Reconciling the Hydrogen and Chlorine Isotopic Signatures of the Moon

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"The Scotsman"

Fifty years after that 'one small step' there's a new rush to reach the moon

The discovery of water in Apollo 11's haul of rocks sparked great interest, writes **Dr Mahesh Anand**

When Apollo 11 landed on the moon on 20 July 1969, history was made. Fifty years later, it stands as arguably the greatest achievement of the 20th century and a testament to human endeavour and perseverance.

Astronauts Neil Armstrong and Buzz Aldrin spent just under 24 hours on the moon, including more than two hours of field work at the lunar surface. Meanwhile, Michael Collins circled the moon in the command module, perhaps best-positioned to contemplate the meaning of life or our place in the universe.

Down at the surface, Armstrong and Aldrin performed several experiments, but arguably their most important task was to collect the first ever samples of moon rock. Apollo 11 returned 22 kg of lunar samples to Earth. It was to be the first time that scientists were able to analyse moon rocks in Earth-based laboratories and set in motion a series of discoveries that continues to this day.

Over the past decade, I have been extremely fortunate to lead several projects working on Apollo samples at The Open University. Thanks to the Apollo astronauts and the curators at NASA, researchers such as myself – who weren't even born when the Apollo moon landings took place – are still able to study moon rocks and feel part of a shared historical adventure.

As the world celebrates the 50th anniversary of the Apollo 11 landing, The Open University also celebrates its 50th anniversary. By sheer coincidence, The Open University was awarded its Royal Charter three months before the first moon landing, heralding a new era, not just in space exploration, but in higher education. Not surprisingly perhaps, The Open University has championed space research for most of its existence. We are very proud of our continuing leadership in this global endeavour. Indeed, it has been very exciting to be involved in the theory-changing discovery of water in moon rocks, which had been thought to be devoid of it for almost four decades since the first samples were analysed in 1969.

Over the past decade, my team at The Open University have been undertaking cutting-edge laboratory research to look for water – and other associated elements such as carbon, nitrogen, oxygen – in moon rocks.

Our findings suggest the presence of a water reservoir in the moon which is similar to certain parts inside the Earth's structure. Furthermore, the distinctive chemical composition of the water in the lunar samples points towards it having a common origin with that of the Earth and asteroids.

Despite these Apollo samples having been collected 50 years ago, this field of research remains active, as many new questions have arisen. Some of these new questions can only be addressed effectively by returning to the moon with custom-built instruments to perform experiments, followed by missions returning samples from areas of the moon not visited by the Apollo missions.

As water is a key commodity and a precious resource for supporting space exploration – it is required for life support and can be used in radiation protection and rocket fuel – finding water on the moon has reignited interest beyond traditional space powers and a new "moon rush" has begun – just look at the number of new spacefaring nations and private entities targeting the moon.

