

# Degradation of Endeavour Crater, Mars

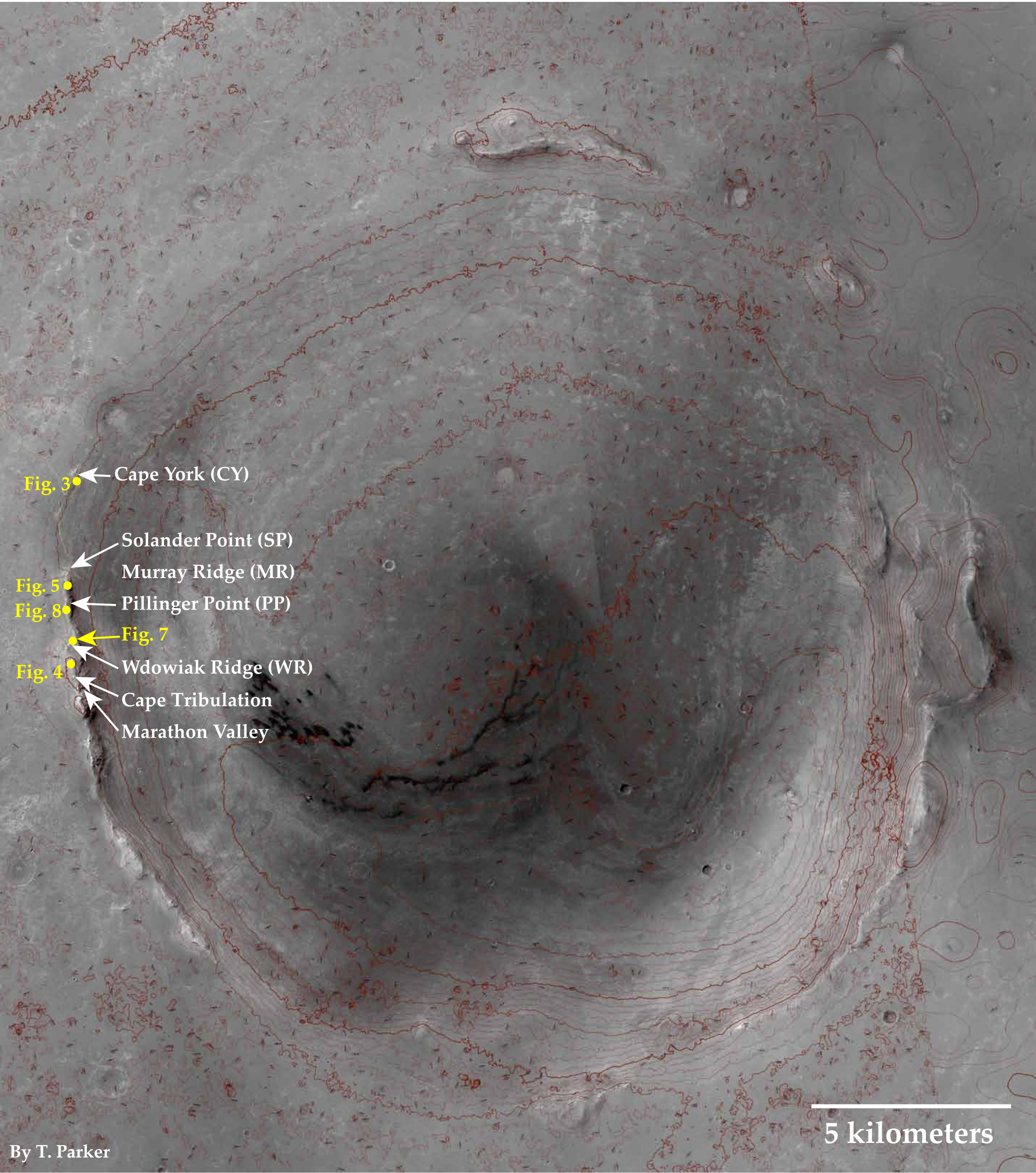
