MODELS, MODELING, SCIENTIFIC REASONING, AND TERRESTRIAL PERSPECTIVE ON FORMATION OF ZEOLITES ON EARLY MARS. G. R. L. Kodikara[1], L. J. McHenry[1], T. J. Grundl[1], F. D. van der Meer[2], and M. T. Harris[1], [1]Department of Geosciences, University of Wisconsin-Milwaukee (gayantha@uwm.edu), [2]University of Twente, Faculty of Geo-information Science and Earth Observation (ITC), Hengelosestraat 99, 7514 AE Enschede, the Netherlands.

Introduction: Analcime is the only zeolite group mineral identified on Mars based on its distinctive broad absorption band centered at ~ 2.5 μm and a weaker absorption at ~ 1.8 μm. Identifying other zeolite species is complicated by the lack of diagnostic absorption bands in the visible-shortwave infrared (VIS-SWIR) region, their spectral similarity with polyhydrated Mg-sulfates, and whether the target mineral is mixed with other minerals [1]. It is also important to note that zeolite minerals have not yet been identified from in situ observations or from Martian meteorites.

In this study, we examined the use of multiple hypotheses and different scientific reasoning styles to address why zeolites are not commonly observed in paleolake basins on Mars. Zeolites may not be identifiable in certain locations on Mars using spectral data if they are absent (H1), or they were originally present and later removed by chemical processes (H2), or they are present but are covered by or mixed with other materials (H3), or they are present, but the methods applied are not capable of detecting and mapping them (H4), or they are present, but we are not looking in the correct places (H5). These five working hypotheses were tested using six different styles of scientific reasoning as introduced in Alistair Crombie's 20-year study of Styles of Thinking in the European Tradition [2] with suitable examples. The scientific reasoning methods implemented in this study include 1) analogical reasoning, 2) categorization and classification, 3) hypothetical modeling, 4) historical-based evolutionary reasoning, 5) experimental evaluation, and 6) probabilistic and statistical reasoning. The overall concept of the study is illustrated in Figure 1.

Methods: 1) *Analogical reasoning:* We used spaceborne hyperspectral Hyperion and multispectral ASTER data at zeolite-bearing paleolake Tecopa, California as an analog site to identify the capabilities and limitations of identifying and mapping zeolites from orbital data following ground truthing and X-ray Diffraction and VIS-SWIR spectral analysis of collected samples containing zeolites and other associated minerals [3]. 2) *Categorization and classification:* The most common authigenic minerals and their paragenetic relations in saline-alkaline paleolake systems on Earth were examined using a combination of two machine learning classification methods, Self-Organizing Maps (SOM) and Decision Tree (DT) analysis. The published bulk mineral abundance data from 1648 zeolitic tuff bed samples from thirteen paleolake deposits from the USA, Mexico, Greece, and Tanzania were used [4]. 3) *Hypothetical modeling:* Geochemical modeling was used to identify zeolite phases that could have formed in closed lake basins of late Noachian Mars. The simplified composition of the high-silica Buckskin sample from Gale crater and the rainfall collected during the eruption at the subglacial basaltic Bardarbunga volcano at Holuhraun, Iceland, in 2014 was selected as starting material and solution for the model, respectively [5]. The calculation was done using the EQ3/6 code [6]. 4) *Historical-based evolutionary reasoning:* We compiled the database of 150 non-marine zeolite deposits from multiple continents using available published studies that documented the time period of their formation. The frequency of occurrence of analcime, chabazite, clinoptilolite, erionite, and phillipsite as a function of geologic age (place substituting for a time in stage-theorizing) was plotted to understand the stability of these minerals over the geological history of natural earth environments. 5) *Experimental evaluation:* A series of mineral mixtures were prepared using ground (< 150 μm particle sizes) clinoptilolite, montmorillonite, and epsomite at 10 % increments. The VIS-SWIR reflectance spectra of these mineral mixtures were used to examine the effects of other minerals, in this case, montmorillonite and epsomite for the identification of clinoptilolite using spectral data [7]. 6) *Probabilistic and statistical reasoning:* A data-driven fuzzy-based weights-of-evidence predictive model was developed to delineate the best areas to look for zeolites on Mars. The model used the global mineralogical, geological, geomorphological, physical, and elemental abundance maps derived from the orbital data as evidence maps with the locations of the detected hydrous minerals using orbital data for the known mineral occurrences. The map of the pyroclastic ash distribution is used to delineate the areas where zeolites can be found with higher probabilities based on the conceptual model created in this study. All the input maps were created using available published data [8].

