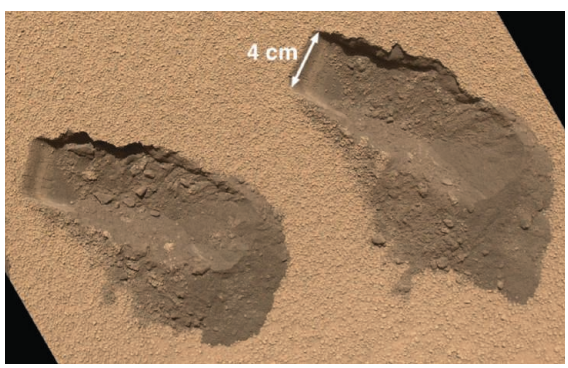
Analysis of Surface Materials by the Curiosity Mars Rover

THE 6 AUGUST 2012 ARRIVAL OF THE CURIOSITY ROVER ON THE SURFACE of Mars delivered the most technically advanced geochemistry laboratory ever sent to the surface of another planet. Its 10 instruments (*1*)* were commissioned for operations and were tested on a diverse set of materials, including rocks, soils, and the atmosphere, during the first 100 martian days (sols) of the mission. The five articles presented in full in the online edition of *Science* (www.sciencemag.org/extra/curiosity), with abstracts in print (pp. 1476–1477), describe the mission's initial results, in which Curiosity's full laboratory capability was used.

Curiosity was sent to explore a site located in Gale crater, where a broad diversity of materials was observed from orbit. Materials representing interactions with aqueous environments were targeted for study because of the emphasis on understanding habitable environments. In addition, the mission's science objectives also include characterizing the geologic diversity of the landing site at all scales, including loose surface materials such as impact ejecta, soils, and windblown accumulations of fine sediments. In certain cases, such characterization may even provide constraints on the evolution of the planet as a whole. Two notable points along Curiosity's initial 500-m traverse included Jake_M, a loose rock sitting on the plains, and Rocknest, an accumulation of windblown sand, silt, and dust that formed in the lee of some rocky outcrops. Sparse outcrops of lithified fluvial conglomerate were also encountered (*2*).



Curiosity used its scoop to collect two samples of a small aeolian deposit. The deposit's upper surface is armored by sand grains 0.5 to 1.5 mm in size. These coarse grains are coated with fine dust, giving the deposit an overall light brownish red color. Beneath the coarse sand crust is finer sand, dark brown in color. This Mars Hand Lens Imager image was acquired on sol 84.

As described by Stolper *et al*., Jake_M was encountered ~282 m away from the landing site and is a dark, macroscopically homogeneous igneous rock representing a previously unknown martian magma type. In contrast to the relatively unfractionated Fe-rich and Al-poor tholeiitic basalts typical of martian igneous rocks, it is highly alkaline and fractionated. No other known martian rock is as compositionally similar to terrestrial igneous rocks; Jake_M compares very closely with an uncommon terrestrial rock type known as a mugearite, typically found on ocean islands and in rift zones. It probably originates from magmas generated by low degrees of partial melting at high pressure of possibly water-rich, chemically altered martian mantle that is different from the sources of other known martian basalts.

Over the first 100 sols of the mission, the ChemCam instrument returned >10,000 laser-induced breakdown spectra, helping to characterize surface material diversity. ChemCam's laser acts effectively as a microprobe, distinguishing between fine soil grains and coarser ~1-mm grains. Based on these data, Meslin *et al*. report that the coarse soil fraction contains felsic (Si- and Al-rich) grains, mimicking the composition of larger felsic rock fragments found during the traverse and showing that these larger components probably break apart to form part of the soil. In contrast, the fine-grained soil component is mafic, similar to soils observed by the Pathfinder and Mars Exploration Rover missions.

