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ABSTRACT

The Spirit rover completed a 2.5 km traverse across gently sloping plains on the floor of Gusev crater from its location on the outer rim of Bonneville crater to the lower slopes of the Columbia Hills, Mars. Using the Athena suite of instruments in a transect approach, a systematic series of overlapping panoramic mosaics, remote sensing observations, surface analyses, and trenching operations documented the lateral variations in landforms, geologic materials, and chemistry of the surface throughout the traverse, demonstrating the ability to apply the techniques of field geology by remote rover operations. Textures and shapes of rocks within the plains are consistent with derivation from impact excavation and mixing of the upper few meters of basaltic lavas. The contact between surrounding plains and crater ejecta is generally abrupt and marked by increases in clast abundance and decimeter-scale steps in relief. Basaltic materials of the plains overlie less indurated and more altered rock types at a time-stratigraphic contact between the plains and Columbia Hills that occurs over a distance of one to two meters. This implies that regional geologic contacts are well preserved and that Earth-like field geologic mapping will be possible on Mars despite eons of overturn by small impacts.

Keywords: Mars, planetary geology, rover, geotraverse, field geology.

INTRODUCTION

Gusev crater was selected as a Mars Exploration Rover landing site in part because of the potential for water-lain sediments on its floor (Kuzmin et al., 2000; Golombek et al., 2003). The terrain characteristics, morphology, chemistry, mineralogy, and near-infrared spectra of rocks at the landing site are instead consistent with basaltic lava flows (Squyres et al., 2004; Arvidson et al., 2004; Christensen et al., 2004a; Gellert et al., 2004; Grant et al., 2004; McSween et al., 2004; Morris et al., 2004), reworked by small impacts to a depth of a few meters (Grant et al., 2004), locally overlain by young ejecta deposits of recent origin and mixed with poorly sorted aeolian sands composed of basaltic material (Greeley et al., 2004) and air fall dust in topographic lows. A traverse to the nearby Bonneville crater and inspection of the walls and ejecta during the primary mission (sols [Martian days] 01–91) did not support the presence of flu-

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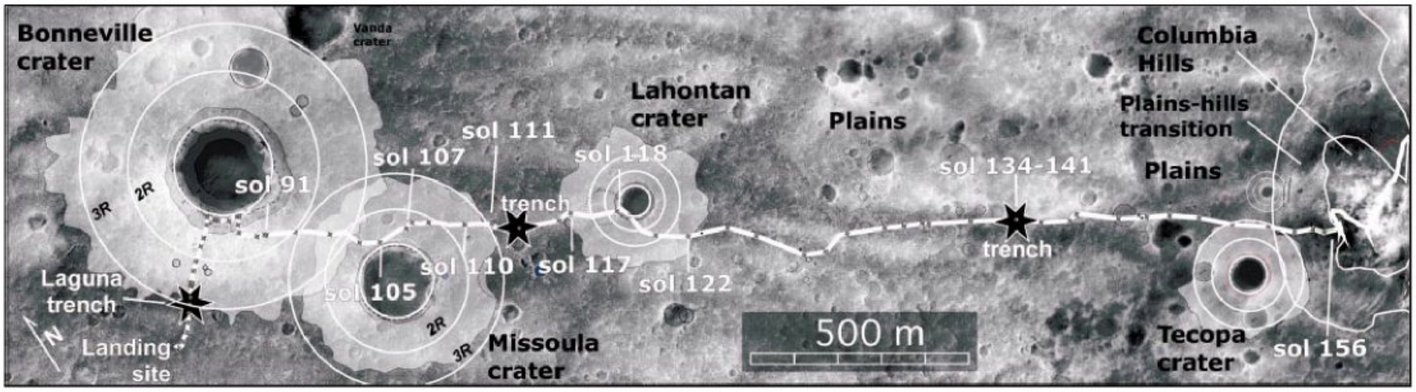

Figure 1. The traverse by Spirit from sol 01 (the landing site) to base of the Columbia Hills (sol 156). Shown in light tones are ejecta units surrounding larger impact craters and contact with Columbia Hills mapped prior to traverse, and examined during traverse. Concentric circles show 1, 2, and 3 crater radii for four largest impact craters. Also shown are locations of three trenching sites (Laguna, Big Hole, and The Boroughs). Dots along traverse represent location of end-of-sol panoramas and observations. (All names are informal and subject to approval by the International Astronomical Union.) Image base from Mars Global Surveyor / Mars Orbiter Camera (Malin et al., 1992) images R1303051 and R1301467.50.

