NEW TOOLS TO DETECT CARBONATE-BEARING SURFACES ON MARS AND POSSIBLE DETECTIONS OF LOW ABUNDANCE CARBONATE IN NOACHIAN CRUST. E. S. Amador\textsuperscript{1}, B. L. Ehlmann\textsuperscript{1,2}, J. L. Bandfield\textsuperscript{3}, N.H. Thomas\textsuperscript{4}, \textsuperscript{1}California Institute of Technology, Division of Geological and Planetary Sciences (esamador@caltech.edu), \textsuperscript{2}Jet Propulsion Laboratory, California Institute of Technology, \textsuperscript{3}Space Science Institute

**Introduction:** Carbonate-bearing signatures have been observed in martian meteorites, martian dust, and on the martian surface from in-situ and orbital data [1-4]. However, discrete carbonate occurrences account for only a small percentage of the occurrences of secondary phases detected on the surface of the planet [5]. The apparent paucity of carbonates is of particular importance to understanding the evolution of Mars climate because they should form readily under the presence of a thicker CO\textsubscript{2} rich atmosphere and surface liquid water [6,7]. Transfer of CO\textsubscript{2} from atmosphere to the crust via carbonates may be an important process in its loss [8,9]. Several studies have argued that there may be a reservoir of carbonate-bearing bedrock in the subsurface that is yet to be probed by orbital datasets [10].

This work aims to comprehensively search for carbonate phases using statistical tools that can tease out their spectral signatures that may otherwise be missed. Use of factor analysis and target transformation (FA/TT) on shortwave-IR CRISM hyperspectral data to identify carbonate has been validated in regions with known carbonate-bearing outcrops identified by traditional CRISM analysis techniques [11,12]. A strength of this principal components-based method is that it can be used to identify endmember spectral components that may not exist on the surface in pure unmixed form [13]. Here we examine clear FA/TT fits to carbonate spectral components in regions where carbonate has not been observed previously. These may represent an underlying low-concentration of carbonate in portions of Noachian bedrock.

**Methods and Approach:** Factor analysis is a form of eigenanalysis that reduces a set of data, (in this case a CRISM hyperspectral image) into eigenvectors and values. Each eigenvector represents an abstract factor of that set of data that independently varies. If the data were free of error, then the process would yield \( n \) eigenvectors (where the \( n+1 \) and higher eigenvalues would be 0), one for each independently variable factor of the data, which represent compositional endmembers, (i.e., minerals). Previous studies [11] and this work have shown that for CRISM data, the first 15-20 eigenvectors can be used to reconstruct most variability within an image. We employ similar methods to those described in [11,12].

Via target transformation, the calculated eigenvectors can be combined to evaluate whether the datasets contain specific components. We test for target library endmembers, such as Mg-carbonate, that can be reconstructed with eigenvectors [13]. If the target vector is an independently varying component within the data, the modeled fit will be similar to the target. If the target and modeled fits are dissimilar, the tested parameter is not a real factor, leading to the rejection of the particular target endmember as a component within the data.

To extend prior work [11,12], we evaluate statistical criteria for determining the success or failure of the target testing. This involves testing various “goodness of fit” or spectral similarity parameters such as relative root squared error and spectral angle distance (SAD) [14]; for both these approaches, a lower value implies a better fit. We also test whether the SAD index can be used to predict the spatial surface expression of the tested component.

**Results:** Validation. We used CRISM image FRT3E12 to test various approaches in the number of eigenvectors calculated, the number of pixels included in the calculation, and use of the SAD approach to predict spatial occurrences of carbonate within an image (Fig 1). We found that 20 eigenvectors were necessary to match a strong fit to Mg-carbonate in this image using every third pixel of the entire image. We have created a SAD index image to understand how each pixel within the image relates to the modeled target transformation spectrum. The example shown in Fig. 2 indicates that the SAD value can correctly identify the pixels with the strongest match to the modeled Mg-carbonate endmember.
We validated the robustness of this method by confirming carbonate non-detections in regions where carbonate is not expected to occur, e.g., in Cross Crater, where the discovery of alunite [15] indicates acidic and sulfurous waters. The target transformation generates poor fits to carbonate and relatively strong fits to an alunite library endmember (Fig. 2), providing confidence in this method’s ability to identify primary components within an image. The lack of carbonate was similarly validated in Gale Crater CRISM images where ground-truthed rover data do not indicate the presence of measureable carbonate [16].

**Preliminary Global Search for Carbonate.** A global sampling of CRISM images were tested for fits to Mg, Ca, and Fe-carbonate, yielding promising results. Regions with known occurrences of carbonates were correctly identified with this independent method (e.g., Nili Fossae, Leighton Crater). Dusty regions were void of carbonate matches, consistent with dust obscuring the underlying surface to spectral investigation. Several regions were identified with strong fits to carbonate where they have not been previously detected using surface I/F measurements. E.g., images from the Mawrth Vallis region, known for a high concentration of Fe/Mg- and Al-bearing phyllosilicates, show consistent detections of Mg-carbonate (e.g., FRTA955 Fig.3A). SAD values for the modeled magnesite to the target case are strong, however, a SAD index image (Fig.3B) shows relatively weak fits to the modeled magnesite across the image, related to regions that contain phyllosilicate. This indicates that there are no discrete locations that contain this “pure” endmember but rather this spectral component may be present at a low spectral variance within the altered bedrock (and therefore likely low concentration) such that it is identified by the factor analysis.

The region west of Nili Fossae within and around Toro and Negril Craters also have strong modeled fits to all three carbonate endmembers tested, and form two spectral groups implying a diverse carbonate compositional suite (Fig. 4). Hydrated silica and phases indicative of localized hydrothermal activity have been identified in and around these craters by previous studies [17,18] and corroborated by the target transformation method. Similar to Mawrth Vallis, the SAD index does not identify discrete occurrences of carbonate outcrops but maps moderate SAD values in surfaces associated with the previously identified hydrated silicate phases. In both Mawrth Vallis and near the W. Nili Fossae craters, multiple images taken at different times show similar fits, indicating that some characteristic of the surface is producing a spectral fit to carbonate.

**Implications.** The results of this preliminary study confirm that FA/TT can identify carbonate where others have in the past and does not produce obvious false-positives in regions where carbonates are not likely to exist. The data imply a diverse set of carbonate compositions west of Nili Fossae, and point to perhaps a reservoir of carbonate found in Noachian bedrock at low concentrations that is difficult to detect with traditional orbital techniques. These results provide insight into the potentially missing carbonate component of the martian crust.

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