HILL DRIVING WITH THE OPPORTUNITY AND CURIOSITY MARS ROVERS. R. E. Arvidson[1], F. Zhou[1], N. Ballintyn[1], P. Bellutta[2], O. Toupet[2], [1]Washington University in St. Louis, Dept. of Earth and Planetary Sciences, arvidson@wunder.wustl.edu, [2]Jet Propulsion Laboratory.

Introduction: The Opportunity [1] and Curiosity [2] Mars Rovers share the same rocker-bogie suspension system and similar wheel-to-ground pressures, even though Opportunity is ~18% of Curiosity's mass. This is a consequence of larger wheels (0.5 m diameter and 0.4 m width vs. 0.26 m and 0.16 m) with greater ground contact area for the Curiosity rover. As of 12/16/17 (sol 4950) Opportunity has traversed 45.1 km whereas Curiosity has traversed 17.9 km (sol 1916). Most traverses have been accomplished as planned, with some exceptions where the rovers encountered steep slopes and/or terrain properties (e.g., deep aeolian sand ripples [3]) that led to high slip values that exceeded specified limits, thereby automatically stopping the drives. In this abstract we analyze several of these drives, with a focus on understanding the terramechanics, i.e., the nature of interactions between the rovers and terrain slopes and materials.

Opportunity's Drives on Endurance Crater's Cape Tribulation Rim Segment: Opportunity explored numerous sites on Cape Tribulation, characterizing the nature of outcrops and evidence for aqueous alteration (Fig. 1). Only two major mobility issues arose out of many drives (Fig. 2). The first was while attempting to reach an outcrop in Marathon Valley called Whitehouse wherein the rover reached almost 100% slip on a 32° slope, with pitch and tilt aligned (Fig. 2). This sol 4311 uphill drive clearly put the rover in a nonlinear slip-pitch-roll situation for the traversed rubble-covered terrain. The second was an ascent on sol 4589 to reach Beacon Rock, when one wheel became embedded in relatively loose regolith. In both cases the rover was commanded to drive back downhill and proceed along less egregious paths. Fig. 3, which is a summary of many drives in Cape Tribulation and Cape Byron (to the South), shows the general trends of slip uphill and skid downhill, with variations for given pitch and roll values indicative of varying terrain properties. Note that this is only one way to examine the mobility trends in that it only shows the magnitude of the actual path relative to the commanded step (usually ~1 m) between visual odometry measurements (Fig. 3).

Curiosity's Drives on Logan and Marias Passes: Curiosity, after touching down on Bradbury Landing and characterizing rocks and soils on the plains and in Yellowknife Bay, began traversing to the southwest, with terrain dominated by mesas and valleys. Traverses on the side of a mesa just before Logan's Pass proved to be beyond the mobility limits of the rover (Figs. 4, 5). Specifically, on sol 983 the drive was automatically halted when slip values in the drive direction, combined with downhill skid values, exceeded set thresholds, mainly because of the left front wheel embedding in loose ripple sands. Backing out of the ripples on sol 984 and continuing to Logan's Pass also proved to be problematic due to traversing on the steep side of a mesa on a surface with loose sands and rubble thinly covering bedrock (Fig. 5). High drive-direction slip and downhill skid values again led to a drive halt, and the science team decision was made to take a more northerly route with lower slopes (Fig. 4). For reference, the ending pitch, roll, and tilt values that led to drive halts for sols 983 and 984 are 6.6°, -6.6°, 9.3°, and 16.3°, -13.5°, and 21.0°, respectively. The orientations were such that the front of the rover was pointing uphill and the left side was tilted downhill.

Implications for Terramechanics and Path Planning: Multiple drive results are currently being tabulated for Curiosity to compare the trends evident for Opportunity and other renditions of mobility parameters. In addition, Artemis simulations [5] are being run as a function of pitch, roll, and terrain properties for each rover to correlate against actual data (e.g., in Fig. 3) and image-based terrain properties (e.g., sand sheets, rubbly terrain, smooth bedrock), to understand the terramechanics of how each rover interacts with terrain slope distributions and material properties. The results will provide information on the nature of the Martian surface, using the rovers as virtual instruments, in addition to providing guidance for safe and efficient path planning as a function of the terrain to be crossed.

References: [1]. Squyres, S. W. et al. (2003) *JGR* doi:10.1029/2003JE002121. [2] Grotzinger, J. P. et al. (2012) *Space Sci. Rev*. doi:10.1007/s11214-012-9892-2. [3]. Arvidson, R. E. et al. (2016) *J. Field Rob*. doi:10.1002/rob21647. [4]. Maimone, M. et al. (2007) *J. Field Rob.* doi:10.1002/rob.20184. [5]. Zhou, F. et al. (2014) *J. Field Rob*. doi:10.1002/rob.21483.