vial sediments in the upper tens of meters of the regolith (Squyres et al., 2004; Arvidson et al., 2004; Grant et al., 2004). Geologic mapping of orbital image data (Fig. 1) indicates that the basaltic plains material embays, and is younger than, the Columbia Hills, a range of low hills to the southeast of the landing site. A traverse across the plains to the Columbia Hills to examine this stratigraphically lower material provided an additional opportunity to document the plains surface in regions on and between larger impact craters.

SYSTEMATIC TRAVERSE

The traverse to the Columbia Hills followed a heading of N130 degrees E from the south rim of Bonneville crater (Fig. 1), deviating locally for targets of opportunity and to avoid mobility obstacles. Summed traverse distances across the plains from the rim of Bonneville crater on sol 68 (the point of initial arrival at the rim) to arrival within a few meters of the geologic contact between the plains material and underlying materials of the Columbia Hills on sol 156 was 2.59 km from point to point (map distance), 3.39 km from wheel turns (odometery), and 2.71 km in summed straight line segments between localization stations (Arvidson et al., 2004; Li et al., 2005), the higher value for odometry reflecting slippage and back-tracking. Maximum relief as measured through acquisition of rover tilt, wheel turns, and rover image correlation data (Li et al., 2005) was associated with the rims of Bonneville ($\Delta h = 6.4$ m) (Grant et al., 2004), and Missoula ($\Delta h \sim 4$ m) and Lahontan ($\Delta h \sim 2.5$ m) craters (Li et al., 2005). Numerous small impact craters probably account for most of the rolling relief on the plains, which created local relief on the order of 1 m over tens of meters horizontal distance in the vicinity of several small impact craters ("hollows") between Lahontan crater and the base of the Columbia Hills. The elevation of the surface also increased from Bonneville crater to the base of the Columbia Hills by approximately 20 m along the traverse, implying a regional gradient on the order of 6 m/km ($\sim$0.44 degrees) in the direction (N130E) of the traverse, reflecting possible topography underlying or associated with the plains basalts.

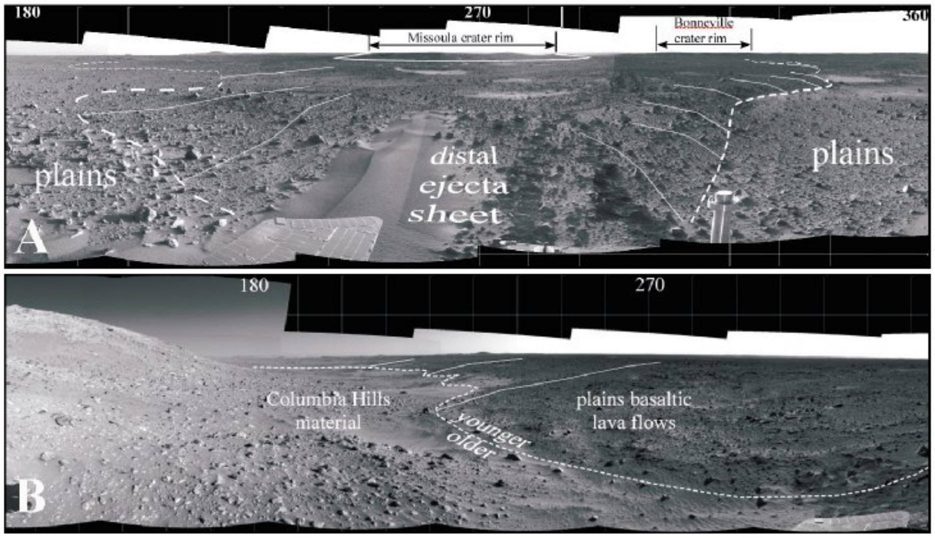

Figure 2. A: View west from south to north showing contact between plains surface and overlying distal margin of continuous ejecta sheet from Missoula crater. Part of Navcam image mosaic 2NN111EFF36CYL00P1818L. Azimuths at top of image. B: View south-southwest along regional contact between plains materials and Columbia Hills materials (sol 159). Navcam image mosaic 2NN159EFF69CYL00P1911L.