Results: The identified analcime detections from previous studies are hypothesized to form by hydrothermal alteration (e.g., [1]). However, this study and previous geochemical modeling showed that these zeolites can also form at low temperatures (0 - 25° C), both from basaltic and high silica starting materials [5]. Therefore, based on the orbital detection of "analcime" and thermodynamic point of view, there is no reason to accept hypothesis 1 (H1). Geochemical modeling showed that some zeolites (e.g., clinoptilolite) are dissolved over time while other zeolites (e.g., analcime) precipitate [5]. The frequency of occurrence of zeolites as a function of geological age shows that analcime is more stable than the other zeolites over the long geological time span (also suggested by geochemical modeling). While analcime might be the most common zeolite detected on Mars, this does not mean that other zeolites are absent, as they might be present but less abundant. The experimental study on the spectra of mineral mixtures shows that our ability to recognize zeolites from reflectance spectra is suppressed when zeolites are mixed with clay minerals or polyhydrated Mg-sulfates [7]. Therefore, if zeolites are mixed with clay minerals, as commonly observed in Lake Tecopa and other saline-alkaline terrestrial sites described in [4], they will be difficult to identify using orbital data. The Lake Tecopa analog study showed that most zeolite-rich tuff beds are covered by other types of beds and later mixed with other beds due to erosion and/or formed as an accessory phase in claystone [3]. The burial of thinner beds due to later deposition (e.g., layering) or dust and erosion are also common processes in sedimentary environments on Mars. Our experimental data from binary mineral mixtures also shows that it is difficult to distinguish non-analcime zeolites from Mg-sulfate minerals as some previous studies discussed (e. g., [9]). The results of the fuzzy weights-of-evidence model provide the potential sites to look for zeolites for future detailed analysis using in situ or orbital data [8].

Conclusions: Based on the above studies, H1 can be rejected and H2 can be modified (even though some zeolite facies dissolve or alter with time, some zeolite facies remain or form). H5 will need to be studied in detail and H2, H3, and H4 can be fully answered only by using in situ observations.

The geochemical-thermodynamic and analog terrestrial studies conclude that there is a high possibility of the presence of zeolites on Mars but covered by and/or mixed with dust or other sediments or cannot be definitively identified using orbital data.

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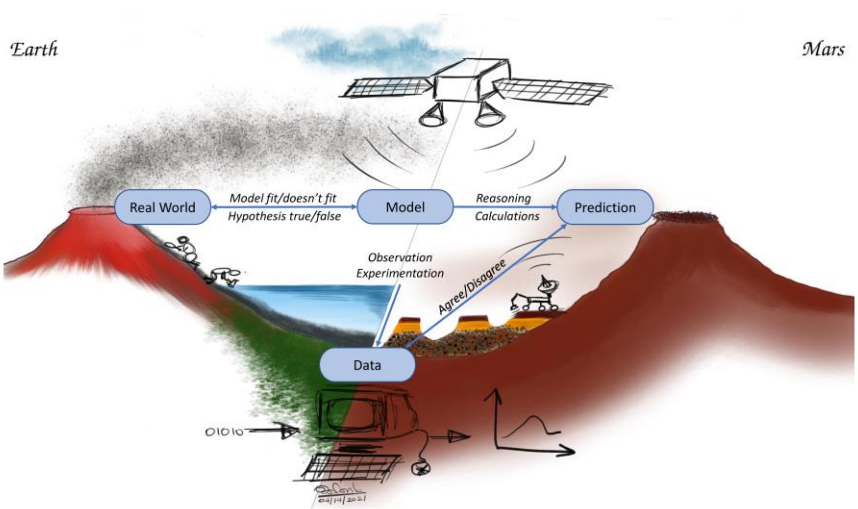

Figure 1. The relationship between the real world, conceptual models, and the concepts behind the scientific reasoning methods used in this study. Paleolake Tecopa and other zeolite-bearing paleolake deposits on the Earth were taken as real-world examples and data collected from those sites were compared with the in situ, orbital, and meteorite data from Mars using different models to assess the formation and possible presence of zeolites on Mars. The different environmental conditions on both planets were incorporated into the models. Predictions were assessed using the multiple hypotheses formulated in this study.