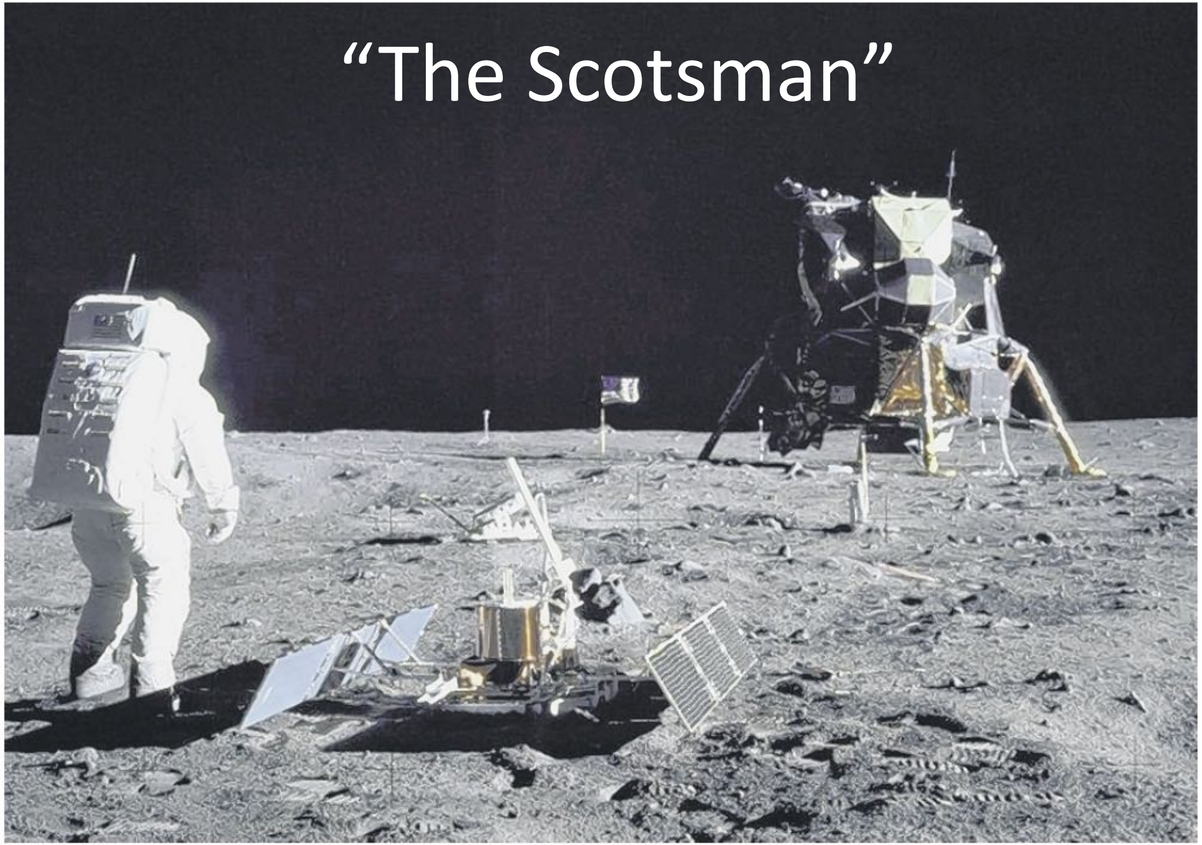
New research will explore the possibility of building habitats on the moon. The availability of water on the moon will play a vital part in realising our bold ambition of living there in the not too distant future.

As we look forward to the next 50 years of space exploration, we must acknowledge the contributions countless individuals made towards the success of what was once an unimaginable dream, of landing humans on another planetary surface.

Just as the members of the Armstrong clan in Dumfries and Galloway several centuries ago couldn't know that one of their descendants would walk on the moon, we must continue to inspire and engage the future Neil Armstrongs of the world who will realise the dream of extending humanity's presence to the moon and beyond in a safe and sustainable manner.

Dr Mahesh Anand is a reader in planetary science and exploration at The Open University. He co-ordinates the UK node of the NASA Solar System Exploration Research Virtual Institute.

Visit www.open.edu/openlearn/science-maths-technology/astronomy/apollo-11-and-50-years-research-on-moon-rocks



↑ Astronauts Neil Armstrong and Buzz Aldrin spent less than 24 hours on the surface of the moon but the samples they brought home from that brief visit proved to be an enduring field of study


8 DAYS
TO THE MOON AND BACK
Wednesday 10th July 2019, 9pm BBC2
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10058 (larger piece 5 cm)

