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Relating geologic units and mobility system kinematics contributing to Curiosity wheel damage at Gale Crater, Mars

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Abstract

Curiosity landed on plains to the north of Mount Sharp in August 2012. By June 2016 the rover had traversed 12.9 km to the southwest, encountering extensive strata that were deposited in a fluvial-deltaic-lacustrine system. Initial drives across sharp sandstone outcrops initiated an unacceptably high rate of punctures and cracks in the thin aluminum wheel skin structures. Initial damage was found to be related to the drive control mode of the six wheel drive actuators and the kinematics of the rocker-bogie suspension. Wheels leading a suspension pivot were forced onto sharp, immobile surfaces by the other wheels as they maintained their commanded angular velocities. Wheel damage mechanisms such as geometry-induced stress concentration cracking and low-cycle fatigue were then exacerbated. A geomorphic map was generated to assist in planning traverses that would minimize further wheel damage. A steady increase in punctures and cracks between landing and June 2016 was due in part because of drives across the sharp sandstone outcrops that could not be avoided. Wheel lifetime estimates show that with careful path planning the wheels will be operational for an additional ten kilometers or more, allowing the rover to reach key strata exposed on the slopes of Mount Sharp.

Keywords: Mars rovers; Curiosity rover; Ackerman arcs

1. Introduction

The NASA Mars Science Laboratory Curiosity rover landed on the northern plains of Gale Crater at the base of Mount Sharp (formally known as Aeolis Mons) on August 6, 2012 (Grotzinger et al., 2012; Vasavada et al., 2014) (Figs. 1 and 2). By June 1, 2016 Curiosity had traversed 12.9 km during its first 1358 sols (Mars days) on the surface, using its remote sensing and in-situ instruments to show that strata encountered consist of sedimentary rocks deposited in an ancient fluvial-deltaic-lacustrine sys-

Abbreviations: NASA, National Aeronautics and Space Administration; Hazcams, hazard avoidance cameras; Navcam, navigation camera; IMU, inertial measurement units; Mastcam, mast camera; MAHLI, Mars Hand Lens Imager; HiRISE, High Resolution Imaging Science Experiment; T-HEMIS, Thermal Emission Imaging System; VIS, visible

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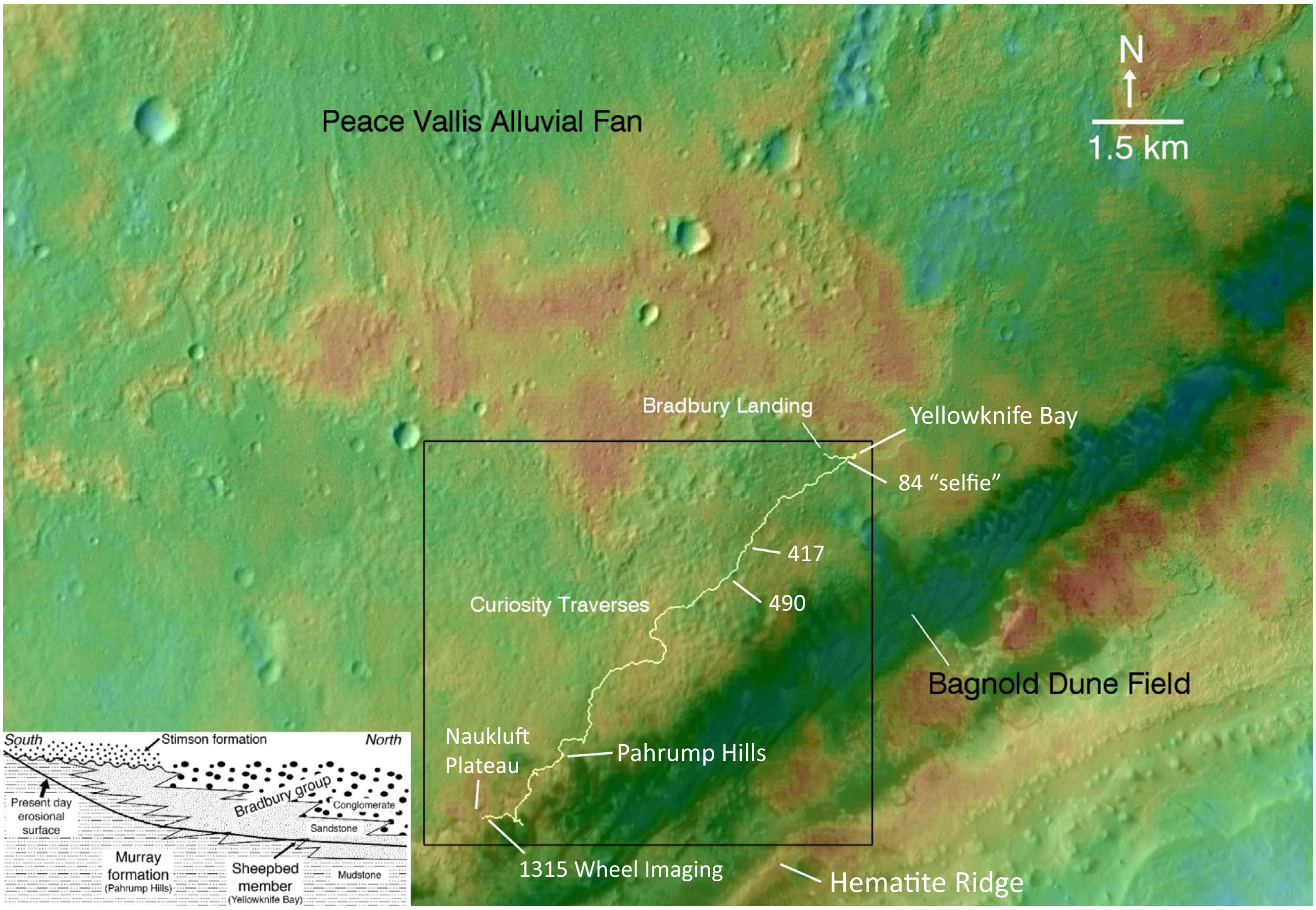