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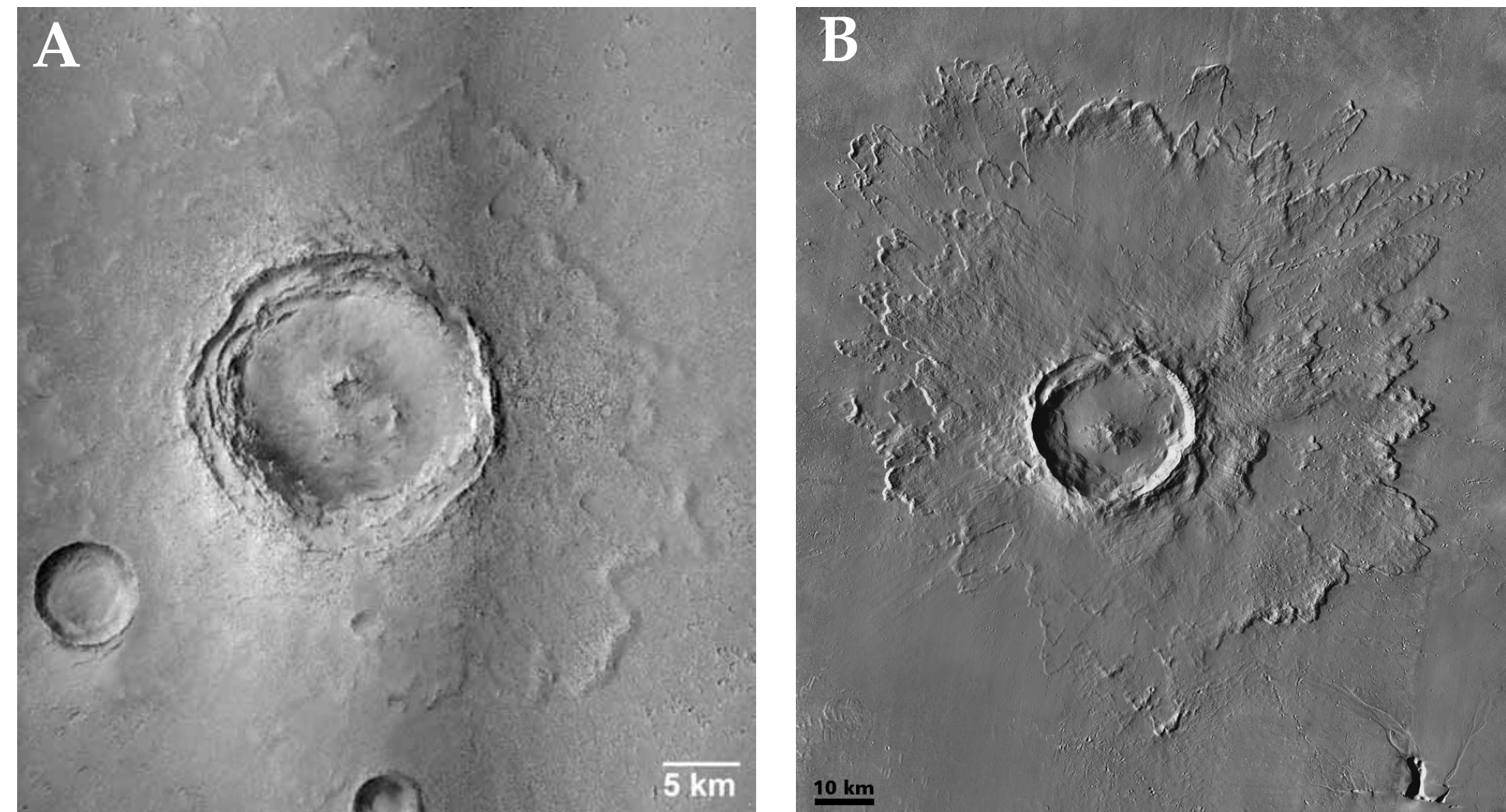
## INTRODUCTION