Curiosity scooped, processed, and analyzed a small deposit of windblown sand/silt/dust at Rocknest that has similar morphology and bulk elemental composition to other aeolian deposits studied at other Mars landing sites. Based solely on analysis of CheMin x-ray diffraction (XRD) data from Mars, calibrated with terrestrial standards, Bish *et al*. estimate the Rocknest deposit to be composed of ~71% crystalline material of basaltic origin, in addition to ~29% x-ray–amorphous materials. In an independent approach, Blake *et al*. used Alpha Particle X-ray Spectrometer data to constrain the bulk composition of the deposit and XRD data and phase stoichiometry to constrain the chemistry of the crystalline component, with the difference being attributed to the amorphous component, resulting in estimates of ~55% crystalline material of basaltic origin and ~45% x-ray–amorphous materials. The amorphous component may contain nanophase iron oxide similar to what was observed by earlier rovers. The similarity between basaltic soils observed at Rocknest and other Mars sites implies either global-scale mixing of basaltic material or similar regional-scale basaltic source material or some combination of both. No hydrated phases were detected. However, as shown by Leshin *et al*., pyrolysis of Rocknest fines using the Sample Analysis at Mars (SAM) instrument suite revealed volatile species, probably in the amorphous component, including H_2O, SO_2, CO_2, and O_2, in order of decreasing abundance. ChemCam measurements of these materials also revealed the presence of H. It is likely that H_2O is contained in the amorphous component and CO_2 was liberated via the decomposition of Fe/Mg carbonates present below the XRD detection limit of 1 to 2%. Isotopic data from SAM indicate that this H_2O, and possibly the CO_2, were derived from the atmosphere. SAM analysis also revealed oxychloride compounds similar to those found by earlier missions, suggesting that their accumulation reflects global planetary processes. The evolution of CO_2 during pyrolysis and the observation of simple chlorohydrocarbons during SAM gas chromatograph mass spectrometer analyses could be consistent with organic carbon derived from a terrestrial instrument background source, or a martian source, either exogenous or indigenous.

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*References may be found on page 1477 after the abstracts.

10.1126/science.1244258

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ABSTRACTS

The Petrochemistry of Jake_M: A Martian Mugearite

E. M. Stolper,* M. B. Baker, M. E. Newcombe, M. E. Schmidt, A. H. Treiman, A. Cousin, M. D. Dyar, M. R. Fisk, R. Gellert, P. L. King, L. Leshin, S. Maurice, S. M. McLennan, M. E. Minitti, G. Perrett, S. Rowland, V. Sautter, R. C. Wiens, MSL Science Team†

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"Jake_M," the first rock analyzed by the Alpha Particle X-ray Spectrometer instrument on the Curiosity rover, differs substantially in chemical composition from other known martian igneous rocks: It is alkaline (>15% normative nepheline) and relatively fractionated. Jake_M is compositionally similar to terrestrial mugearites, a rock type typically found at ocean islands and continental rifts. By analogy with these comparable terrestrial rocks, Jake_M could have been produced by extensive fractional crystallization of a primary alkaline or transitional magma at elevated pressure, with or without elevated water contents. The discovery of Jake_M suggests that alkaline magmas may be more abundant on Mars than on Earth and that Curiosity could encounter even more fractionated alkaline rocks (for example, phonolites and trachytes).

>> Read the full article at http://dx.doi.org/10.1126/science.1239463

Soil Diversity and Hydration as Observed by ChemCam at Gale Crater, Mars

P.-Y. Meslin,* O. Gasnault, O. Forni, S. Schröder, A. Cousin, G. Berger, S. M. Clegg, J. Lasue, S. Maurice, V. Sautter, S. Le Mouélic, R. C. Wiens, C. Fabre, W. Goetz, D. Bish, N. Mangold, B. Ehlmann, N. Lanza, A.-M. Harri, R. Anderson, E. Rampe, T. H. McConnochie, P. Pinet, D. Blaney, R. Léveillé, D. Archer, B. Barraclough, S. Bender, D. Blake, J. G. Blank, N. Bridges, B. C. Clark, L. DeFlores, D. Delapp, G. Dromart, M. D. Dyar, M. Fisk, B. Gondet, J. Grotzinger, K. Herkenhoff, J. Johnson, J.-L. Lacour, Y. Langevin, L. Leshin, E. Lewin, M. B. Madsen, N. Melikechi, A. Mezzacappa, M. A. Mischna, J. E. Moores, H. Newsom, A. Ollila, R. Perez, N. Renno, J.-B. Sirven, R. Tokar, M. de la Torre, L. d'Uston, D. Vaniman, A. Yingst, MSL Science Team†