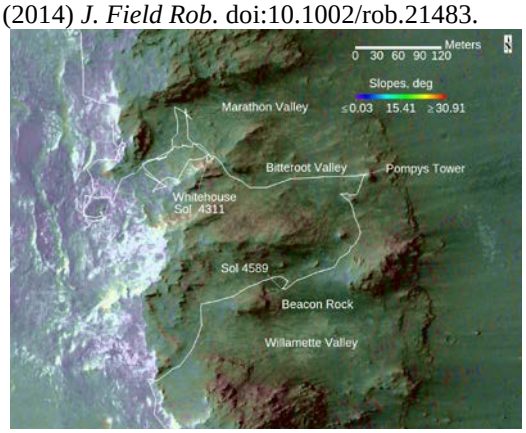

Figure 1: *Portion of a HiRISE mosaic overlain with rover-scale slopes and Opportunity's traverses for a portion of Cape Tribulation. Mobility difficulties were encountered while attempting uphill drives to Whitehouse and Beacon Rock.*

Figure 2: *Front Hazcam image acquired on sol 4313 after Opportunity backed down after an unsuccessful-sol 4311 uphill drive to the outcrop known as Whitehouse. Note the deep wheel tracks generated during the uphill drive attempt.*

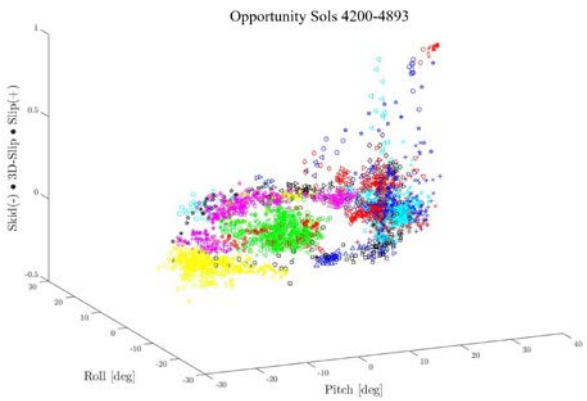

Figure 3: *Plot of slip/skid as a function of pitch and roll for a wide range of Opportunity's drives on Cape Tribulation. High slip values are associated with high pitch values traversing uphill whereas high skid values are associated with steep descents. Each color/pattern is for a specific drive. Skid and slip are derived using visual odometry [4]. Slip occurs when the 3D distance is less than commanded and skid when it is more than commanded.*

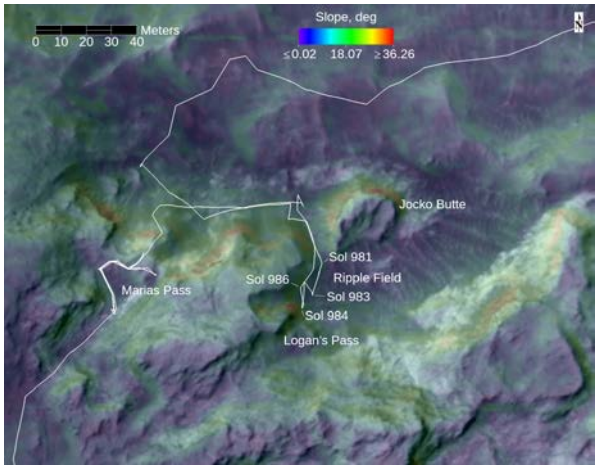

Figure 4: *Portion of a HiRISE mosaic overlain with rover-scale slopes for Curiosity's traverses toward Logan's Pass and in Marias Pass. The rover was commanded to start a northerly route on sol 986, which led to successful traverses through Marias Pass.*

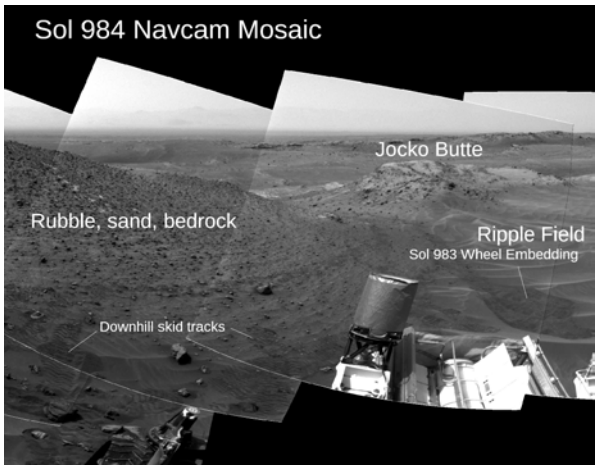

Figure 5: *Portion of a Curiosity Navcam mosaic looking back at the rover left front wheel embedding in ripple sand that caused termination of the sol 983 drive, together with the wheel tracks showing skid during the aborted sol 984 drive on the rubble, sand, and bedrock-dominated slope.*