WORKSHOP SUMMARY: FRONTIERS IN MARS SAMPLE CHRONOLOGY

Whether Mars could have supported life has driven intensive exploration of the planet's surface through satellite and robotic missions. Complementary research has focused on identifying and understanding meteorites from Mars, which offer the only direct samples of the martian crust available to science. These studies have sought not only signs of extraterrestrial life and habitable environments but also to understand how the planet has changed over time, from an ancient world of oceans and landforms with striking similarities to Earth, to the cold, barren, planet we observe today. Why Mars has followed a dramatically different path to Earth is one of the key questions in the understanding of terrestrial planet evolution.

Determining the absolute ages of samples from Mars is key to addressing these issues and a principal objective for current and future Mars exploration. Recent work on martian meteorites has pushed the analytical envelope for Mars sample geochronology, overcoming the challenges posed by pervasive shock metamorphism during impact ejection from Mars, microscale heterogeneity, and very low concentrations of radiogenic isotopes. This work is vital for interpreting the geochronology of the martian samples that are to be returned to Earth through the Mars Sample Return, an effort that will start with the collection and caching of samples by the NASA Mars 2020 *Perseverance* Rover Mission. A virtual workshop on Mars geochronology, which was co-sponsored by the Mineralogical Society of Great Britain and Ireland and the Meteoritical Society, was held 24 March 2021 via Zoom.

Over 60 people from 13 countries registered for the workshop; online attendance peaked at 30 attendees midway through the 4-hour session. The workshop began with opening remarks by co-convener James Darling (University of Portsmouth, UK). Fellow co-convener Chris Herd (University of Alberta, Canada) then gave an overview of progress made in the geochronology of martian meteorites, beginning with the seminal 1986 U–Pb study by J.H. Chen and Gerald J. Wasserburg – done at a time when only a handful of martian meteorites were known – progressing through the Rb–Sr and Sm–Nd isotopic studies of Lars E. Borg, Laurence E. Nyquist, and others, and finishing with recent advances in ion microprobe analyses of U–Pb isotopes in accessory minerals such as baddeleyite.

The first few talks of the Frontiers in Mars Sample Chronology workshop summarized recent geochronological studies of martian meteorites. Leanne Staddon (University of Portsmouth, UK) described the correlation – or lack thereof – between the degree of shock metamorphism and the amount of Pb loss in baddeleyite, demonstrating that microstructural studies of baddeleyite are important to carry out but that this mineral lives up to its reputation of retaining Pb through shock events. Stephanie Suarez (University of Houston, Texas, USA) summarized work done on the famed Tissint meteorite from Mars, which fell 18 July 2011, including new Rb–Sr isotopic results indicating that labile Sr is present in the rock, perhaps mobilized at the time of impact ejection from Mars. Minako Righter (University of Houston) summarized the wide range of studies done in the University of Houston laboratory in recent years, highlighting results from some meteorites that have ages distinct from others; significantly, these "oddballs" also have igneous textures that differ from other martian meteorites. The takeaway message is that it may be worth concentrating geochronological effort on these igneous textured meteorites. This would be a useful criterion given the plethora of martian meteorites that now exist in the world's collections.

The toolkit for the geochronology of planetary materials (whether meteorites or returned samples) is increasingly broad. James Darling provided an overview of some of these tools, highlighting new approaches to extract grains for high-precision mass spectrometry that uses a plasma source focused ion beam, as well as the utility of methods for microstructural analysis (e.g., electron backscatter diffraction) which can provide geological context for microbeam analyses and atom probe tomography. The latter technique has provided impressive trace element and preliminary isotopic results from nanoscale sample volumes. This was no more evident than in a presentation by Gabe Arcuri (University of Western Ontario, Canada) who showed that a remarkably detailed history can be obtained from atom probe tomography analysis of baddeleyite or zircon, including the effects of thermal metamorphism (or lack thereof) to low-temperature alteration events.

The limitations of current methods were also a common theme in the workshop. Alex Sheen (University of Alberta, Canada) used micro-drilling to extract mineral powders to study the minimum amount of analyte (e.g., Sr) required to determine an isochron using current mass spectrometry techniques. The answer is that, at least with current technology, micro-drilling provides no real advantages over mineral separation. However, Alex's study indicated the directions in which the micro-drilling technology needs to advance.

Noting that we cannot always bring back samples from other planets, Barbara Cohen (NASA's Goddard Spaceflight Center, Maryland, USA) provided a comprehensive overview of state-of-the-art instruments designed for in situ geochronology. Multiple techniques are in development, including those that utilize the K–Ar, the Rb–Sr, and the U–Th–Pb systems. Advances in laser-induced breakdown spectroscopy, coupled with mass spectrometry, are particularly intriguing, because this technique obviates the need for samples to be collected and manipulated onboard a spacecraft: this is an advance that parallels those made in ion microprobe mass spectrometry for laboratory-based analyses.

One of the main goals of the Mars Sample Return is to assist in establishing a timescale for Mars. Currently, this timescale is based on the cratering chronology of the Moon, extended (with assumptions) to Mars. Fred Calef (NASA's Jet Propulsion Laboratory, California, USA) provided an invited overview of the challenges involved in this endeavour, highlighting the assumptions that are intrinsic to a crater frequency–based chronology. An absolute age derived from a returned Mars sample that represents a specific event on Mars would provide a "golden spike" for a Mars chronology and a test of the assumptions involved in the extrapolation of the lunar record. But how to choose the right rock for this? Studies of the floor of Jezero Crater (*Perseverance*'s landing site) have already demonstrated the complex exhumation history of the surface and the challenges involved in choosing a sample that would be suitable. Perhaps more useful would be an impactite that could be tied to the impact event that formed the Isidis Basin. Alternatively, at least two samples from a unit that extends across the area within and near Jezero Crater would be even better choices.

We know that there are numerous challenges involved in developing a Mars sample chronology: these include the complex histories of martian meteorites, and the difficulty in finding samples that will establish an absolute martian timescale. The good news is that the toolkit for establishing such a geochronology continues to grow. In this way, the frontiers advance at a remarkable pace, and the organizers of the workshop Frontiers in Mars Sample Chronology hope to hold follow-up workshops and track these advances into the future.

Recordings of the presentations are available at the workshop website: https://www.minersoc.org/mars-chron.html

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