HOW TO ACQUIRE A SUCCESSFUL IN-SITU DATE: CODEX MISSION DESIGN. F. S. Anderson[1], T. J. Whitaker[1], and J. Levine[2], [1]Southwest Research Institute, Department of Space Operations, Southwest Research Institute, 1030 Walnut St., Boulder, Colorado 80302, USA (whitaker@boulder.swri.edu), [2]Department of Physics and Astronomy, Colgate University, Hamilton, New York 13346, USA.

Introduction: We have developed a rubidium-strontium (Rb-Sr) in-situ dating technology called the Chemistry, Organics, and Dating EXperiment (CODEX) [see abstract *CDEX/CODEX Instrumentation for In-situ Dating on the Moon and Mars*]. Using CODEX requires careful mission design and site selection to maximize the confidence in the measurement and better constrain the history of the solar system. In this abstract, we describe our approach for optimizing results for the Moon, though the planning process is equally applicable to Mars.

Science Background: The chronology of the inner solar system is based on models relating the crater densities of planetary surfaces to calibrated radiometric dates of well-provenanced lunar samples that primarily constrain the era between 3.5 and 4.2 Ga, as well as the very recent past. These results have been extrapolated to Mars, and throughout the solar system. However, recent work comparing the numerous lunar chronology models in the literature [e.g., 1, 2], illustrates differences between the models of up to one billion years for the period between ~2.8 to 3.3 Ga [3]. For the Moon and Mars, this period is geologically rich, including the cessation of abundant volcanism, and, for Mars, the apparent termination of volatile production and formation of hydrated minerals. Under the new chronology functions, these processes could have lasted for a billion additional years, undermining models for thermal evolution of the Moon; similarly, Mars would have undergone a longer epoch of voluminous, shield-forming volcanism and associated mantle evolution, as well as a longer era of abundant volatiles and hence potential habitability.

These differences are primarily due to different estimates of crater densities observed in Lunar Reconnaissance Orbiter data, and a lack of samples from terrains with N(1) crater densities of ~0.0015 km^{-2} to 0.0025 km^{-2}. This seemingly small range is associated with the time period from ~1-3.5 Ga, with model differences of 1.1 Ga (**Fig. 1**) occurring at about 3 Ga. For periods older than 4.2 Ga, chronology models are limited by the lack of N(1) observations, and may be best constrained by returned samples. Thus, the most straightforward part of the chronology curve to refine is associated with previously unsampled Eratosthenian near-side terrains, such as the Aristarchus basalts.

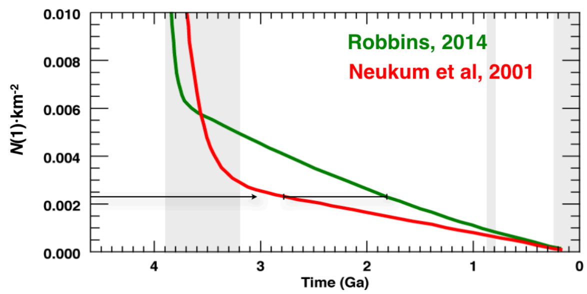

Figure 1: Example of different models mapping N(1) crater density to time, resulting in differences of up to 1.1 Ga [5]. Gray zones are well constrained by samples. Arrows show previously unsampled N(1) densities optimal for obtaining new dating constraints.

Large lava flows in the Schiaparelli region could be readily targeted for future missions. Similar regions could be identified for Mars, and used as a constraint on models relating cratering rates to the Moon, and hence the lunar chronology.

Mission/Instrument Approach: Maximizing scientific confidence for in-situ dating will require verifying that the landing site has a) sufficient samples (rocks) that are basalts (not breccia's) appropriate for dating, and b) that they are compositionally similar and hence likely endogenous. Following the Apollo missions, a rake provides a simple way to reveal numerous rocks, and this is not expected to be a limiting factor. These samples will need to be examined at a near microscopic level for vesicles and potential brecciation, and elementally and mineralogically assessed.

We have developed missions scenarios for raking the terrain, mapping rock positions, and then analyzing each sample. The analysis process consists of two phases, the first assessing the sample microscopically and mineralogically (using a camera and NIR/IR spectrometer), and the second elementally and isotopically (using CODEX) [see abstract *CDEX/CODEX Instrumentation for In-situ Dating on the Moon and Mars*]. During the first phase we use a robotic arm to pick up rocks of size 0.5-2" (appropriate for CODEX analysis), assess them microscopically and mineralogically, then grind a flat onto a sample face, and finally reassess them microscopically and mineralogically. This process is automated with the exception of sample acquisition, and takes about 10 hours each. Grasping the sample takes about two of these hours, including contingency for six total grasping attempts. Note that for lunar missions, latency is such that grasping of samples can be accomplished with real-time video feedback, and is unlikely to take this long.