Data from the Opportunity rover and MRO enables evaluation of the degradation state of Endeavour, a 22 km-diameter Noachian-aged crater in Meridiani Planum (**Fig. 1**). The crater form is largely buried by younger sulfate-rich rocks (**Fig. 1**). Modern analogs for Endeavour may include Santa Fe and (or) Tooting craters (**Fig. 2**).

Opportunity explored rim segments dubbed Cape York (CY) and Solander Point-to-Murray Ridge (MR)-to-Marathon Valley located ~1500 m from CY. Rover images reveal breccias interpreted as remnants of the ejecta deposition at both rim locales, dubbed the Shoemaker Formation [1]. At CY the Shoemaker Formation overlies pre-impact rocks, dubbed the Matijevec Formation [1, 2] (**Fig. 3**).

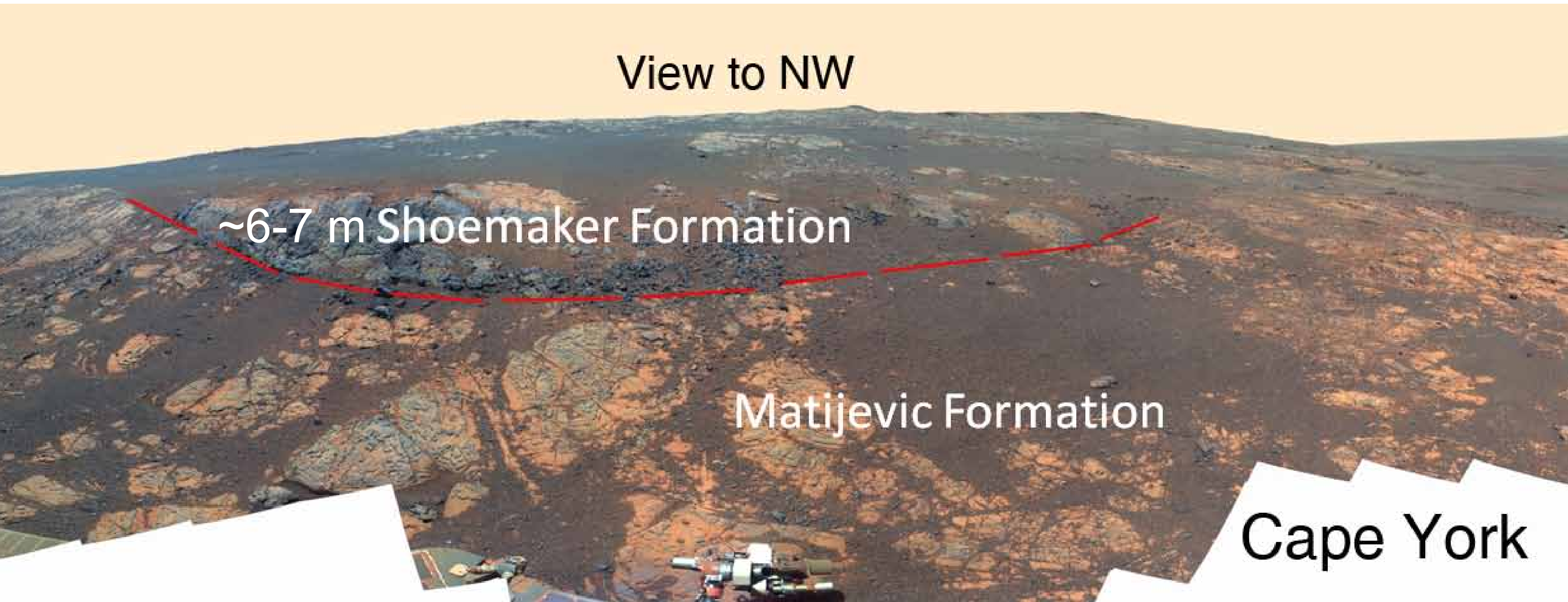


**Figure 1.** The 22 km-diameter, complex morphology, Noachian-aged, Endeavour crater in Meridiani Planum (2.3°S, 354.8°E), Mars. 20 m contours indicated and produced by co-author T. Parker. Faint yellow line indicates rover traverse. Exposed rim segments are embayed by younger plains materials that also partially fill the crater interior. Rim outline “notched,” characteristically slightly scalloped in places (SE, SW, quadrants). Only one large terrace block on east rim (where ~300 m exposed relief on interior wall is typical (except to north). No evidence of terrace blocks elsewhere around rim, though isolated blocks are found in deeper portions of the SE interior. Opportunity has been exploring western segments of the crater rim for the past three years. CTX image G02\_018912\_1779\_XN\_025005W and G04\_019980\_1779\_XN\_025005W, 6 m pixel scale. CTX ORR/DEM processed with Ames Stereo Pipeline. North to top.



