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Classification scheme for sedimentary and igneous rocks in Gale crater, Mars

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ABSTRACT

Rocks analyzed by the Curiosity rover in Gale crater include a variety of clastic sedimentary rocks and igneous float rocks transported by fluvial and impact processes. To facilitate the discussion of the range of lithologies, we present in this article a petrological classification framework adapting terrestrial classification schemes to Mars compositions (such as Fe abundances typically higher than for comparable lithologies on Earth), to specific Curiosity observations (such as common alkali-rich rocks), and to the capabilities of the rover instruments. Mineralogy was acquired only locally for a few drilled rocks, and so it does not suffice as a systematic classification tool, in contrast to classical terrestrial rock classification. The core of this classification involves (1) the characterization of rock texture as sedimentary, igneous or undefined according to grain/crystal sizes and shapes using imaging from the ChemCam Remote Micro-Imager (RMI), Mars Hand Lens Imager (MAHLI) and Mastcam instruments, and (2) the assignment of geochemical modifiers based on the abundances of Fe, Si, alkali, and S determined by the Alpha Particle X-ray Spectrometer (APXS) and ChemCam instruments. The aims are to help understand Gale crater geology by highlighting the various categories of rocks analyzed by the rover. Several implications are proposed from the cross-comparisons of rocks of various texture and composition, for instance between in place outcrops and float rocks. All outcrops analyzed by the rover are sedimentary; no igneous outcrops have been observed. However, some igneous rocks are clasts in conglomerates, suggesting that part of them are derived from the crater rim. The compositions of in-place sedimentary rocks contrast significantly with the compositions of igneous float rocks. While some of the differences between sedimentary rocks and igneous floats may be related to physical sorting and diagenesis of the sediments, some of the sedimentary rocks (e.g., potassic rocks) cannot be paired with any igneous rocks analyzed so far. In contrast, many float rocks, which cannot be classified from their poorly defined texture, plot on chemistry diagrams close to float rocks defined as igneous from their textures, potentially constraining their nature.

1. Introduction

The Mars Science Laboratory (MSL) Curiosity rover landed on Mars within the 160 km diameter Gale crater in August 2012 at a location named Bradbury Landing. Gale crater is characterized by a 5 km high mountain at its center, Aeolis Mons, informally named

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Mt. Sharp, composed of layered sediments in which phyllosilicates, sulfates and hematite were recognized from orbital spectrometers (Milliken et al., 2010; Anderson et al., 2010). In its first martian year, the rover crossed hummocky plains with local outcrops of conglomerates (Williams et al., 2013) and analyzed in-depth outcrops of fine-grained sandstones and mudstones at the Yellowknife Bay and Kimberley field sites, both being interpreted as fluvial and lacustrine deposits (Grotzinger et al., 2014, 2015; Vasavada et al., 2014.). After ~750 sols (i.e. martian days), the rover reached fine-grained sandstones and mudstones of the Murray formation, which was identified form orbital images as one of the basal layers of Mt. Sharp (Grotzinger et al., 2015).

During this ~10 km traverse, the Curiosity Rover has explored a geochemically diverse region of Mars (McLennan et al., 2014; Sautter et al., 2014; Schmidt et al., 2014; Thompson et al., 2014; Sautter et al., 2015, Le Deit et al., 2016; Mangold et al., 2016). Rocks encountered in Gale crater include clastic sedimentary rocks, of interest for understanding the aqueous history of Mars, and a variety of igneous float rocks (e.g., Stolper et al., 2013; Sautter et al., 2014, 2015, Schmidt et al., 2014). As exploration of Gale crater is ongoing and as Curiosity is heading into new rock types as suggested by orbital observations (Milliken et al., 2010; Fraeman et al., 2014), the amount of geochemical and geological data will continue to multiply. Working with diverse, and growing datasets requires formal classification of rocks with similar textures and compositions and the development of a common nomenclature in order to facilitate geological discussion. A further intent of the classification scheme presented here is to help scientists from the broader geological community become more familiar with the diverse lithologies of Gale crater.

Here we present a rock classification scheme that adapts terrestrial classification schemes (e.g., Wentworth, 1922; Le Maître, 2002) to the imaging and analytical capabilities of Curiosity as well as for rock types distinctive to Mars, such as iron-rich rocks (Sections 2 and 3). The core of this classification involves the characterization of rock type according to grain size and texture and the assignment of geochemical modifying terms that are defined relative to average Mars crust (Taylor and McLennan, 2009). Future, more in-depth studies may consider the mineralogy, of the geographic distribution, and the geologic context of the rocks.

