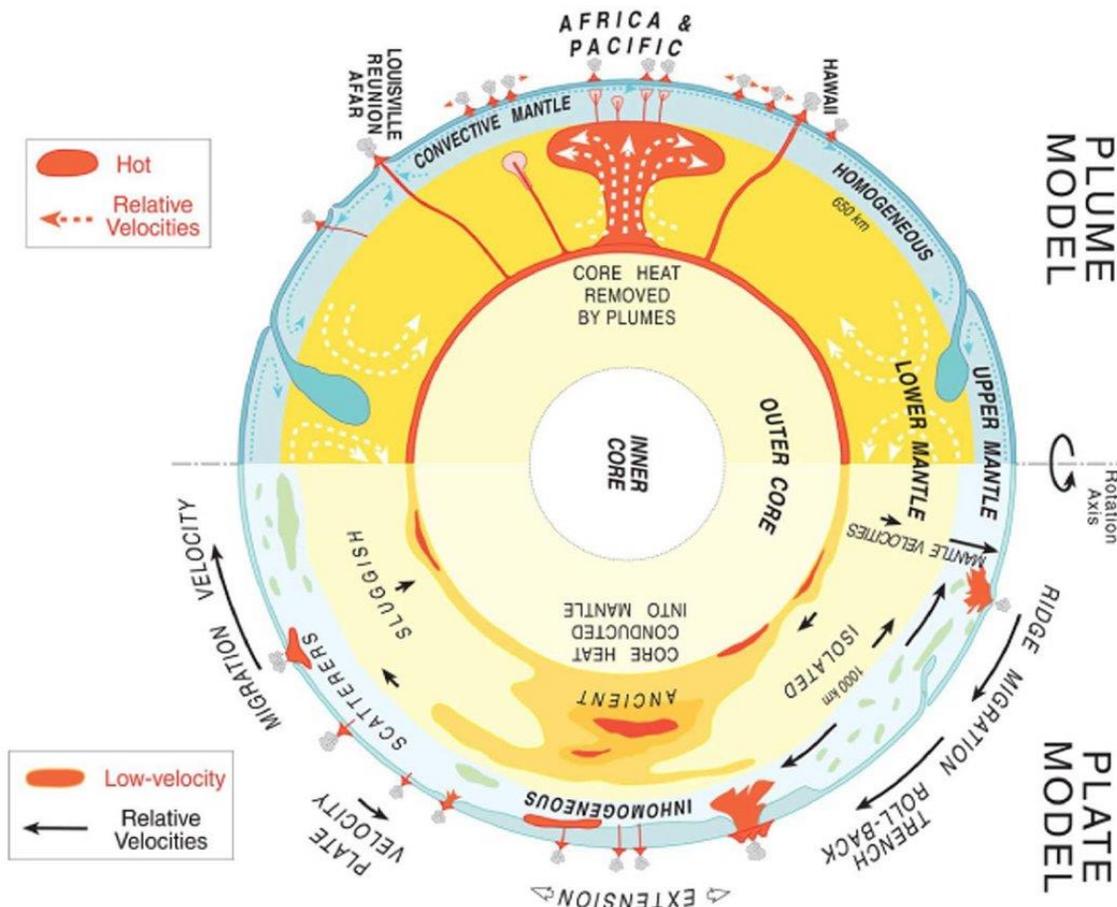


Figure 16<sup>[22]</sup>: Two models of the internal activity and structure of the Earth – an active environment from the outset.