**Figure 2.** Modern Analogs for Endeavour?

**A)** Santa Fe crater (19.5°N, 312°E) is 20.2 km diameter and is characterized by nearly continuous wall terraces that give a diameter of 16.3 km. Hence the inner terrace diameter to outer diameter (I/O) ratio is 0.81. CTX P04\_002563\_1992 and B16\_016052\_1994 with 6 m pixel-scale. North towards the top. **B)** Tooting crater (23.1°N, 207.1°E) is 27.5 km in diameter and is characterized by discontinuous terrace blocks whose inner diameter is close to 25.7 km, giving an I/O diameter ratio of 0.93. Image is a THEMIS VIS mosaic modified from **Fig. 1** in [6] with 19 m pixel-scale and north towards the top.



**Figure 3.** The false color Matijevec panorama of outcrops on the eastern side of CY annotated to show contact between the pre-Endeavour impact Matijevec Formation and the overlying impact breccias of the Shoemaker Formation. From Solander Point (SP) to Marathon Valley, a section of up to ~150 m Shoemaker Formation is present but, Matijevec has not been observed. For comparison, at Tooting crater (**Fig. 2**), a 400 m section of ejecta occurs everywhere around rim. Pancam mosaic obtained by Opportunity over sols 3137-3150, filters L2, 5, 7 (432 nm, 535 nm, and 753 nm).

## EROSIONAL FORM OF RIM

At CY, present relief along the exposed rim segment is ~10 m and consists of 6-7 m of Shoemaker Formation over at least several meters of Matijevec Formation. By contrast, relief along the MR segment is considerably higher and the Shoemaker Formation/Matijevec Formation contact is not visible and up to ~150 m section of Shoemaker Formation is preserved at MR. Offset between rim segments is possible and could relate to faulting during late stage crater formation and fractures are observed at MR (**Fig. 4**). Such fractures may be similar to those around smaller terrestrial impacts [4].

Comparison to similar sized fresh, complex craters on Mars [5-8] suggests on order of 300 m of ejecta was originally present at the rim of Endeavour crater. Hence, CY may have experienced ~300 m erosion, whereas MR has been lowered by ~150 m. A paucity of debris from the Shoemaker and Matijevec Formations relegates most erosion to before the plains deposits were emplaced, implying more efficient erosion in the past [9].

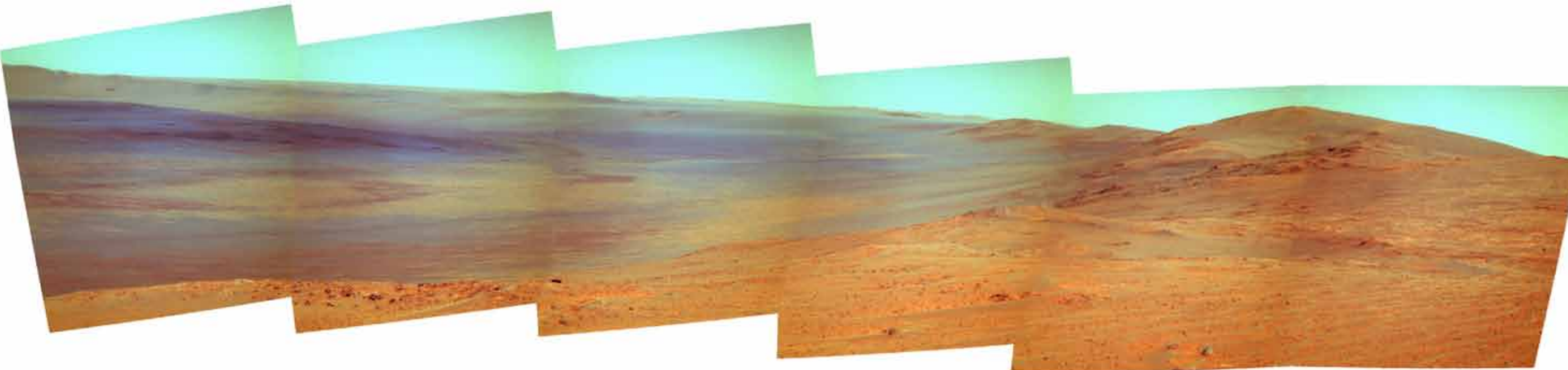
Moreover, ejecta comprise ~40-70% of the relief around selected Mars complex craters [6-8]. Hence, original rim relief [3, 5, 7, 8, 10] at Endeavour may have been ~430-750 m. Based on exposed rim relief, ~150-500 m are needed to bury the uplifted rim and is less than estimated plains thickness of 800-900 m farther to the east and north [11-13]. Thinner plains at Endeavour is consistent with its location on the flank of buried Miyamoto crater, within ~40-60 km of the edge of the plains, and thickness observed in the rim of nearby Bopolu crater.



