

**RESULTS AND IMPLICATIONS OF MINERALOGICAL MODELS FOR CHEMICAL SEDIMENTS AT MERIDIANI PLANUM.** B. C. Clark<sup>1</sup>, S.M. McLennan<sup>2</sup>, R.V. Morris<sup>3</sup>, R. Gellert<sup>4</sup>, B. Jolliff<sup>5</sup>, A. Knoll<sup>6</sup>, T.K. Lowenstein<sup>7</sup>, D.W. Ming<sup>3</sup>, N.J. Tosca<sup>2</sup>, P.R. Christensen<sup>8</sup>, A. Yen<sup>9</sup>, J. Brückner<sup>4</sup>, W. Calvin<sup>10</sup>, W. Farrand<sup>11</sup>, J. Zipfel<sup>4</sup>, S. Gorevan<sup>12</sup>, S.W. Squyres<sup>13</sup>, and the Athena Science Team. <sup>1</sup>Lockheed Martin Space Systems, POB 179, MS S-8000, Denver, CO 80201, benton.c.clark@LMCO.com, <sup>2</sup> State University of New York (SUNY), Stony Brook, NY, <sup>3</sup> NASA Johnson Space Center, Houston, TX, <sup>4</sup> Max Planck Institut für Chemie, Kosmochemie, Mainz, Germany, <sup>5</sup> Washington University, St. Louis, MO, <sup>6</sup> Harvard University, Cambridge MA, <sup>7</sup> SUNY, Binghamton, NY, <sup>8</sup> Arizona State University, Tempe, AZ, <sup>9</sup> JPL, California Institute of Tech., Pasadena, CA, <sup>10</sup> University of Nevada, Reno, NV, <sup>11</sup> Space Science Institute, Boulder, CO, <sup>12</sup>Honeybee Robotics, New York, NY, <sup>13</sup> Cornell University, Ithaca, NY.

**Introduction:** The Mars Exploration Rover (MER) “Opportunity” has explored chemically-enriched sedimentary outcrops at Meridiani Planum, Mars. In its first year, three different crater sites – Eagle, Fram and Endurance – have been explored.

Nineteen high-interest outcrop rocks were investigated by first grinding a hole to reach the interior (using the Rock Abrasion Tool, RAT), and then conducting APXS (alpha particle x-ray spectrometry) analysis, MB (Mössbauer) analysis, and close up imaging (MI, microscopic imager). Sixteen elements and four Fe-bearing minerals were assayed to good accuracy in each sample, producing 380 compositional data points. The Miniature Thermal Emission Spectrometer (Mini-TES) obtained spectra on outcrop materials which provide direct indication of several mineral classes.

Preliminary reports on Eagle crater and three RAT samples have been published [1-4]. Chemical trends and a derived mineralogical model for all RAT'd outcrop samples to date has been developed [5].

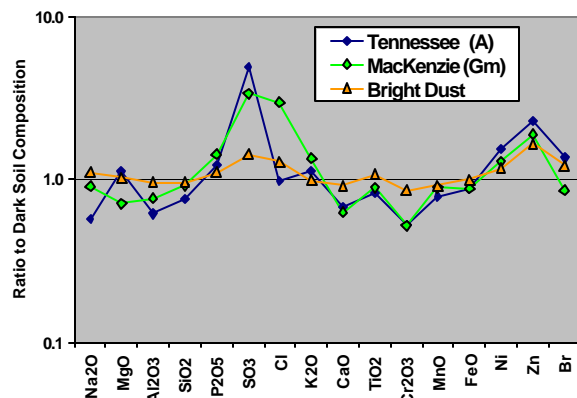


Fig. 1. Ratio of element concentrations in indicated samples to Meridiani average dark soil.

