ASSESSMENT OF MARS EXPLORATION ROVER LANDING SITE PREDICTIONS. M. P. Golombek[1], R. E. Arvidson[2], J. F. Bell III[3], P. R. Christensen[4], J. A. Crisp[1], B. L. Ehlmann[5], R. L. Fergason[4], J. A. Grant[6], A. F. C. Haldemann[1], T. J. Parker[1], S. W. Squyres[3], and the Athena Science Team, [1]Jet Propulsion Laboratory, Caltech, Pasadena, CA 91109, [2]Washington University, St. Louis, MO 63130, [3]Cornell University, Ithaca, NY 14853, [4]Arizona State University, Tempe, AZ 85287, [5]Oxford University, OX1 3PG, UK, [6]Smithsonian Institution, Washington, D.C. 20560,

Introduction: The Mars Exploration Rover (MER) landing sites in Gusev crater and Meridiani Planum were selected because they appeared acceptably safe for MER landing and roving and had strong indicators of liquid water. The engineering constraints critical for safe landing were addressed via comprehensive evaluation of surface and atmospheric characteristics from existing and targeted remote sensing data and models that resulted in a number of predictions of the surface characteristics of the sites [1], which are tested more fully herein than a preliminary assessment [2]. Relating remote sensing signatures to surface characteristics at landing sites allows these sites to be used as ground truth for the orbital data and is essential for selecting and validating landing sites for future missions.

General Predictions: General predictions made prior to landing were that both landing sites would be safe for the MER landing system and trafficable by the rovers. At Gusev crater, available data suggested its appearance would be generally similar to the Viking Lander (VL) and Mars Pathfinder (MPF) landing sites, roughly as dusty but less rocky. At Meridiani Planum, available data suggested a low albedo surface with few rocks and little dust that would look completely unlike any of the VL or MPF landing sites [1]. Evaluation of the geologic setting of Meridiani suggested a flat plain composed of basaltic sand with hematite and sparse outcroppings of a thin bright layer [2,3]. All of these general predictions appear correct in the exploration of the landing sites by the rovers. In addition, we have compared the specific remote sensing data at the same landing and traverse locations to the surface characteristics observed by the rovers.

Thermal Inertia: Orbital thermal inertia measurements of both landing sites suggested surfaces that are competent, load bearing (without thick deposits of fine-grained dust) and pose no special risk to landing or roving. The landing location in Gusev crater has a bulk TES thermal inertia [4] of 315 J m^{-2} $s^{-0.5}$ K^{-1} (units used throughout), which is consistent with Viking (284) and THEMIS (306) derived thermal inertias. These thermal inertias suggested the surfaces are dominated by duricrust to cemented soil-like materials or cohesionless sand or granules [5], which is consistent with observed soil characteristics [6] and Mini-TES measured thermal inertias (150-430) from the surface [7]. Average THEMIS thermal inertia along the traverse at Gusev varies from 285 at the landing site, to 290 partway up the Bonneville ejecta, to 330 around Bonneville rim and show systematic variations that can be related to observed variations in rock abundance [7].

In contrast, the landing location in Meridiani has a TES and THEMIS bulk inertia of 200 and 190, respectively, although Viking inertias are slightly higher (~315). The TES inertias are similar to Mini-TES measured inertias of 225 and correspond to surfaces dominated by 0.2 mm sand size particles [5], which is consistent with the ubiquitous fine sand observed [8].

Albedo, Dustiness: Spirit landed in the lowest albedo portion of the Gusev landing ellipse characterized by dark dust devil tracks. As a result, the surface observed at the landing site is substantially less dusty than inferred for the rest of the ellipse. The average TES albedo [4] of the Gusev ellipse is ~0.23 and bright areas have albedos as high as 0.26. The low albedo portion of the ellipse in the dust devil track region that Spirit landed has a much lower TES albedo of ~0.19, comparable to Pancam surface measurements (0.20) [9] which is lower than the VL and MPF landing sites. The landing surface is characterized by reddish soil with many dark granules, pebbles and small rocks as a lag or pavement and only modest bright atmospheric dust coating the rocks and soil surfaces, consistent with the lower albedo and the low dust index for this portion of the ellipse [10]. The albedo of non-dust-devil-track areas like the rim of Bonneville crater are much higher (0.30), consistent with orbital measurements.

The average albedo of the Meridiani landing site in orbital data is ~0.15 and thus it represents the first landing in a characteristically low albedo portion of Mars [11]. Opportunity landed in an area of the ellipse with even lower albedo (~0.12) and the dust index of this part of the ellipse is among the lowest on Mars [11]. The dark sand-rich and dust-free surface observed in Eagle crater is consistent with its low albedo. The brighter rim of Eagle crater observed in the orbital and descent images is consistent with bright outcrops and brighter red soil surfaces that Opportunity has observed. Pancam surface measurements yield comparable albedos of 0.12 on the dark plains and higher albedos for the outcrops (0.25) and brighter wind streaks (0.19 to 0.29) [11]. The consistency between orbital and surface albedo and the presence or absence of bright dust, further supports the use of albedo as a proxy for the dustiness of surfaces on Mars.

Rock Abundance: Average rock abundance of the Meridiani ellipse is ~5% as estimated from thermal differencing of the Viking data [12]. Rock abundance of the Gusev ellipse is higher (~7%) and similar to the global mode of ~8%. Opportunity landed at a location near the border of 1% and 6% rock abundance pixels [12], suggesting a rock abundance of a few percent. Spirit is in an 8% rock abundance pixel and is not in a dense boulder field identified in MOC images [13]. These estimates suggested moderate rock abundance at Gusev and very few rocks at Meridiani, both of which have been relatively benign for driving the rover as expected.