**Figure 4.** False color mosaic of a large fracture zone extending to the east-southeast from the rover and located along the Endeavour rim south of Wdowiak Ridge (WR, **Fig. 1**). The fracture zone is generally ~1-2 m across and continues to the west of the rover as well. The fractures are locally filled by sulfate materials and likely confirm the structural influence of the formation of Endeavour crater during and shortly after impact. Tear faults and other offsets expected during crater formation/modification. No obvious offset in section occurs across the fracture at Endeavour and no obvious faults (with large offset) are observed, but may be buried between exposed rim segments. Hence, faults cannot account for minimal Shoemaker section remaining at CY. Pancam mosaic was obtained by the Opportunity rover on sol 3861 using filters L2, 5, 7 (432 nm, 535 nm, and 753 nm).

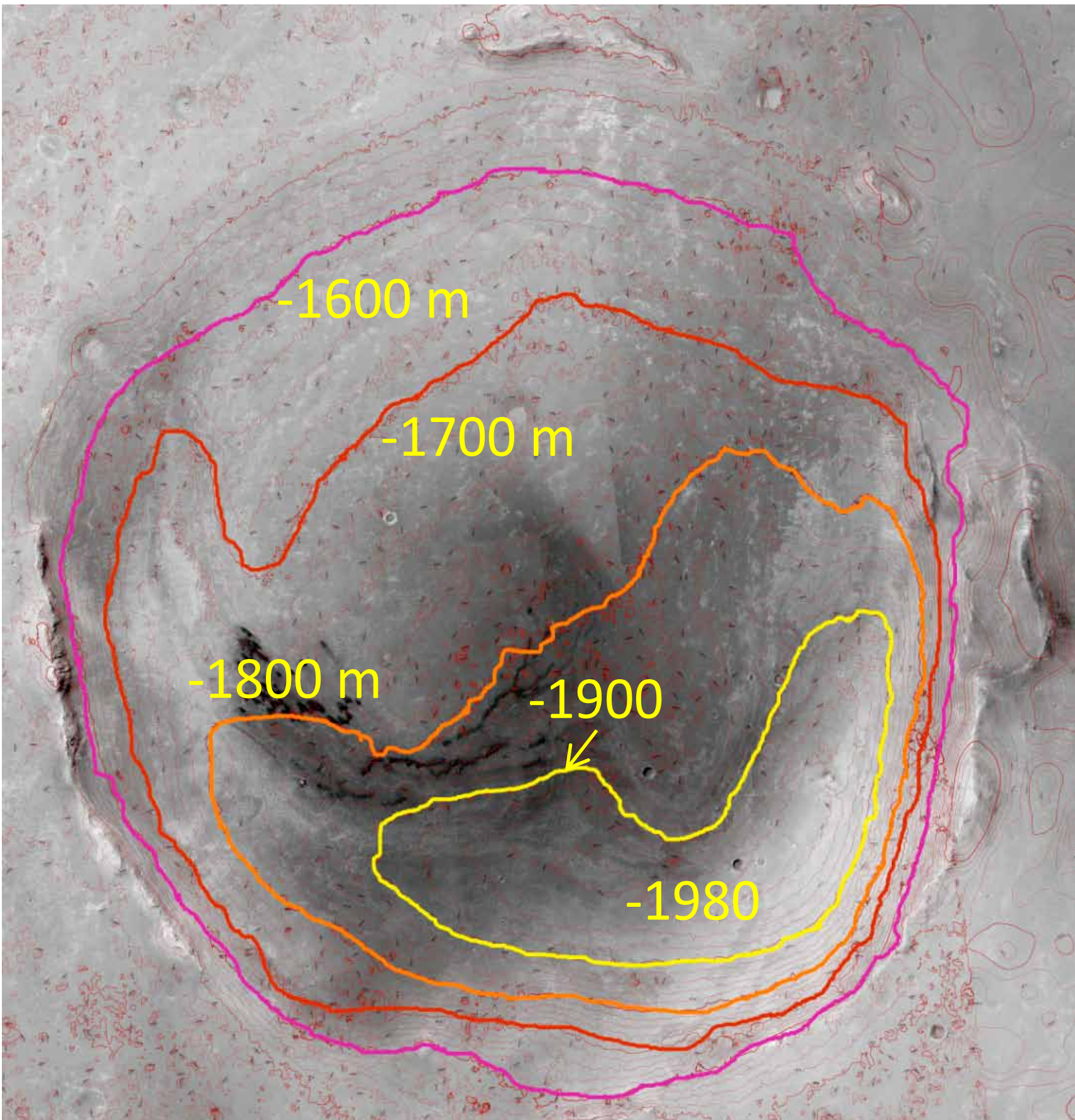
## THE CRATER INTERIOR

Sulfate-rich plains materials extend into and partially fill Endeavour crater (**Fig. 5**): the depth is 200-300 m in the north and up to 500 m depth in the south. Studies of complex craters on Mars [3, 5, 7, 10, 14-18] suggests the original depth was probably between ~1-3 km and most likely ~0.8-1.5 km, thereby indicating on order of 0.8 to 1.5 km of fill remains in the crater. However, some fill may relate to pre-plains materials shed from the crater walls. The eroded expression of the interior deposits (**Fig. 6**) might be related to prevailing winds [19] interacting with rim topography.