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The ChemCam instrument, which provides insight into martian soil chemistry at the submillimeter scale, identified two principal soil types along the Curiosity rover traverse: a fine-grained mafic type and a locally derived, coarse-grained felsic type. The mafic soil component is representative of widespread martian soils and is similar in composition to the martian dust. It possesses a ubiquitous hydrogen signature in ChemCam spectra, corresponding to the hydration of the amorphous phases found in the soil by the CheMin instrument. This hydration likely accounts for an important fraction of the global hydration of the surface seen by previous orbital measurements. ChemCam analyses did not reveal any significant exchange of water vapor between the regolith and the atmosphere. These observations provide constraints on the nature of the amorphous phases and their hydration.

>> Read the full article at http://dx.doi.org/10.1126/science.1238670

X-ray Diffraction Results from Mars Science Laboratory: Mineralogy of Rocknest at Gale Crater

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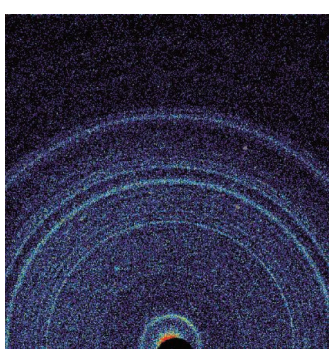
The Mars Science Laboratory rover Curiosity scooped samples of soil from the Rocknest aeolian bedform in Gale crater. Analysis of the soil with the Chemistry and Mineralogy (CheMin) x-ray diffraction (XRD) instrument revealed plagioclase (~An57), forsteritic olivine (~Fo62), augite, and pigeonite, with minor K-feldspar, magnetite, quartz, anhydrite, hematite, and ilmenite. The minor phases are present at, or near, detection limits. The soil also contains 27 ± 14 weight percent x-ray amorphous material, likely containing multiple Fe^{3+}- and volatile-bearing phases, including possibly a substance resembling hisingerite. The crystalline component is similar to the normative mineralogy of certain basaltic rocks from Gusev crater on Mars and of martian basaltic meteorites. The amorphous com-



CREDITS: (LEFT) NASA; (TOP RIGHT) MESLIN *ET AL.*; (BOTTOM RIGHT) BISH *ET AL.*

ponent is similar to that found on Earth in places such as soils on the Mauna Kea volcano, Hawaii.

>> Read the full article at http://dx.doi.org/10.1126/science.1238932

Curiosity at Gale Crater, Mars: Characterization and Analysis of the Rocknest Sand Shadow

D. F. Blake,* R. V. Morris, G. Kocurek, S. M. Morrison, R. T. Downs, D. Bish, D. W. Ming, K. S. Edgett, D. Rubin, W. Goetz, M. B. Madsen, R. Sullivan, R. Gellert, I. Campbell, A. H. Treiman, S. M. McLennan, A. S. Yen, J. Grotzinger, D. T. Vaniman, S. J. Chipera, C. N. Achilles, E. B. Rampe, D. Sumner, P.-Y. Meslin, S. Maurice, O. Forni, O. Gasnault, M. Fisk, M. Schmidt, P. Mahaffy, L. A. Leshin, D. Glavin, A. Steele, C. Freissinet, R. Navarro-González, R. A. Yingst, L. C. Kah, N. Bridges, K. W. Lewis, T. F. Bristow, J. D. Farmer, J. A. Crisp, E. M. Stolper, D. J. Des Marais, P. Sarrazin, MSL Science Team†