COMPARISON OF GEOLOGY OBSERVED ON THE SURFACE WITH GEOLOGY INFERRED FROM ORBITAL DATA

Geomorphic and thermal inertia units, mapped in Mars Global Surveyor Mars Orbiter Camera (Malin et al., 1992) and Mars Odyssey Thermal Emission Imaging System (THEMIS) (Christensen et al., 2004b) data prior to the traverse, were examined out to the accurate ranging distance (20 m) of Navcam mosaics arrayed along the traverse (Fig. 1). A range of nighttime temperature values in THEMIS data indicated variability in rock size and abundance (Golombek et al., 2003) in the intercrater plains along the traverse. A traverse across ejecta and rims occurred at Bonneville (220 m), Missoula (180 m), and Lahontan (70 m) craters. Prior to the traverse, geologic maps prepared using standard planetary mapping methods (Greeley and Batson, 1990) implied that ejecta from craters larger than 50 m extended out to 3 crater radii ($r = 3R$) from the crater centers, that the margins of the ejecta follow undulating (lobe-like) traces, and that crater rims and floors are distinct topographic and textural material units. Pancam and Navcam image data (Bell et al., 2004; Maki et al., 2003) and rover localization data (Li et al., 2005) confirm this and showed that the outer boundaries of ejecta are locally defined by coarse ejecta mounds (Fig. 2A) with lobe-shaped map boundaries at approximately three crater radii or greater from the crater centers. Clast abundances and maximum size increase three to four times at approximately two crater radii, and block abundance is great enough at $r < 2R$ that rover mobility was more difficult. Most of the relief within the ejecta to the crater rims occurred on the inner part of ejecta deposits ($r < 2R$). The lobe-like outlines of the outer ejecta, dominated by fines and small clasts, and the coarser clasts of inner ejecta, may represent two depositional environments dominated by horizontal flow and ballistic emplacement, respectively.

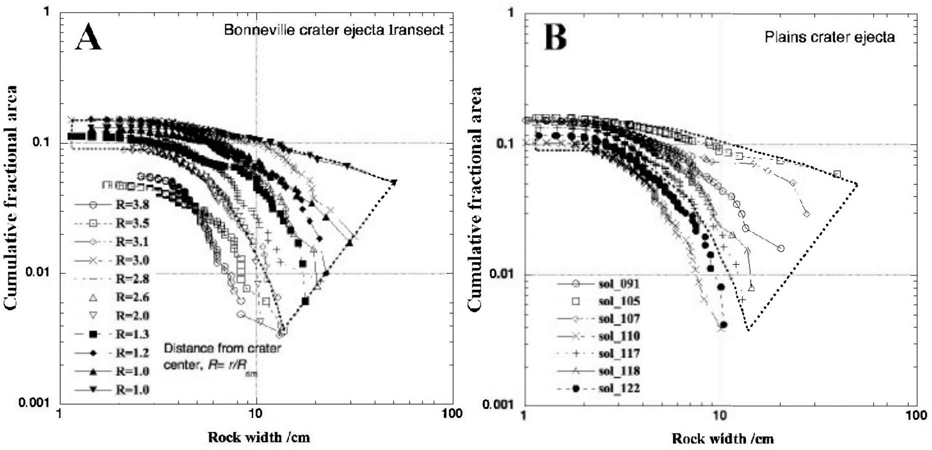

Figure 3. Sampled rock abundances between 2 cm and 40 cm width reported as cumulative fractional areas at sites along traverse within standard 4 m^2 sub-areas centered 1.5 m from camera mast in Navcam mosaic. Rock abundances measured (A) along a transect from margins of Bonneville crater ejecta to rim, and (B) within ejecta sheets of Missoula and Lohantan craters.