**Figure 5.** False color mosaic of the interior and rim of Endeavour crater from between Murray Ridge (MR) and Pillinger Point (PP, **Fig. 1**). Younger, bedded plains materials of the Burns and Grasberg Formations partially fill the crater and remnants appear to extend up the crater walls, thereby suggesting that these plains materials may once have been more extensive. Pancam mosaic obtained by Opportunity on sol 3637, filters L2, 5, 7 (432 nm, 535 nm, and 753 nm).

**Figure 6 (right).** CTX contour map of Endeavour crater (**Fig. 1**) with 100 m contour intervals highlighted. The crater is only 200-300 m deep to the north, but up to 500 m deep in the southeast quadrant. The contours trace a horseshoe-shaped depression that extends from the south around to the east and west and may be the result of enhanced stripping related to the interaction between prevailing winds [19] and crater rim topography.



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## REFERENCES

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## ENIGMATIC WDOWIAK RIDGE

Wdowiak ridge (WR) is located immediately west of Endeavour's rim and oriented NE-SW (**Figs. 1 and 7**). The ridge is capped by more resistant dark rocks that are not breccia and are chemically and texturally distinct from the overlying Shoemaker Formation [20]. Origin of the ridge is uncertain, but possibilities include exhumation of a local pre-impact high or ejecta megablock [20] or impact melt and would support estimates of significant erosion.



**Figure 7.** False color mosaic of the northern end of WR showing the relatively more resistant and darker appearance of the rocks that cap the ridge. Origin of the rocks capping the ridge remains uncertain, but may relate to the eroded expression of impact melt, exhumed ejecta megablock, or exhumed relief on the pre-impact surface [20]. Mosaic was obtained by Opportunity on sol 3750, filters L2, 5, 7 (432 nm, 535 nm, and 753 nm).