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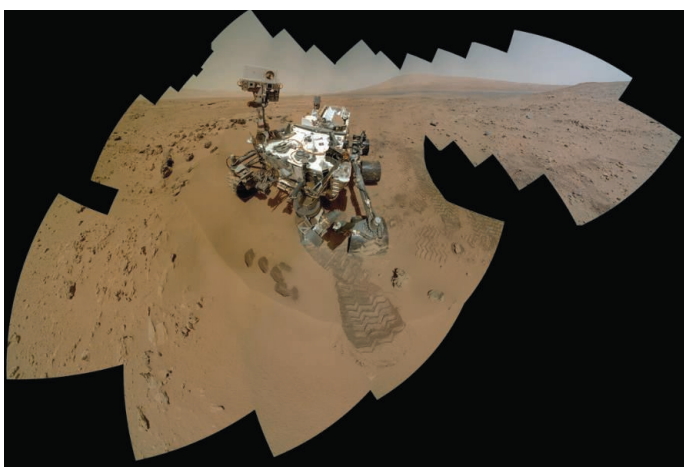

The Rocknest aeolian deposit is similar to aeolian features analyzed by the Mars Exploration Rovers (MERs) Spirit and Opportunity. The fraction of sand <150 micrometers in size contains ~55% crystalline material consistent with a basaltic heritage and ~45% x-ray amorphous material. The amorphous component of Rocknest is iron-rich and silicon-poor and is the host of the volatiles (water, oxygen, sulfur dioxide, carbon dioxide, and chlorine) detected by the Sample Analysis at Mars instrument and of the fine-grained nanophase oxide component first described from basaltic soils analyzed by MERs. The similarity between soils and aeolian materials analyzed at Gusev crater, Meridiani Planum, and Gale crater implies locally sourced, globally similar basaltic materials or globally and regionally sourced basaltic components deposited locally at all three locations.

>> Read the full article at http://dx.doi.org/10.1126/science.1239505

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Volatile, Isotope, and Organic Analysis of Martian Fines with the Mars Curiosity Rover

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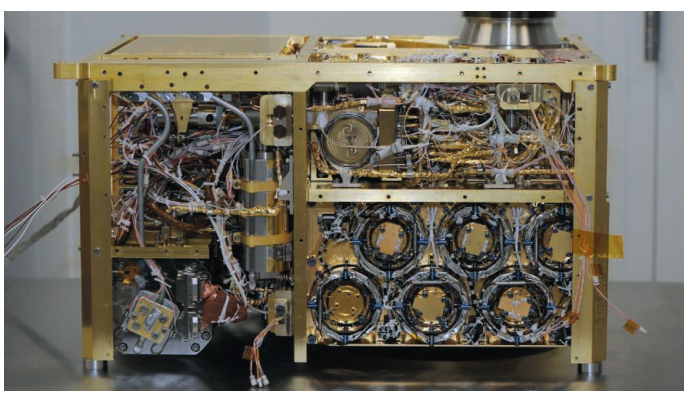

Samples from the Rocknest aeolian deposit were heated to ~835°C under helium flow and evolved gases analyzed by Curiosity's Sample Analysis at Mars instrument suite. H_2O, SO_2, CO_2, and O_2 were the major gases released. Water abundance (1.5 to 3 weight percent) and release temperature suggest that H_2O is bound within an amorphous component of the sample. Decomposition of fine-grained Fe or Mg carbonate is the likely source of much of the evolved CO_2. Evolved O_2 is coincident with the release of Cl, suggesting that oxygen is produced from thermal decomposition of an oxychloride compound. Elevated δD values are consistent with recent atmospheric exchange. Carbon isotopes indicate multiple carbon sources in the fines. Several simple organic compounds were detected, but they are not definitively martian in origin.

>> Read the full article at http://dx.doi.org/10.1126/science.1238937

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