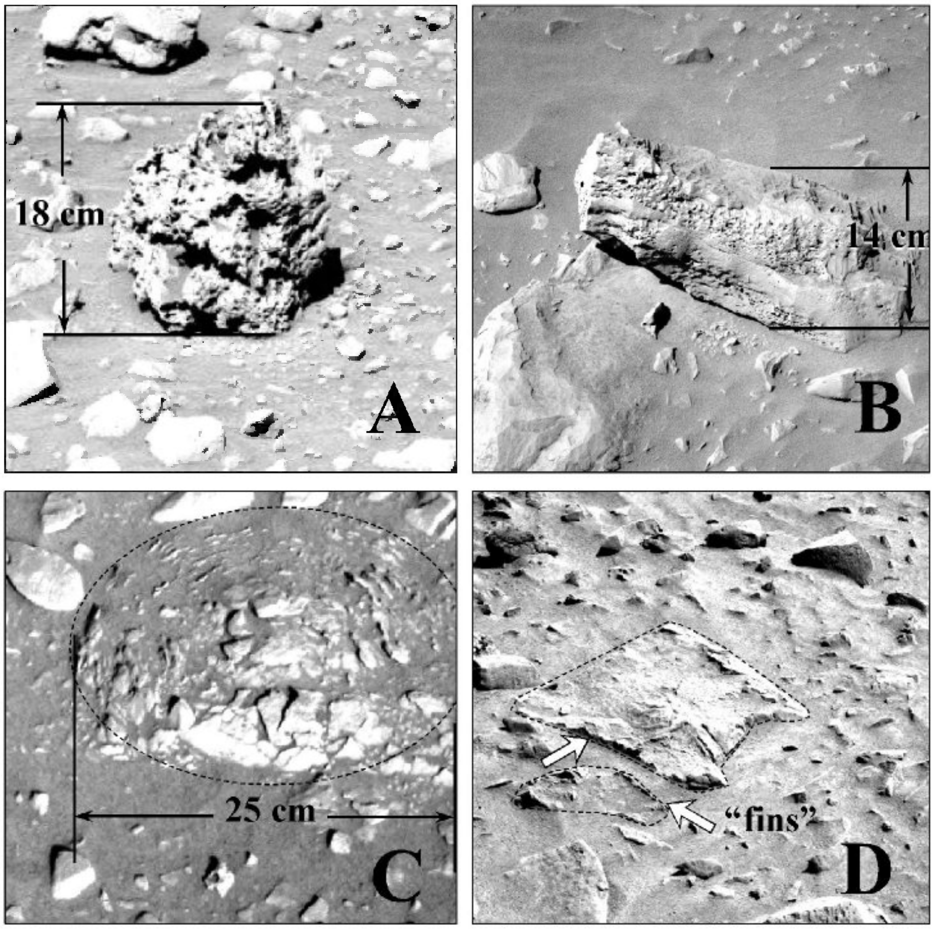

Figure 4. Examples of unusual rocks on ejecta units and within plains traverse. A: Scoria block ("Potrillo") in an area with abundant vesicular clasts. Delicate points and knobby protuberances imply relatively little physical weathering of primary scoria. Sol 111, site 36, Pancam frame 2P136222446EFF35AYP2560L7. B: 14-cm-high block ("Dagwood") with vesicle layering and central vesicle-free zone. Sol 142, site 35, Pancam frame 2P139054174EFF5500P2580L7. C: Partially buried spheroidally exfoliated blocks within inner ejecta sheet near rim of Missoula crater. Sol 103, site 30, Pancam image frame 2P135521029EFF3000P2450L7; D: Internally etched block. Note resistant fins implying hardened exterior surfaces. Sol 68, site 18, Pancam frame 2P132395641EFF1800P2284L6.

The contact between the plains and the Columbia Hills, crossed on sol 156, (Fig. 2B) corresponds with a change in lithology from olivine-bearing plains basaltic materials to rocks in the Columbia Hills where deployments of a Mössbauer spectrometer, a microscopic imager, and an Alpha Particle X-ray Spectrometer indicate substantial alteration of the rocks compared with the plains materials (Haskin et al., 2005). The fact that the contact occurred within a distance of 1–2 m and is mappable in surface image data implies that regional geologic contacts on Mars are well preserved and easily mapped from surface traverses despite eons of overturn by small impacts.

