SCIENTIFIC LEGACY FROM THE OPPORTUNITY ROVER'S EXPLORATION OF MERIDIANI PLANUM.
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Introduction: The NASA Mars Exploration Rover, Opportunity, landed on Meridiani Planum on 1/25/04 (sol 1) and maintained communications with Earth until 6/10/18 (sol 5112), when a major dust storm reduced power on the solar panels to the point where further communications were not possible. Opportunity far exceeded its 90 sol primary mission and set records for longevity, distance traveled (45 km, Fig. 1), and scientific discoveries for planetary rovers. This abstract highlights the scientific legacy derived from analysis of imaging and spectroscopic data acquired using Opportunity's instrument payload [1].

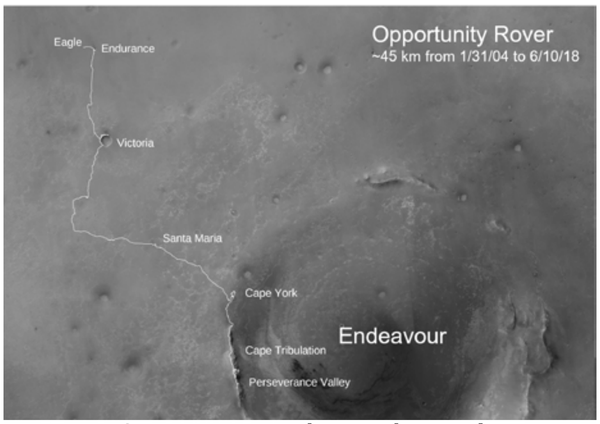

Fig. 1: HiRISE image mosaic showing the complete traverse of Opportunity across Meridiani Planum and onto Endeavour Crater's (22 km diameter) western rim segments. Names on the plains refer to craters examined by Opportunity to characterize Burns formation sulfate-bearing strata. Erebus Crater, not shown, is just north of Victoria Crater.

Paleoenvironmental Conditions Inferred From Burns Formation Rocks: Analysis of Opportunity data (e.g., mineralogy, composition, bedding, grain size distributions, diagenetic features) (Fig. 2) demonstrate that the Burns formation sediments were originally deposited as saline groundwaters ascended through the Noachian basement, producing evaporitic sulfate-rich muds in an interdune environment [2, 3, among many!]. Reworking by wind and water generated the "second-cycle" sulfate-cemented, cross-bedded Burns formation sandstones that underlie Meridiani Planum, which were subsequently altered by later ground waters. Opportunity was thus the first to characterize in detail a sedimentary deposit on another planet, one that demonstrates the prolonged presence of water on and beneath the surface of Mars.

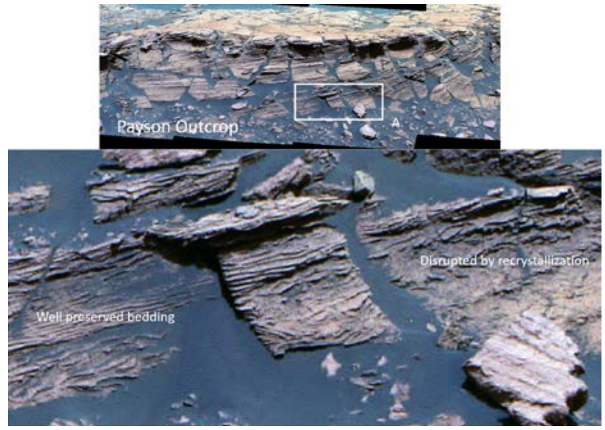

Fig. 2: View of the Payson outcrop on the western side of Erebus crater. This outcrop displays evidence for interdune wet conditions, including the presence of shallow surface water flow based on ripple patterns. There is also evidence for bedding disruption by recrystallization soon after deposition of the sulfate-rich deposits [4].

Endeavour Crater's Rim Geology and Extent of Rock Alteration: Opportunity's extensive exploration of Endeavour Crater's western rim (Fig. 1) provided the first detailed view of a complex crater on any planet [5]. One unexpected characteristic is that Endeavour's rim is segmented into topographically and structurally distinct domains bounded by radial fractures located both within and between segments. Abrupt along-strike termination of outcrops, right and left-stepping offsets of local topographic rim crests, and changes in strike and dip of local slabs and foliations are evident at the transitions between rim segments. Opportunity data show that the rim is composed of coarse impact breccias (upper Shoemaker formation) overlying a pre-impact substrate that includes the Matijevic formation and lower Shoemaker formation breccias (Fig. 3) [6]. Inner crater rim units dip toward the crater interior and are interpreted to be due to uplift over blind thrust faults generated at the time of crater formation. Fluvial erosion of Endeavour, followed by minor weathering, mass movements, and wind-related erosion, are interpreted to have produced the current shape and rock exposures characterized by Opportunity [7]. Analysis of Opportunity data also show that Endeavour's rim rocks have been modified by aqueous processes, particularly for the lower Shoemaker and Matijevic formation rocks [6, 8]. This alteration tends to be concentrated along fractures, implying a dominance by ground water related processes.