**Results: Comparison to Soil.** In many respects, the elemental composition of the outcrop has considerable similarities with the local dark soil, Fig. 1, and for some elements even more with the bright dust at Meridiani (a close match to universal dust, [7]). Tennessee is unit A, the highest in the Endurance Karatepe stratigraphic sequence; MacKenzie (Gm) is the lowest.

**Variability of Elements.** The data span a range of concentration variations, with rank order of elements in Fig. 2, from the least variable (first 5 elements, at  $\pm 12\%$ ) to  $\text{SO}_3$  (at  $\pm 23\%$ ) to the hyper-variable Br. This variability enables trend analysis.

All samples from units E through F have significantly enhanced Cl concentrations compared to units higher in the sequence. This dichotomy produces a bimodal distribution for this element, Fig. 3.

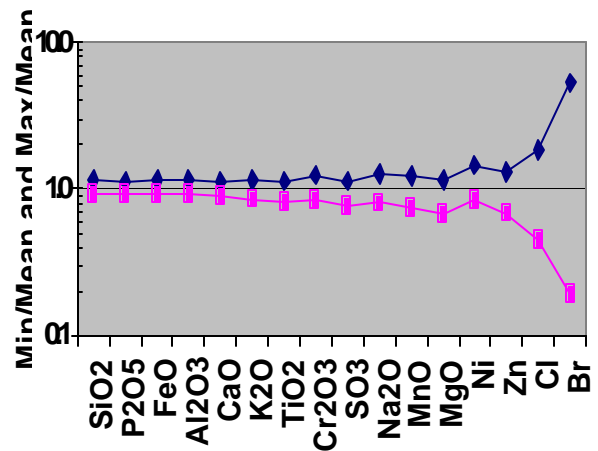


Fig. 2. Ratio plots of minimum-to-mean and maximum-to-mean for element ranges in outcrop samples.

**Mineralogical Model.** The salt minerals implicated include Mg-sulfates (with various hydration states possible, from kieserite to epsomite), Ca-sulfates (variously hydrated), and chlorides of Mg (bischofite) and possibly Na (halite). Aluminosilicates are abundant as well as some form of or enrichment in silica, and an apparent pyroxene (“Px”) remnant depleted in Ca and Mg. Mini-TES observations have demonstrated that crystalline silica minerals, such as quartz and chert, and carbonate phases are not present in these outcrops at abundances  $> \sim 5\%$ . Iron minerals, as reported by MB, include the “Px”, hematite, F3D3 (an unknown  $\text{Fe}^{3+}$  oxide or sulfate), and jarosite (Jar). Correlating APXS and MB trends implies an oxide or a low-S sulfate for

F3D3, and hydronium jarosite, although (Na,K)-jarosite is more consistent with MB spectral details for this mineral.

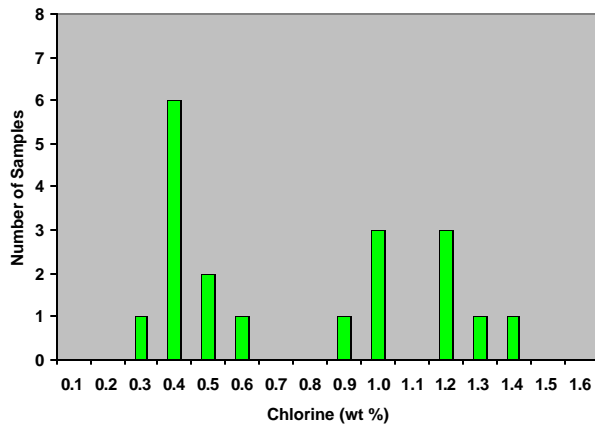


Fig. 3. Occurrence frequencies for Cl are bimodal.