2. Rover capabilities

Standard techniques that human geologists practice to classify rocks, such as exposing fresh surfaces with a hammer and examining them with a hand lens and thin section analysis, are not possible on Mars with the present rovers. Our ability to classify rocks on Mars depends on available instrument capabilities, but is also limited by external conditions such as viewing angle, dust cover, or quality of the observations (e.g., image resolution). That said, the Curiosity rover carries a remarkable suite of imaging, geochemical, and mineralogical instruments for rock characterization (Grotzinger et al., 2012).

2.1. Imaging

The MSL payload includes a total of 17 cameras, including five science cameras and two types of engineering cameras. The engineering cameras (ECams) include the Navcam (Navigation Camera) and the front and rear Hazcams (Hazard avoidance Cameras; Maki et al., 2012). ECam images are useful for recognizing gross characteristics (e.g., albedo, large scale textures including bedding) and for identifying rock targets of interest, but their resolution is not sufficient for characterizing the fine textures, such as grain size and shape, that are necessary to classify rocks. The Mars Descent Imager (MARDI) is used for systematic survey of clasts below the rover (Malin et al., 2009), but those clasts cannot be analyzed with the other instruments without an additional time- and resource-consuming maneuvering of the rover, so MARDI images are rarely used in the classification of targets.

Table 1
Grain size capabilities with imaging tools in optimum conditions (well-focused and viewed perpendicular to the surface, absence of dust, not shadowed, high contrast between grains and between grains and matrix).

Camera (distance to target)	Sampling (mm/pixel)	Minimum grain size detected (in mm, based on 3 pixels)	Wentworth size class
MAHLI (2 cm standoff)	0.014	~0.042	Silt
RMI (2 m–5 m)	0.04–0.1	~0.12–0.3	Fine sand
Mastcam-M100 (2 m–5 m)	0.15–0.375	~0.45–1.12	Coarse sand

The MSL science cameras acquire images at a range of scales (Table 1). The Mastcam instrument is composed of two cameras: M34 has a 34 mm focal length, a pixel scale of 0.22 mrad/pixel, and an 18.4° × 15° effective field of view (FOV); M100 has a 100 mm focal length, a 0.074 mrad/pixel of sampling, and a 6.3°x 5.1°FOV (Malin et al., 2010; Bell et al., 2012). The Remote Micro-Imager (RMI) provides context imaging for ChemCam analyses with sub-millimeter spatial resolution (Wiens et al., 2012; Maurice et al., 2012; Le Mouélic et al., 2015). The RMI has an angular pixel size of 0.0196 mrad/pixel, and a circular field of view of 20 mrad (1.15°) over 1024 × 1024 pixels. This capability provides a spatial sampling of ~0.04 mm/pixel at 2 m (Le Mouélic et al., 2015). MAHLI was designed for investigating geologic materials at the scale of hand-lens. MAHLI is a 2 megapixel color CCD camera that can focus over a range of distances from 2.1 cm to infinity (Edgett et al., 2012). A standard 1600 × 1200 pixels image provides a field of view of about 2.3 by 1.7 cm at closest focus (~2 cm working distance) and a pixel size of ~0.014 mm/pixel (Edgett et al., 2012).

2.2. Mineralogical and geochemical analysis

While mineralogy is fundamental for the classification of terrestrial rocks, the CheMin instrument (X-Ray Diffractometer) has not and, in all likelihood, could not be used frequently enough to contribute to rock classification (Blake et al., 2012). The complexity of the activities leading to drilling and analyzing rock powders by CheMin results in only a limited number of samples being acquired (11 rock analyses until sol 1340 in the mission), limiting the systematic use of this instrument. Qualitative mineralogy is also provided by Chemcam reflectance spectra (without laser ablation) and by multispectral Mastcam images using seven channels at wavelengths up to ~1 µm (Bell et al., 2012; Johnson et al., 2015). However, the visible-near-infrared wavelengths of these techniques limit mineral identification to a few mineral classes, such as iron oxides and some hydrous minerals. Thus, mineralogy obtained with these observations cannot be used for systematic rock classification.

Geochemical analytical instruments include the Alpha Particle X-ray Spectrometer (APXS) and the ChemCam instrument, which utilizes Laser Induced Breakdown Spectroscopy (LIBS). APXS on Curiosity is derived directly from the instrument built for the Mars Exploration Rovers Spirit and Opportunity (Gellert et al., 2006). APXS examines 1.7 cm diameter area on rock surfaces and analyses are representative of bulk rock composition (Campbell et al., 2012; Schmidt et al., 2014). Multi-area rasters are used to characterize heterogeneities (e.g., veins, nodules, and large phenocrysts) and variable dust coverage (VanBommel et al., 2015). The analytical method is a combination of X-ray fluorescence (XRF) and particle-induced X-ray emission (PIXE) (Gellert et al., 2006;