Rock counts show 7%, 5% and 29% of the surface is covered by rocks greater than ~0.04 m diameter in panoramas at <10 m of the landing site, partway up the ejecta, and at the rim of Bonneville crater, respectively. The size-frequency distribution of larger rocks (>0.1 m diameter) generally follows the exponential model distribution based on the VL and MPF landing sites [13] for total rock abundances of 5%, 7% and 35% at the three respective sites, although there are far more pebbles at the Spirit landing site (consistent with less bright dust and drift material at this site) than at other locations. The largest rock increases as the rock abundance increases from 0.5 m to 0.8 m to 1.3 m diameter towards the rim of Bonneville crater. Assuming that the intermediate rock count is representative of the average surface (based on the thermal inertia), about 4% of the surface is covered by rocks >0.1 m in diameter, which compares favorably with the IRTM rock abundance estimate of 8±5% [12]. For effective thermal inertias of rock populations [12], the increase in bulk inertia on the Bonneville ejecta blanket is more than explained by the increase in rock abundance, and suggests a corresponding decrease in fine component inertia, which appears consistent with observations.

The Meridiani plain is effectively devoid of rocks. The orbital rock abundance estimate at this site is likely due to the distribution of outcrop, which appears to cover roughly 5% of the area within the ~20 m diameter Eagle crater, and is exposed in craters and fractures across the plain. In general, the area covered by outcrops and the rock free plain appears consistent with the orbital estimate of several percent of the surface covered by rocks >0.1 m in diameter at Meridiani.

Slopes: Slopes were evaluated at three length scales important for landing [1]: 1 km, 100 m (from Mars Orbiter Laser Altimeter topography) and ≤10 m (from Mars Orbiter Camera stereogrammetry and photoclinometry). At all three scales Meridiani Planum is extraordinarily smooth and flat. RMS slopes at these three scales derived from reconstructions of Opportunity's traverse [14] are 0.3°, 0.7° and 1.4°, respectively, and follow a self-affine behavior with a Hurst exponent of 0.64. These slopes are consistent with the slopes reported prior to landing [1] and the exceptionally smooth and flat plain traversed by Opportunity. Gusev appeared rougher than Meridiani, but smoother than VL1 and MPF in orbital data [1], which is consistent with the derived RMS slopes from Spirit of 0.5°, 1.4°, and 2.5° at these three length scales (Hurst exponent of 0.58) and the relatively low relief plain traversed by Spirit.

Radar: Radar reflectivity values of 0.05 and 0.04 evaluated prior to landing [1] indicated surfaces with loosely constrained, but reasonable bulk densities of ~1500 and ~1200 kg/m^3 at Meridiani and Gusev, respectively, that pose no special problem to landing or roving and are similar to the range of bulk densities of soils that were successfully landed on and roved over by Mars Pathfinder [15]. Later near-nadir 3.5 cm backscatter data with much higher spatial resolution (5 km x 5 km versus 10 km x 150 km) yield somewhat lower reflectivities of 0.02±0.01 at both landing sites [16], although load bearing surfaces have been confirmed by the successful landing and roving at the two sites.

The RMS slope or roughness derived using the Hagfors model [17] indicated a smoother surface at Meridiani than at MPF (3.5 cm RMS 1.4º versus 4.5º) and a smoother surface at Gusev than at VL1 (12.6 cm RMS 1.7º versus 6º) [1]. Interpretation of radar data predicted that Meridiani Planum would be much less rocky and smoother than the VL 2 site and that Gusev would have a combination of roughness at decimeter scales similar to or greater than VL 1 and MPF sites, but would be smoother at meter-scales [1]. These predictions appear consistent with the flat, rock free plain at Meridinai and the generally smooth, moderately rocky surface at Gusev, where RMS slopes from Front Hazcam stereo pairs average 3º at 3 m scale for both rovers, but average about 30º for Spirit and 20º for Opportunity at 10 cm scale.

Results: The close correspondence between surface characteristics inferred from orbital remote sensing data and that found at the landing sites argues that future efforts to select safe landing sites will be successful. Linking the five landing sites to their remote sensing signatures suggests that they span many of the important, likely safe surfaces available for landing on Mars. Our results show that basic engineering parameters important for safely landing spacecraft such as elevation, atmospheric profile, bulk density, rock distribution, and slope can be adequately constrained using available and targeted remote sensing data.

References: [1] Golombek M. et al. (2003) *JGR 108(E12)* 8072. [2] Golombek M. et al. (2004) *LPS XXXV*, #2185. [3] Arvidson R. et al. (2003) *JGR 108(E12)*. [3] Christensen et al. (2003) *Science 300*, 2056-2061. [4] Mellon M. et al. (2000) *Icarus 148,* 437-455. [5] Presley, M. & P. Christensen (1997) *JGR 102*, 6551-6566 (1997). [6] Herkenhoff K. et al. (2004) *Science 305*, 824-826. [7] Christensen, P. et al. (2004) *Science 305*, 837-842. [8] Herkenhoff K. et al. (2004) *Science 306*, 1727-1730. [9] Bell J. et al. (2004) *Science 305*, 800-806. [10] Ruff, S. & P. Christensen (2002) *JGR 107(E12)*, 5127. [11] Bell J. et al. (2004) *Science 306*, 1703-1708. [12] Christensen, P. (1986) *Icarus 68*, 217–238. [13] Golombek M. et al. (2003) *JGR 108(E12)*, 8086. [14] Arvidson R. et al. (2004) *Science 306*, 1730-1733. [15] Moore H. et al. (1999) *JGR 104*, 8729–8746. [16] Larsen K. et al. (2004) *LPS XXXV*, #1050. [17] Hagfors, T. (1964) *JGR 69*, 3779-3784.