Hydrogen abundance in the Moon

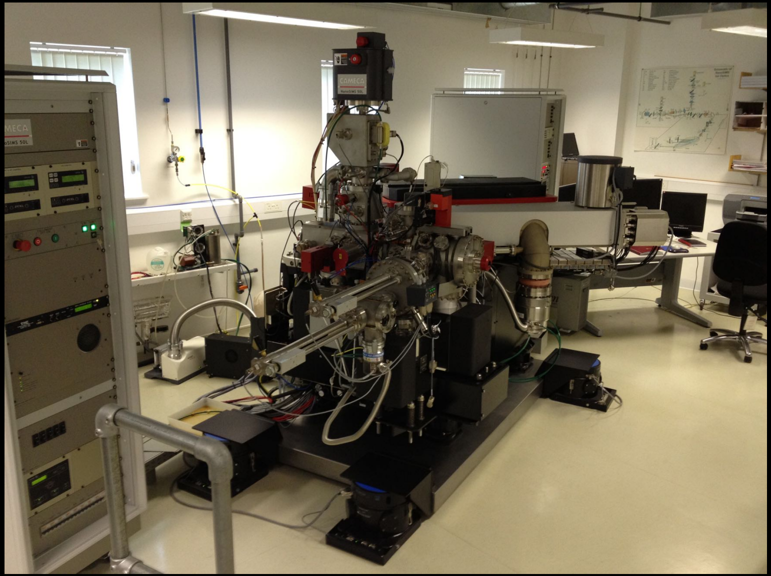
Water content in the lunar mantle ~1-100 ppm H_2O

Hydrogen isotopic composition of the Moon

Average δD of the bulk Moon: broadly chondritic:
-200 to +200 ‰ (Anand et al., 2014)

WR, glasses, melt inclusions, apatite, NAMs

Why melt inclusions?



Apatites

Formed late ~ >95% crystallisation
Prone to magmatic degassing

Melt inclusions

Expected to “keep” the pre-eruptive volatile signatures of the lunar magma

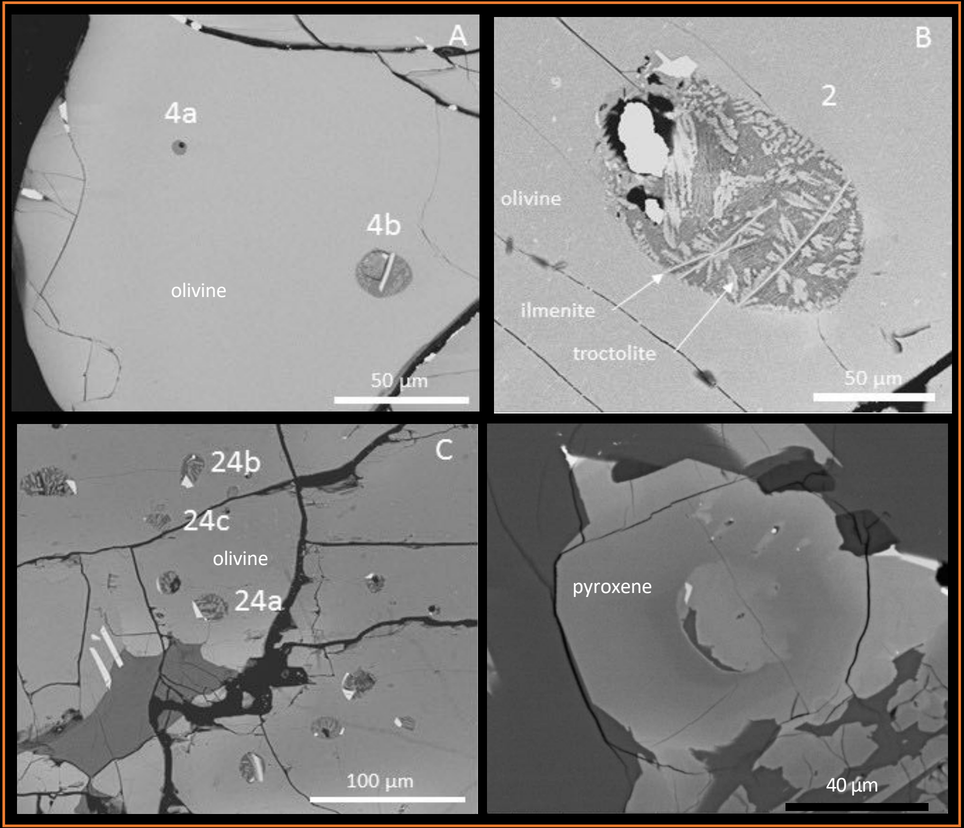
➔ H and Cl abundance of lunar mantle
➔ H and Cl isotopes of lunar samples and track their evolution through crystallisation

