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The degradational history of Endeavour crater, Mars

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ABSTRACT

Endeavour crater (2.28°S, 354.77°E) is a Noachian-aged 22 km-diameter impact structure of complex morphology in southern Meridiani Planum. The degradation state of the crater has been studied using orbital data from the Mars Reconnaissance Orbiter and *in situ* data from the Opportunity rover. Multiple exposed crater rim segments range in elevation from ~10 m to over 100 m above the level of the embaying Burns Formation. The crater is 200–500 m deep and the interior wall exposes over ~300 m of relief around the southern half of the crater. Slopes of 6–16% flank the exterior of the largest western rim segment. On the west side of the crater, both pre-impact rocks (Matijevic Formation) and Endeavour impact ejecta (Shoemaker Formation) are present at Cape York, but only the Shoemaker Formation (up to ~140 m section) outcrops at Cape Tribulation.

Study of similar sized pristine craters Bopolu and Tooting (with complex morphology) and use of metrics for describing the morphometry of martian craters suggest the original rim of Endeavour averaged 410 m in elevation, but relief varied about ±200 m around the circumference. A 250–275 m section of ejecta (±50–60 m) would have comprised a significant fraction of the rim height. The original crater was likely 1.5–2.2 km deep and may have had a central peak (no obvious evidence is present) between 200 and 500 m high.

Comparison between the predicted original and current form of Endeavour suggests 100–200 m of rim degradation ranging from nearly complete ejecta removal in some locations to preservation of a thick ejecta section in others. Differences in rim relief are at least partially due to degradation and not just original rim relief and (or) due to offsets along rim faults. Most degradation occurred prior to deposition of the Burns Formation which is ~200 m thick outside the crater, but likely thicker inside the crater.

Aeolian stripping of the Burns Formation continues today via prevailing winds and lesser mass wasting is important on steeper walls. However, analogy with degraded Noachian craters south of Meridiani suggests fluvial processes were most important in early degradation and is consistent with the nearly complete removal of ejecta from some rim segments, gaps in the rim, formation of Marathon Valley, and interpretation of a pediment flanking the western rim. Slope processes likely accompanied incision that may have accounted for tens of metres rim lowering near Marathon Valley to more than 100 m at Cape York.

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1. Introduction

Insight into the original form of impact craters provides an important framework for understanding the timing, processes, and amount of subsequent degradation experienced over time (e.g., Grant and Schultz, 1993a,b). Most investigations evaluating crater degradation on Earth and Mars (e.g., Grant and Schultz, 1993a,b; Grant et al., 2006, 2008; Golombek et al., 2006, 2014) focus on smaller, simple morphology impact structures (Melosh, 1989) because their initial form is well understood and less modified by late formation processes generally associated with larger, complex morphologies (e.g., late stage wall failure, see Melosh (1989)). Although the variability in the pristine morphology of complex craters is not well quantified, their large scale and persistence on older surfaces makes understanding their initial and degraded morphologies a potentially important tool for constraining geomorphic activity on Mars.

Endeavour (2.28°S, 354.77°E) is a Noachian-aged (Hynek et al., 2002; Arvidson et al., 2014), 22 km-diameter impact structure in

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southern Meridiani Planum (Figs. 1 and 2). It is the first crater rim with a complex morphology (Melosh, 1989) explored *in situ* on Mars (Fig. 3). The Mars Exploration Rover Opportunity characterized the rocks and structures along rim segments dubbed Cape York and Cape Tribulation on the western side of the crater (e.g., Arvidson et al., 2014; Crumpler et al., 2015a). Nobbys Head was visited briefly during the traverse from Cape York south to Cape Tribulation. Cape Tribulation includes (from north to south) Solander Point, Murray Ridge, Wdowiak Ridge, the high point on Cape Tribulation, and Marathon Valley. Marathon Valley marks the furthest south the rover traversed as of May 2015.

Using the Athena science payload (Squyres et al., 2003), Opportunity made detailed observations and measurements that enable the interpretation of rim geology and geomorphic characteristics (Crumpler et al., 2015a,b). These rover data constrain the nature and origin of features observed in orbital data from the Context (CTX; Malin et al., 2007) and HiRISE (McEwen et al., 2007) cameras on the Mars Reconnaissance Orbiter (MRO), which can be used to remotely explore sections of the crater not visited by the rover. The intersection of *in situ* rover observations and orbital data offers a unique opportunity to constrain the amount and type of geomorphic processes responsible for the modification of this complex impact crater.

2. Present expression of Endeavour crater

2.1. Overall character of Endeavour crater

Endeavour crater is mostly buried by Burns Formation sulphate-rich rocks underlying the regionally occurring Meridiani plains (Grotzinger et al., 2005; Squyres and Knoll, 2005; Arvidson et al., 2006), so only portions of Endeavour's rim protrude above the plains rocks (Figs. 1 and 2). The present complete burial of the crater exterior, including ejecta beyond the immediate rim, precludes characterization of the morphologic class of ejecta associated with the crater. Discontinuous rim segments are best exposed around the west-southwest and east-southeast part of the crater, with shorter segments visible to the south, north, and northeast. Broad gaps occur in the northwest, south-southwest, and northeast rim outline.