If the sample is a basalt with appropriate mineralogy, we proceed to phase 2, in which we assess the rock with CODEX; otherwise, the sample is rejected. This takes an additional 2 hours. CODEX has an accuracy better than ±200 Ma (1-σ), the capability to measure elemental context, and in the future, the ability to provide Pb-Pb dates with accuracy as good as ±50 Ma (1-σ) to test concordance [see abstract *Multianalytical Science with the CODEX In-situ Dating Spectrometer*].

Likely Fraction of Datable Rocks: Orbital studies of the Schiaparelli region show that there are large basalt flows that appear to be ideal candidates for landing, that a) have uniform low crater densities, b) are chemically homogenous, and c) present few landing hazards. These regions appear most similar to the Apollo 17 landing site, but share some similarities to Apollo 11 and 16, with 45% and 33% datable rocks, respectively. We consider all of these scenarios, below.

Required Number of Samples: We anticipate that the young flow will not be contaminated with abundant ejecta from other terrains, however, we will conservatively assume that from 1-3 terrains are represented within the lander arms reach. Furthermore, for each potential terrain present, we will require a minimum of three similar measurements for an interpretation. This means that we require 3-9 successful measurements. Using the binomial theorem, the fraction of datable rocks (above), and the number of screening measurements (phase one) required, we can assess the odds of measurement success (**Table 1**); we require a minimum of 95% certainty.

The results of this analysis show that for a fraction of usable samples like Apollo 17 and a single terrain, a total of only 15 samples need be screened using the first phase of analysis. For the worst case scenario of 33% datable rocks, and three terrains, some 50 samples need to be screened in phase one.

Table 1: Required number of samples for a landing site with rocks from 1-3 terrains, and a "datable" fraction of samples ranging from 33%-60%. Numerous landing sites appear similar to Apollo 17, and having only a single terrain, consistent with a requirement of 15 screening measurements; worst case is 50.

Number of terrains =>	1	3
Required samples =>	3	9
Percent suitable	Odds of success (samples required)	
Apollo 16 rake: 33%	100.0% (30)	98.6% (50)
Apollo 11: 45%	100.0% (20)	100.0% (40)
Apollo 17 rake: 60%	**100.0% (15)**	100.0% (30)

Required Mission Duration: If 15 samples need to be screened along with three phase two dating measurements, for one terrain (3 total CODEX measurements), this requires 156 hours total time. However, for the worst case contingency scenario, requiring screening of 50 samples, and three phase two dating measurements for three terrains (a total of 9 CODEX measurements), we require 518 hours. Assuming mission operations occur during usable lunar daylight (~320 hours), a lunar mission requires two lunar days.

Data Sufficiency: To provide confidence in measurement results, most geochronologists assess interpretations against a two-sigma standard. *Robbins et al.*, [3] calculated the differences between models (**Fig. 2**), and determined that at the two sigma level, the models have a range of 500-800 Ma. In both our nominal and contingency cases, we will have three measurements with precision of at worst ±400 Ma (2-σ), limiting our precision to about ±230 Ma (2-σ), more than sufficient to assess differences in the chronological models.

However, if our nominal model is correct, and we have a single terrain, but within our contingency make nine measurements, our statistical precision will improve to about ±140 Ma (2-σ). The limiting precision of CODEX is currently unknown, though our Pb-Pb measurements indicate that it could be as low as ±50 Ma. Because these measurements are of a single element, and are in the process of being implemented, we currently baseline ±140 Ma. This highlights the benefits of implementing both Rb-Sr and Pb-Pb dating, for both the additional accuracy and for assessing concordance.

References: [1] Hartmann et al (2007) *Icarus*, 186(1): 11-23. [2] Marchi et al (2009) *The Astronomical Journal*, 137(6): 4936. [3] Robbins (2014) *EPSL*, 403: 188-198.

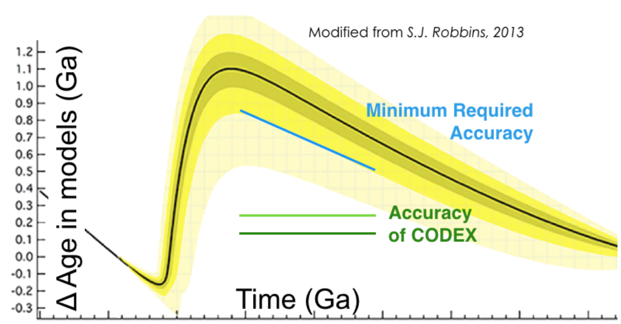

Figure 2: Expected and worst case 2-σ accuracy of CODEX mission is better than 2-σ science requirement.