Sample selection

10020 High-Ti basalt
10058 High-Ti basalt

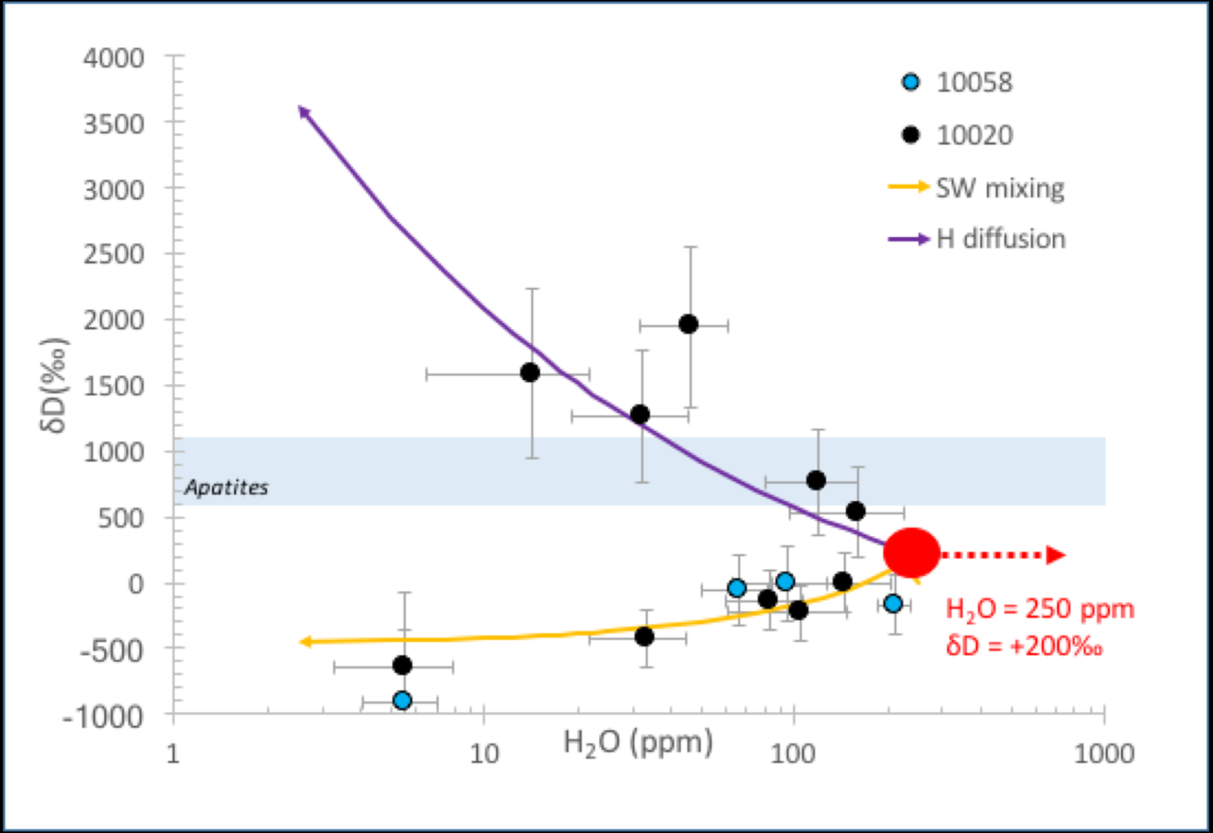
12002 Low-Ti basalt
12004 Low-Ti basalt
12008 Low-Ti basalt
12020 Low-Ti basalt
12040 Low-Ti basalt