ROCKS, SOILS, AND DRIFTED BED FORMS

In order to ensure measurement of soil chemistry in older plains surfaces undisturbed by more recent crater ejecta, sites for soil analysis and two trenching operations ("Big Hole" and "The Boroughs") were specifically targeted on areas along the traverse that were remotely located from large impact craters and ejecta. Higher SO_3 concentrations, possibly associated with an evaporitic Mg-sulfate phase, were measured in intercrater plains soils relative to the soils within the ejecta of Bonneville crater at Laguna hollow (Haskin et al., 2005). These results suggest that soluble species, including an evaporitic Mg-sulfate phase, may have been mobilized and concentrated in subsurface soils. This is consistent with the hypothesis that older plains surfaces may have experienced episodic fluids (frosts and snow) related to long-term climate variability (Arvidson et al., 2004), low water-rock ratio transport of salts, and corresponding variable soil chemistry over more cycles as compared with soils in younger sediment traps, such as Laguna hollow, on younger ejecta deposits.

Aeolian bed forms, ripples, and wind-tails occurred at the rim crests of all three craters (Bonneville, Missoula, and Lahontan), reflecting the relative roughness (blockiness) and disturbance of the surface laminar layer, in which fines are dropped from saltation (Greeley et al., 2004). Drifted bed forms are also banked onto the inner northeastern walls and floors consistent with deposition of sand and dust-sized materials on the leeward crater interior slope. This is consistent with sediment transport by prevailing northwesterly winds.

Pancam clast survey images of surface materials adjacent to the rover were used to measure several variables, including clast size (long and medium axis of clasts within images), sorting (standard deviation of clast size within each image), and roundness (from the standard shape estimation methods of Wentworth, 1936). The maximum observed clast length was 2.81 cm. The standard deviation of clast diameter (1.46 cm) indicates a material that is poorly sorted. Clast shapes varied little over the course of the traverse, with the index for the degree of clast rounding averaging 0.32, which corresponds to sub-angular and sub-rounded shapes, consistent with emplacement as fragmental ejecta rather than fluvial transport. Clast size distributions estimated from Navcam images indicated a relatively uniform distribution of clasts smaller than 40 cm in which clasts exceeding 10 to 15 cm were uncommon. Variability of clast size frequency on crater ejecta results from the presence of a radial gradient in maximum block size and the presence of saltating fines trapped within areas of large blocks that bury small clasts (Grant et al., 2005). Close to crater rims, large rocks (d > 10 cm) account for an order of magnitude more area, while the area of small rocks (d < 10 cm) increases by a factor of less than five, and the corresponding distribution curves appear flatter (Fig. 3).

Rocks along the traverse included small clasts (few centimeters) that are frequently vesicular, and angular rocks that were generally larger and nonvesicular. An area of abundant irregular-shaped vesicular rocks in the eastern half of the Missoula crater ejecta is either a preserved remnant of the original plains lava surface, or a concentration of low-density vesicular clasts along the distal margins of ejecta outflow. Scoriaceous materials (Fig. 4A) are locally preserved despite impact gardening of the surface. A few larger blocks (>30 cm) contained distinct layers of concentrated vesicles surrounded by less vesicular basalt (Fig. 4B). The small dimensions of vesicular clasts may have been derived by fragmentation of the fractured and densely vesicular, upper portions common to lava flows (Aubele et al., 1988). Larger and angular blocks are likely to represent samples of the less vesicular, deeper flow interiors where planar fractures are more easily propagated in the homogeneous medium of nonvesicular flow interiors. Because small vesicular clasts comprised a small fraction of the observed clast population, the upper vesicular zones within the Gusev plains lava flows appear relatively thin compared with the overall thickness of the flow units (Crumpler et al., 2005).

Unusual rocks along the traverse included spherically exfoliated rocks (Fig. 4C) and case hardened rocks (Fig. 4D) that suggest in situ alteration. These occurred near crater rims and in crater ejecta and might indicate that, prior to ejection by impacts, fluids chemically altered the regolith or interiors of flows. This would be the case if the same intermittent fluids that resulted in alteration of basalt (McSween et al., 2004) and soils at the surface had penetrated and resided for extended periods of time below the regolith. Based on the relatively shallow depth of regolith turnover (Grant et al., 2004), altered rocks were likely only a few meters below the surface at the time the alteration occurred. In the absence of compelling evidence for lateral transport of materials, the poorly sorted distribution of rocks bearing differing densities (vesicularity) and angularity, and the preservation of delicate scoria clasts imply that the plains surface is a lava flow modified by small impact craters, aeolian aggradation and deflational events, and low rock-to-water ratio chemical alteration.

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