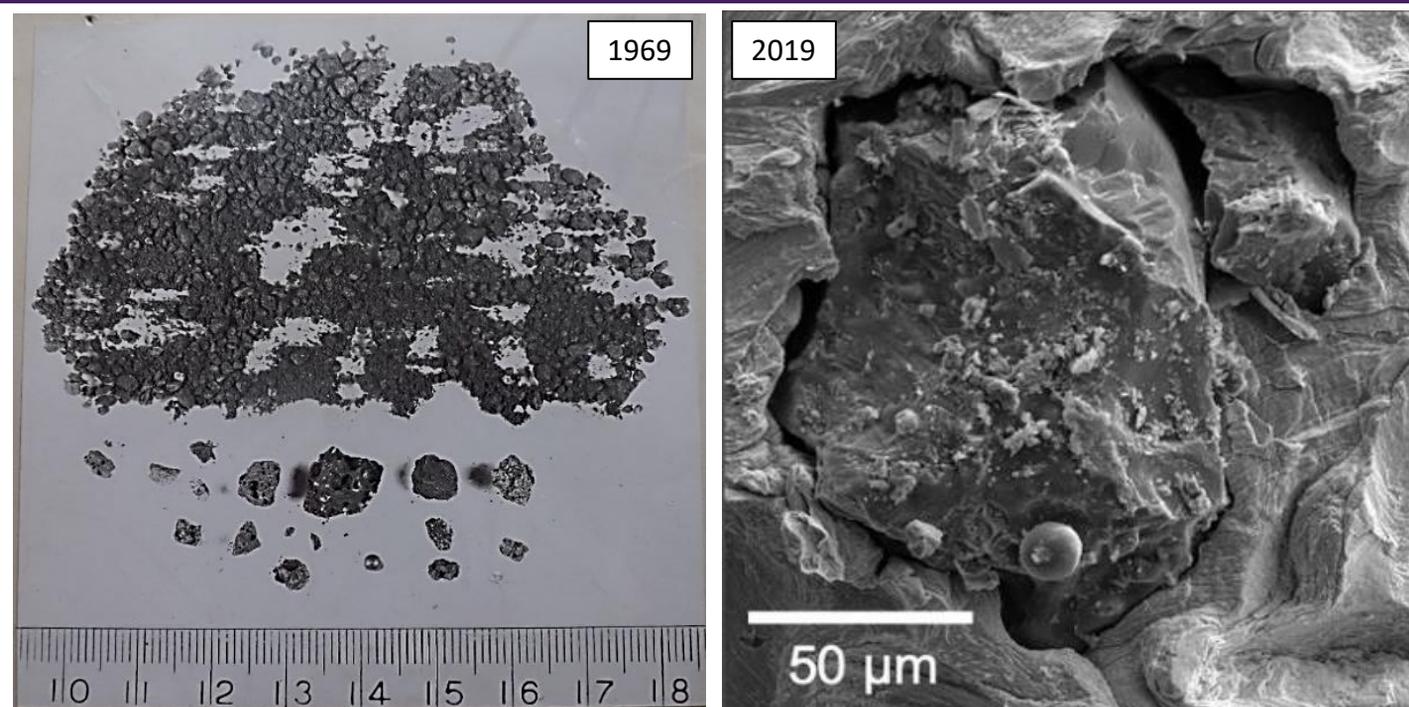


Figure 17: Analytical progress over the last 50 years: from XRF analysis (L), to nano-carpentry and imaging (FIB-SEM) (R).

$^{124}\text{Sn}/^{116}\text{Sn}$  provides further evidence of a similar liquid-vapour equilibration in the Moon-forming disc. Wang et al.<sup>[23]</sup> found that the lunar rocks are enriched in light tin isotopes compared to the Earth. Unlike chlorine, this tin isotope fractionation is inconsistent with volatile loss from a lunar magma ocean. Instead, the authors suggest that it reflects vigorous mixing between the protolunar disc and the Earth in high-energy conditions during the impact, followed by liquid-vapour equilibration and phase separation at around 2,500 K while the disc was cooling.

Cd is a moderately volatile siderophile whose 8 stable isotopes should lend themselves well to an understanding of the Moon's early thermal history. However, their chemistry is closely linked to nucleosynthetic processes and these have complicated their interpretation of lunar processes, Toth et al.<sup>[24]</sup>. Cu has also offered few opportunities to exploit its volatile nature and their tempting  $^{65}\text{Cu}/^{63}\text{Cu}$  ratios.

### State of the Art and Future Possibilities

In summary, the use of stable isotopes in volatile elements now offers a promising opportunity in determining how the Moon formed 4.51 billion years ago and in providing an insight into some of the igneous process that heralded the formation of the early lunar

crust. However, these studies still very much represent work in progress. Radiometric age dating for lunar and terrestrial samples as well chondritic meteorites has benefited over the years from a variety of complementary and now fairly well charted isotopic decay systems and their present estimates are summarised in Table 5.

Although geochemical and petrological differences between the Earth and Moon are subtle but distinctive and identify their common heritage, the physical differences are huge and reflect their separate evolution over the past 4.51 billion years (Figs. 11-16).

The bleak exterior of the Moon, (Fig. 11), displays the absence of water and any significant internal crustal disturbance throughout this extensive time period. The regolith coated surface of the Moon (Fig. 13) enhances this picture of a stagnant environment, a crust battered and crumbling. The geophysical data collected from the Apollo missions and other international sorties reveals a stratified internal structure with an early anorthositic crust, a thick cumulate pyroxene-rich mantle with little or no evidence of convective movement, and a small metallic core (Fig. 14). It is a picture of prolonged inertia, seen also in Fig. 15, based on geophysical data.



One of the oldest examples of this is found in north western Canada with the Acasta Gneiss formation of inter-banded tonalites and meta-basalts (Fig. 12). Older formations have been reported, but as yet unproven, in the Pilbara of western Australia. From the outset the Earth's mantle was busily building crust.

That activity is described by many authors but the concepts have a common pattern (Fig 16).

Scientific advances in the last 50 years have been remarkable. Durham University has managed to get itself a computer, its analytical equipment has moved from working at 1ppm using XRF to 1 ppt with ICP-MS, one million times better in that short time span (Fig. 17).

And that is by no means the end of it. In 1969 our excitement at seeing that 2 gram sample of lunar regolith was shared by the public as it represented a giant leap for mankind. They queued for hours just to get a glimpse of the regolith when it was exhibited for a couple of days in September at Durham University's Oriental Museum then known as the Gulbenkian Museum.

Today we can use nano-carpentry to take individual lunar minerals to pieces, element by element, Greer et al.<sup>[25]</sup>. A new science is borne and, with it, new opportunities to investigate the world we live in.

As we carry forward our research and make use of these new opportunities, we should perhaps just for a moment reflect on what was achieved in the 1960s and commend to our history the vision of John F Kennedy and the courage of that Edward Shackleton of space, Neil Armstrong and his gallant comrades (Fig. 18).



*Figure 18: Commander Neil Armstrong; the Great Explorer*

There is one final postscript. At his debriefing in 1971 I remember David Scott, who commanded the Apollo 15 mission, saying to us: "If, like me, you had stood on the surface of the Moon and looked back at planet Earth set in the inky blackness of space then you would know that mankind has nowhere else to go". To which he then added: "What are we doing in Vietnam?" Today, as we watch desperate refugees begging for our help and refuge one thing is certain: 50 years on, that lesson has still not been learnt; and mankind still has nowhere else to go.

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