14072 High-Al basalt
15016 Low-Ti basalt

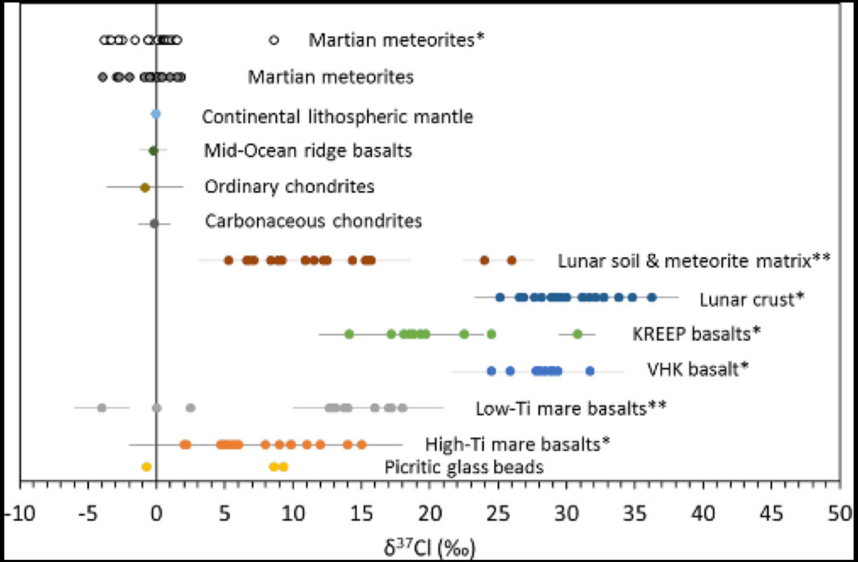


Apollo 11 (10020 + 10058)

H diffusion and
SW mixing



Chlorine isotopic composition of the Moon



Barnes et al., 2016, EPSL

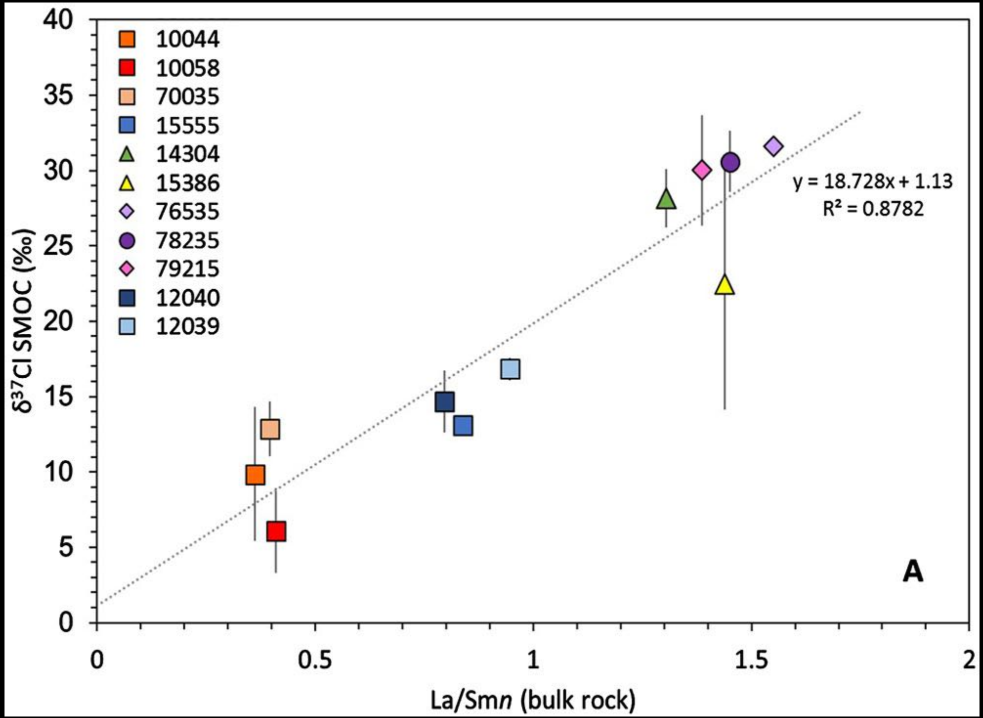
Earth $\delta^{37}\mathrm{Cl}$ ~ 0 ± 1.5‰