Fig. 1. **Orbital view of Curiosity's paths.** THEMIS VIS mosaic (Christensen et al., 2004) color coded with thermal inertia values and covering Gale Crater plains to the north of Mount Sharp, dissected terrains on the lower slopes of Mount Sharp, and the Bagnold dune field, with Curiosity's traverses overlain. Intent is to show smooth plains transitioning into highly eroded terrains exposing fluvial-deltaic-lacustrine deposits. The smooth plains are characterized by relatively low thermal inertias whereas the dissected underlying deposits have higher thermal inertias associated with greater bedrock exposures. View on lower left shows a north to south cross section through the fluvial-deltaic-lacustrine deposits traversed by the rover. Black box delineates area shown in detail in Fig. 8. Traverses are shown from Bradbury landing through the position on sol 1357, when the rover was at the edge of the Naukluft Plateau. MAHLI-based wheel imaging was acquired periodically and the last one acquired during the period reviewed by this paper was on sol 1315 (Fig. 19). On sol 84 Curiosity was commanded to acquire a "selfie" of itself using the arm-based MAHLI instrument (see Fig. 2). Navcam-based mosaics for sols 417 and 490 are shown in Fig. 3 and one for the Pahrump Hills region is shown in Fig. 22. Blue colors correspond to low and red to high thermal inertia values, with a dynamic range of ~200–550 J m^{-2} K^{-1} $s^{0.5}$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

tem (Williams et al., 2013; Grotzinger et al., 2015). After traversing ~12.9 km Curiosity was poised at the edge of the Naukluft Plateau on the lower slopes of Mount Sharp (Fig. 1), ready to continue its ascent and characterization of the exposed strata.

During the first ~4 km of traverses the rover mainly crossed plains surfaces, with a relatively thin, dominantly sand to clay-sized regolith cover over bedrock, with rocks of a variety of sizes dispersed across the landscape (Arvidson et al., 2014). For reference, regolith on Mars is defined as loose or loosely consolidated particulate material generated by impact, physical and chemical weathering of local bedrock, and the addition of wind-blown granule, sand, silt, and clay-size particles (Moore, 1987; Arvidson et al., 1989). As Curiosity continued traversing to the southwest on the way to Mount Sharp the terrain transitioned to exposures within the plains of well-indurated sandstone outcrops shaped into immobile, sharp surfaces by fracturing and wind erosion. This terrain then transitioned to sandstone-capped plateaus with intervening valleys formed as wind erosion carved into the plains and exposed underlying bedrock (Fig. 1). The well-indurated fluvial and deltaic sandstones resisted erosion and formed rough, capping outcrops. Driving over these sharp sandstones on the plains initiated several damage mechanisms, including an unacceptably high rate of punctures and cracks in the 0.75 mm thick aluminum wheel surfaces, thereby initiating efforts designed to understand the damage mechanisms and mitigate further damage during subsequent drives. For reference, punctures are defined as single-event free-field (inter-grouser) wheel skin penetrations. Cracks and low load punctures are a more complex dam-