**Some Implications:** *Horizontal structure of units.*

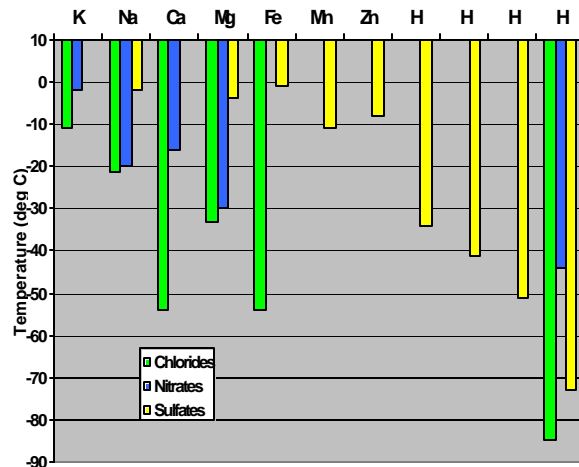
It has been found that rocks in all craters are in-family, with the highest-lying samples corresponding to the composition of Unit A. Free-lying rocks can be assigned locations in A-G, with similar compositions although not identical (high precision of APXS). Generally, the strata seem continuous over the horizontal distance between the three craters, > 650 meters apart.

*Vertical structure of units.* Since no two samples are as identical as the APXS instrument can measure, there may be changes in composition within units which are small compared to the RAT hole and the 1-cm highest sensitivity footprint of APXS. This is consistent with mm-scale laminated structures observed by MI in some samples. In addition, even the units show some oscillation in abundance patterns. For example, units B and D are more similar to one another than to either units A or C, whereas unit C is closer in composition to unit E1. These patterns may reflect systematic fluctuations in environmental conditions during salt deposition, re-equilibration, or mobilization. Beginning with unit E1, a monotonic decrease (except for E2) in  $MgSO_4$  is observed for lower-lying units.

*Aqueous History.* Mg-sulfate gradients could be due to emplacement mechanisms, or, alternatively to upward migration of these highly soluble salts during desiccation of the salt/siliciclastic assemblage to the atmosphere. Later migration of chlorides and then non-systematic extreme changes in Br abundance (<20 ppm in many samples, to well over 300 ppm in certain outcrop samples at both Eagle and Endurance) presumably represent additional aqueous episodes. Diagenetic processes to explain vugs (presumably mineral molds),

and hematite-rich spherules (presumably concretions), also require significant aqueous activity [8]. Serving as a sink for  $H_2O$ , we calculate the outcrop could contain up to 18%  $H_2O$  just in hydration of salts alone. Depression of freezing points, especially by chlorides, Fig. 4, to below martian temperature excursions could cause mobilization of  $MgCl_2$  and other Cl species (including perchlorates) while sulfate remains relatively immobile. Gravity-driven or porosity-aided seepage of phreatic  $H_2O$  could possibly explain opposite directional concentrations of sulfates and chlorides. The enhanced solubilities and depression of freezing point for some bromides ( $-42.7^\circ C$  for  $MgBr_2$ ) could explain the hyper mobility of Br evidenced at the Meridiani site, Gusev crater [10] and in Viking Chryse duricrust sample [11].

Fig. 4. Freezing point depression for chlorides, ni-



trates, and sulfates of candidate cations, including acid (H) eutectics.

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**References:** [1] Squyres et al. (2004), *Science* 306,1709. [2] Rieder et al. (2004), *Science* 306, 1746 [3] Klingelhofer et al. (2004), *Science*, 306, 1740. [4] Herkenhoff et al. (2004), *Science* 306, 1727. [5] Clark et al. (2005), submitted to Earth Planet. Sci. Lett. (*EPSL*). [6] Squyres et al. (2005), submit *EPSL*. [7] Yen et al. (2005), submitted to *Nature*. [8] McLennan et al. (2005), submit *EPSL*. [9] W. Linke, W. Solubilities of Inorganic and Metal Organic Compounds, 4th Edition, Am. Chem. Soc., Washington DC, 1965. [10] R. Gellert (2004), *Science* 305, 829-832. [11] B. C. Clark et al. (1982), *J. Geophys. Res.*, 87, 10,059-67