Moon $\delta^{37}\mathrm{Cl}$ ~ -4 to +40‰

$$\delta^{37}Cl(‰) = \left(\frac{^{37}Cl/^{35}Cl_{\mathrm{sample}}}{^{37}Cl/^{35}Cl_{\mathrm{SMOC}}} - 1\right) \times 1000$$

One of the few isotopic system that shows a difference between Earth and Moon.

Hypotheses to explain Cl isotope fractionation

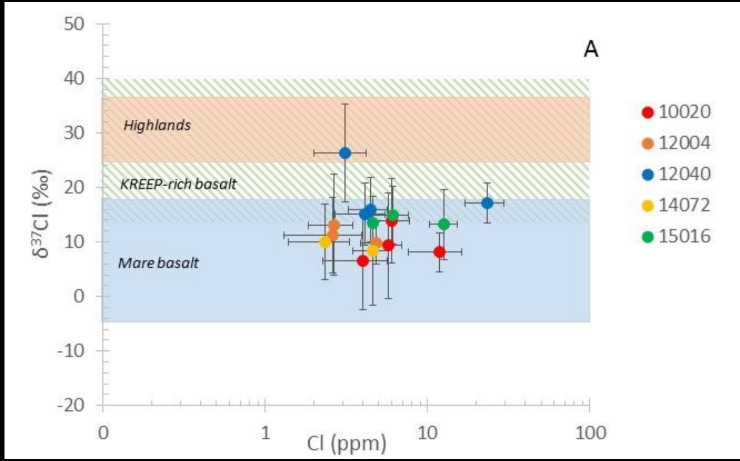


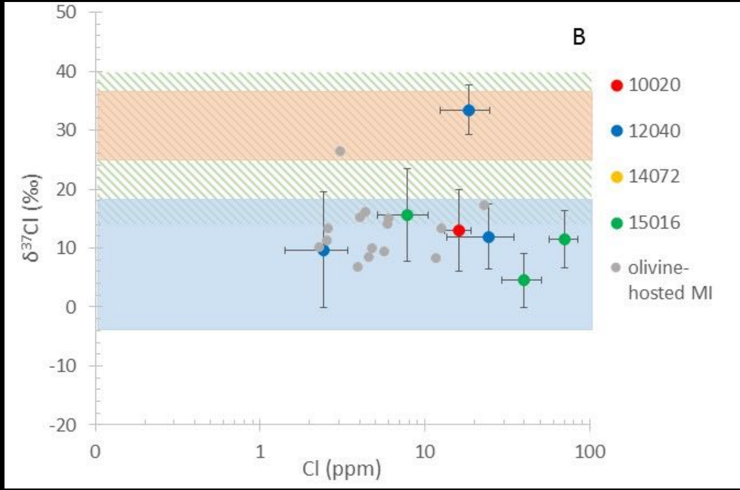
- Magmatic degassing (Sharp et al., 2010)
- Incremental degassing of the LMO (Boyce et al, 2015)
- Degassing of the KREEP-rich layer during crust-breaching impact (Barnes et al, 2016)
- Apollo 14: Vapour induced metasomatism (Potts et al, 2018)

Exceptions : High-Ti basalts, Kal 009 (Barnes et al., 2019)