## EROSIONAL PROCESSES

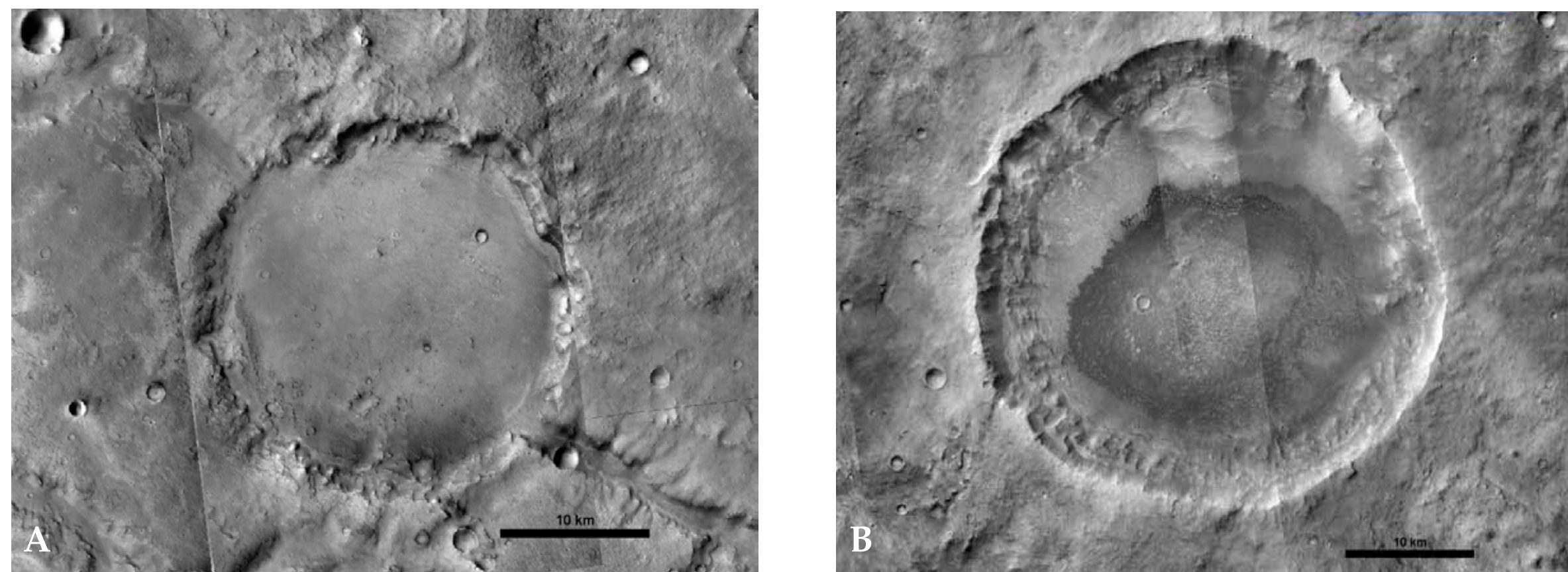
The original form of Endeavour crater has been considerably degraded by ~150-300 m erosion at the rim (**Figs. 8 and 9**). Emplacement and subsequent partial stripping of the plains and rim reveals a subdued impact form (**Figs. 1 and 6**) and identifying signatures other than the eolian forms associated with the plains remain elusive. The range of inferred degradation, however, implies sufficient modification by processes of locally varying intensity to account for differences in relief along and between exposed rim segments (**Fig. 1**). This may point to a fluvial component to early erosion and is important in modification of Noachian craters just to the south of the Meridiani plains (**Fig. 10**). Colluvial, eolian, and local mass-wasting activity was also probably important, but the rim form and position does not support wholesale collapse of rim segments except for where observed along the east rim.



**Figure 8.** False color view of outcrops along south end of Murray Ridge (MR) on rim of Endeavour crater. The stripped appearance of the rocks and local mantling of surfaces by drift reflects ongoing eolian modification. Pancam mosaic was obtained by Opportunity rover on sol 3720 using filters L2, 5, 7 (432 nm, 535 nm, and 753 nm).



**Figure 9.** View of Marathon Valley from the north rim of the valley. The valley represents relatively deep radial erosion into the exposed rim and could reflect local mass-wasting into the crater and/or rim incision whose signatures have been subsequently modified by eolian erosion. Mosaic was obtained by Opportunity on sol 3927 using filters L2, 5, 7 (432 nm, 535 nm, and 753 nm) and was processed using a 1% linear stretch and some enhancement of fine details.



**Figure 10.** Examples of degraded Noachian-aged craters south of Meridiani Planum that are not buried by younger plains materials.

**A)** An unnamed crater centered at 5.46°S, 354.7°E with a diameter of 27 km and d/D = 0.015. The crater has an irregular rim outline and a rim that is wholly breached by incision in multiple locations and is likely more degraded than Endeavour. CTX B05\_011620\_1747, G03\_019268\_1741 and P06\_003300\_1738.

**B)** An unnamed crater centered at 4.66°S, 357.38°E with a diameter of 37 km and d/D = 0.032. The rim outline preserves subtle scallops, and local topography that is of a similar scale and orientation to Marathon Valley-like features. Although it is unclear whether the ejecta remaining around the crater is comparable to that at Endeavour, the rim morphology suggests that the craters may have experienced comparable amounts of degradation. CTX B02\_010565\_1748, B01\_009998\_1758 and P16\_007137\_1748.