Perseverance Valley and Wind Erosion: Opportunity's last communication was from Perseverance Valley, a prime target for the extended mission. The valley is a ~200 m long, ~10 to 20 m wide anastomosing set of shallow, channel-like features extending down Endeavour's inner rim from a gentle swale between Capes Tribulation and Byron (Fig. 4). Before communications ceased Opportunity had traversed ~40% of the way down Perseverance Valley and conducted numerous imaging and compositional measurements. Our working hypotheses for formation of the valley included dry downhill mass movements of debris, debris flows lubricated by water, flowing water and associated erosion, transport and deposition of sediment due to overtopping of a former catchment located to the west of the rim, and wind erosion of a complex fracture system located between Capes Tribulation and Byron. Surprisingly, wind action funneled from easterlies blowing uphill is most consistent with Opportunity's data, which includes outcrop patterns best explained by faulting, and miniature yardangs carved into outcrops [9].

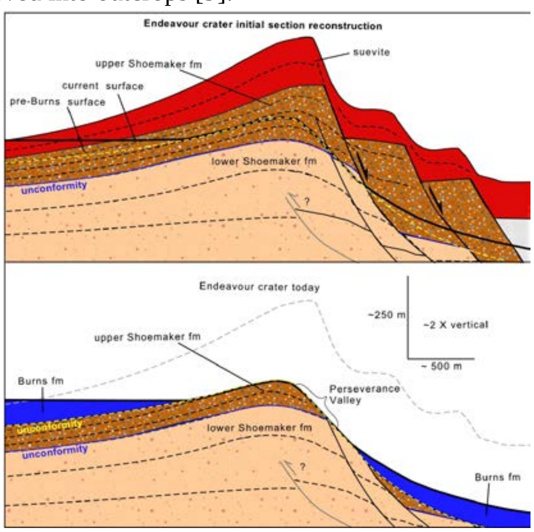

Fig. 3: Schematic cross sections showing the original and partially eroded versions of the structure and geology inferred for Endeavour's rim. Crumpler, pers. comm.

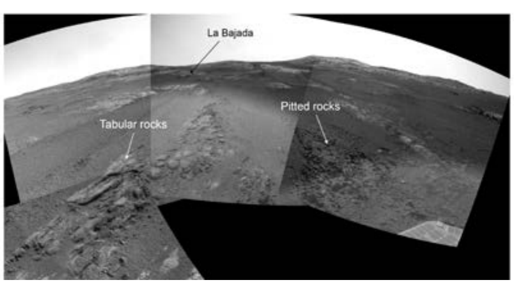

Fig. 4: Navcam-based view from Opportunity, sol 5083, looking uphill toward the top of Perseverance Valley, showing what are interpreted to be various outcrops juxtaposed by faulting and shaped by wind action.

Meteorites on the Plains: Opportunity was the first planetary rover to identify and characterize meteorites. Among the analyses was the use of the extent of meteorite weathering to characterize the post-Burns formation atmosphere-surface physical and chemical processes and rates [10,11].

Atmospheric Dynamics: Opportunity's last reported atmospheric normal optical depth was 10.8, indicative of the largest dust storm on record for Mars. The legacy of measurements from 2004 to 2018 provides the longest continuous record of this important parameter [12]. Use of the APXS for atmospheric measurements of argon (as a tracer of atmospheric dynamics), a novel use of this instrument, has provided valuable information on formation and sublimation of the polar CO_2 winter ice caps (Fig. 5) [13].

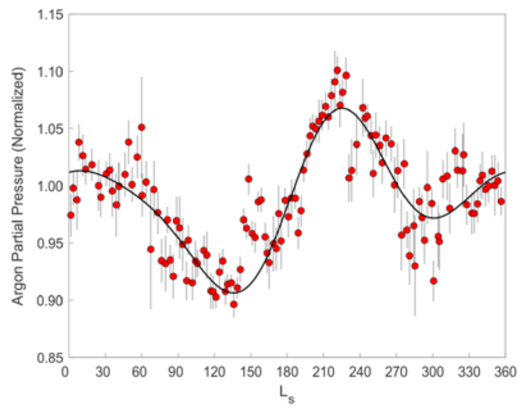

Fig. 5: Opportunity APXS argon data fit with a sinusoidal trend showing low concentrations during formation of the southern winter cap. The deviation around Ls 155 is consistent with a northward migrating front enriched in noncondensable gases. A more-subtle southward migrating front is evident ~Ls 325 [13].

References: [1] Squyres S. W. et al. (2003) *JGR-Planets*, doi:10.1029/2003JE002121. [2] Squyres S. W. and Knoll A. H. (2005) *Earth and Planet. Sci. Lett.*, doi:10.1016/j.epsl.2005.09.038. [3] Hurowitz J. A. et al. (2010) *Nature Geoscience*, doi:10.1038 /ngeo831. [4] Grotzinger J. et al. (2006) *Geology*, doi:10.1130/G22985. [5] Crumpler L. S. et al. (2019) *LPS L, Abs*. #1179. [6] Mittlefehldt D. W. (2019) *LPSC Abs* #1100. [7] Hughes M. N. et al. (2019) *JGR-Planets*, doi: 10.1029/2019JE005949. [8] Arvidson R. E. et al. (2014) *Science*, doi: 10.1126/science.1248097. [9] Sullivan R J. et al. (2019) *LPS L, Abs.* #3244. [10] Ashley J. W. (2015) Elements 11(1), 10-11. [11] Schröder C. et al. (2016) *Nat. Commun.*, doi: 10.1038/ncomms13459. [12] Lemmon M. T. et al. (2015) *Icarus*, doi:10.1016/j.icarus. 2014.03.029. [13] VanBommel S. J. et al. (2018) *JGR-Planets*, doi:10.1002/2017JE005454.