Barnes et al., 2016, EPSL

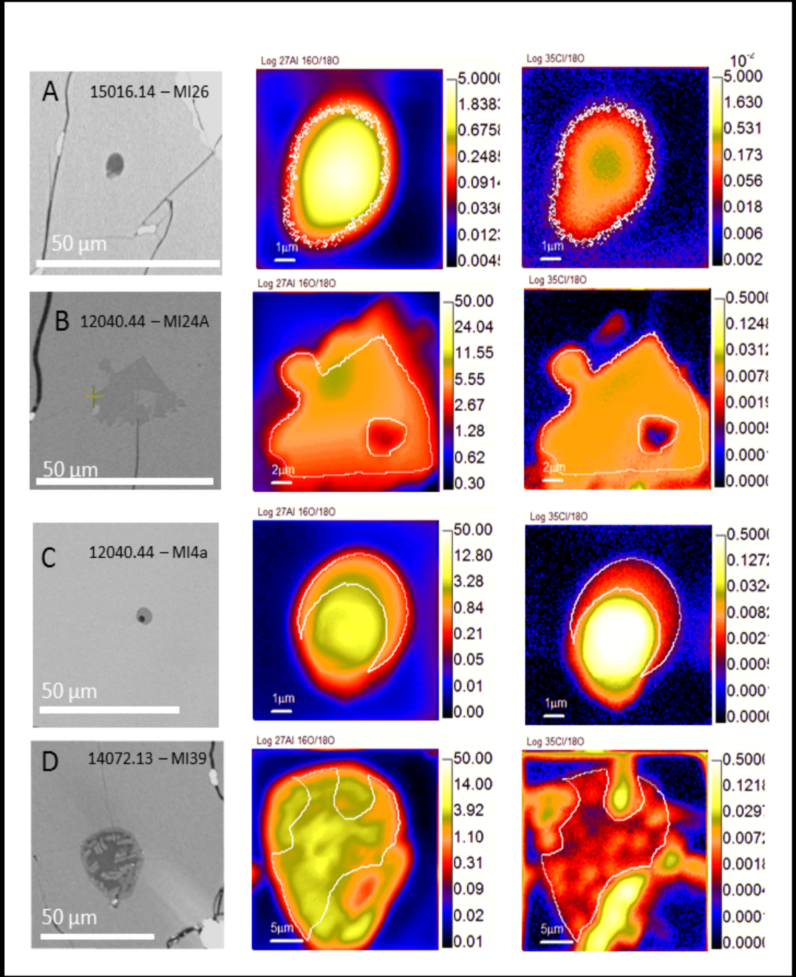
Melt Inclusions in Apollo Mare Basalts





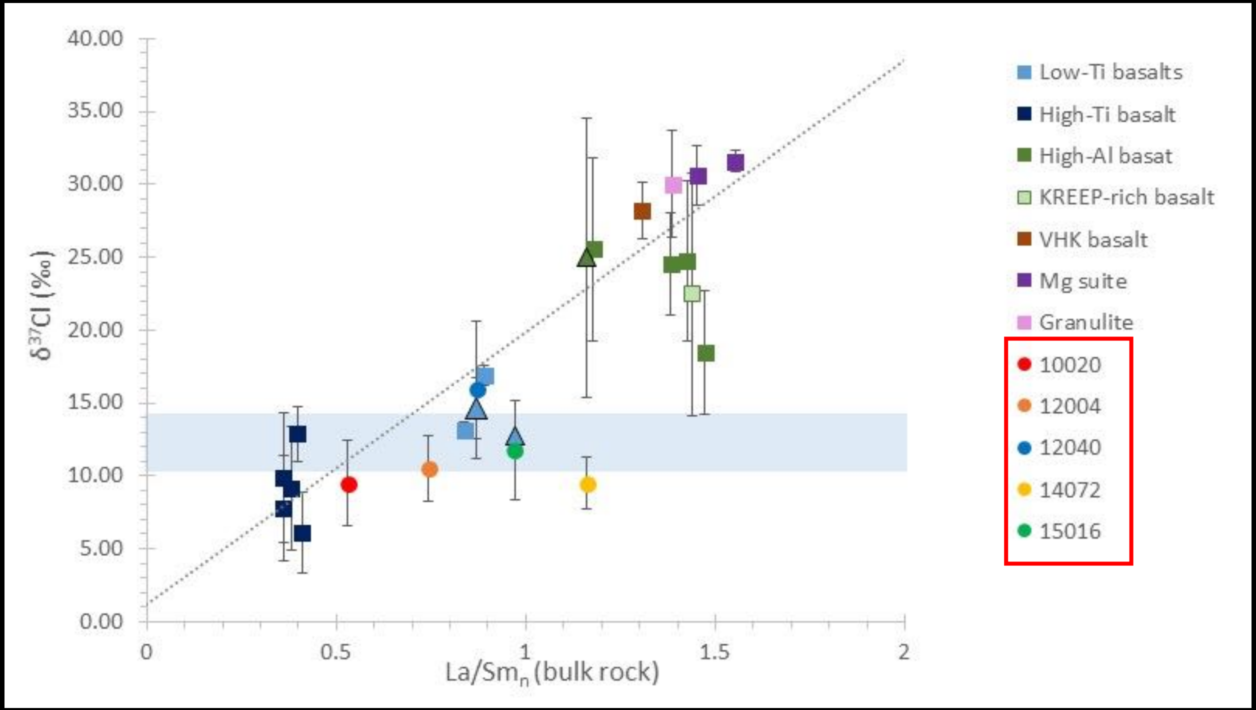
$\delta^{37}Cl$

12 ± 2 ‰



Stephant et al., 2019, EPSL (accepted)

Comparison with apatites



All MIs from 5 samples from 4 different locations have a similar $\delta^{37}Cl = +12 \pm 2$ ‰

➔ Heavy $\delta^{37}Cl$ not entirely a function of urKREEP (additional processes)

Conclusions

- Lunar mantle H_2O concentration lower limit at ~25 ppm
- H_2O-δD systematics of lunar MI show large fractionation, induced by a variety of processes (solar wind mixing, H diffusion)
- The initial lunar juvenile δD = -200 ‰ and 200 ‰,

- The average $\delta^{37}Cl$ of MI from olivines and pyroxenes is similar to the average in apatites from *most* basaltic samples
- Suggest chlorine isotope signature of mare magmas weren't modified during eruption and crystallisation (i.e. original signature < 12 ‰)

- Appreciable H in the lunar interior with an elevated Cl isotope signature (view from Apollo) – **samples from other areas of the Moon required for a complete picture!**

Acknowledgements

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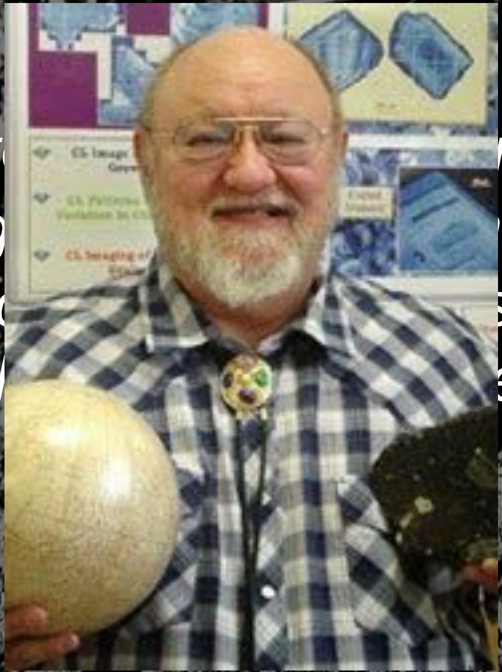
- NASA CAPTEM
- Prof Lawrence (Larry) Taylor



"As we look forward t… rs of space exploration, we must acknowledg… s countless individuals made towards the suc… s once an unimaginable dream, of landing … er planetary surface"