2.2. The rim of Endeavour crater

The Opportunity rover has explored multiple rim segments on the west side of the crater (Figs. 2 and 3), but the overall expression of the rim of Endeavour is best characterized by MRO data. A key aspect of these orbital data includes a digital terrain model (DTM) of the entire crater derived using stereo CTX images that are of a ~6 m pixel-scale (Fig. 2) and are supplemented along individual rim segments by HiRISE images that are typically of a 0.25–0.50 m pixel-scale (Fig. 3). The exposed segments of Endeavour's rim are at fairly uniform radii and rise tens of metres above the nearly flat younger plains (the regional slope of the plains is only 0.2–0.3% to the southeast). Inboard margins of rim sections in the southwest and southeast, however, are broadly and gently scalloped (Fig. 2).

The interior wall on the eastern rim of Endeavour covers ~300 m in relief and is characterized by a discontinuous terrace block (Fig. 2). The terrace block defines an inner diameter of 17–19 km, thereby yielding a ratio of the terrace-to-rim diameter of 0.78–0.87. This ratio is similar to that measured around the larger Theopolis crater and other craters on the Moon (Melosh, 1989). Despite ˜300 m exposed relief on the wall of segments to the south and west, there is no obvious evidence of other terrace blocks with the possible exception of an isolated knob roughly 1 km inboard of the southern rim (Fig. 2). Wall relief is lowest on the northern side of the crater.

Rim segments emerge from the plains rocks at generally similar elevations (relative to the MOLA datum, Fig. 4 and Table 1) but rim relief above the plains is variable both along and between

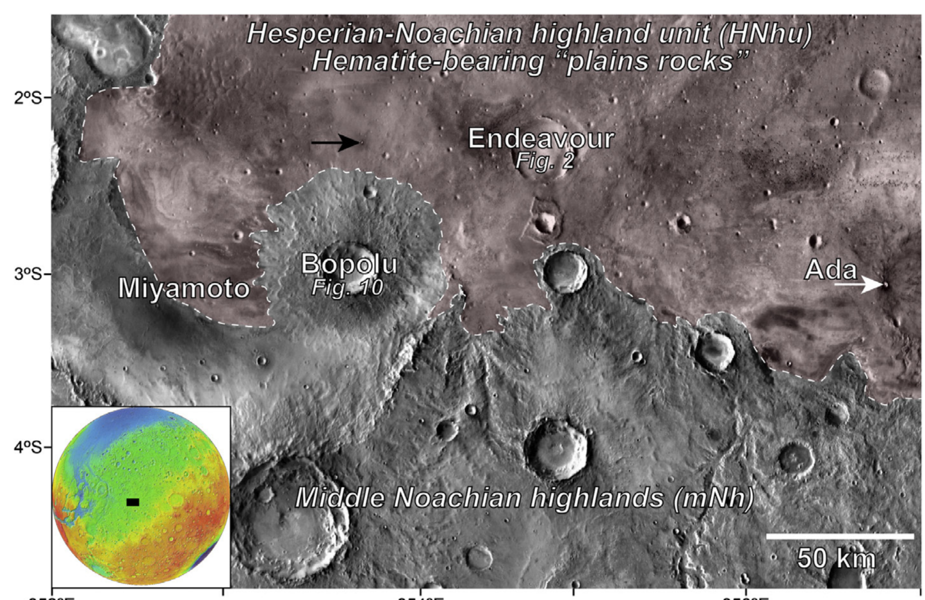

Fig. 1. Meridiani region centred near 3°S, 354.5°E (see black box on MOLA globe in inset for context) showing locations of craters Endeavour, Bopolu, Miyamoto and Ada. The Middle Noachian highlands (mNh) and the Hesperian–Noachian highland unit (HNhu) characterize the southern and northern portions of the study area, respectively (Tanaka et al., 2014). The approximate extent of the Burns Formation/Grasberg unit or "plains rocks" is shaded red (after Fig. 1 in Arvidson et al. (2006)). Endeavour is 22 km in diameter and mostly buried by the younger Meridiani plains rocks, whereas Bopolu post-dates the emplacement and most modification of the plains rocks. Miyamoto is partially buried by plains rocks and Bopolu crater is within Miyamoto crater. Endeavour crater is on the northeastern flank of Miyamoto. Two fresh craters identified with exposures of Burns Formation in their interior rims are Ada and an unnamed 0.84 km diameter crater (black arrow) (Golombek et al., 2010). Note valley networks in the highlands to the south that are buried by the Burns Formation. Subframe of the THEMIS Day IR Global Mosaic in Simple Cylindrical projection, resolution of 256 pixels/degree, and scale of 231.55 m/pixel. North towards the top.

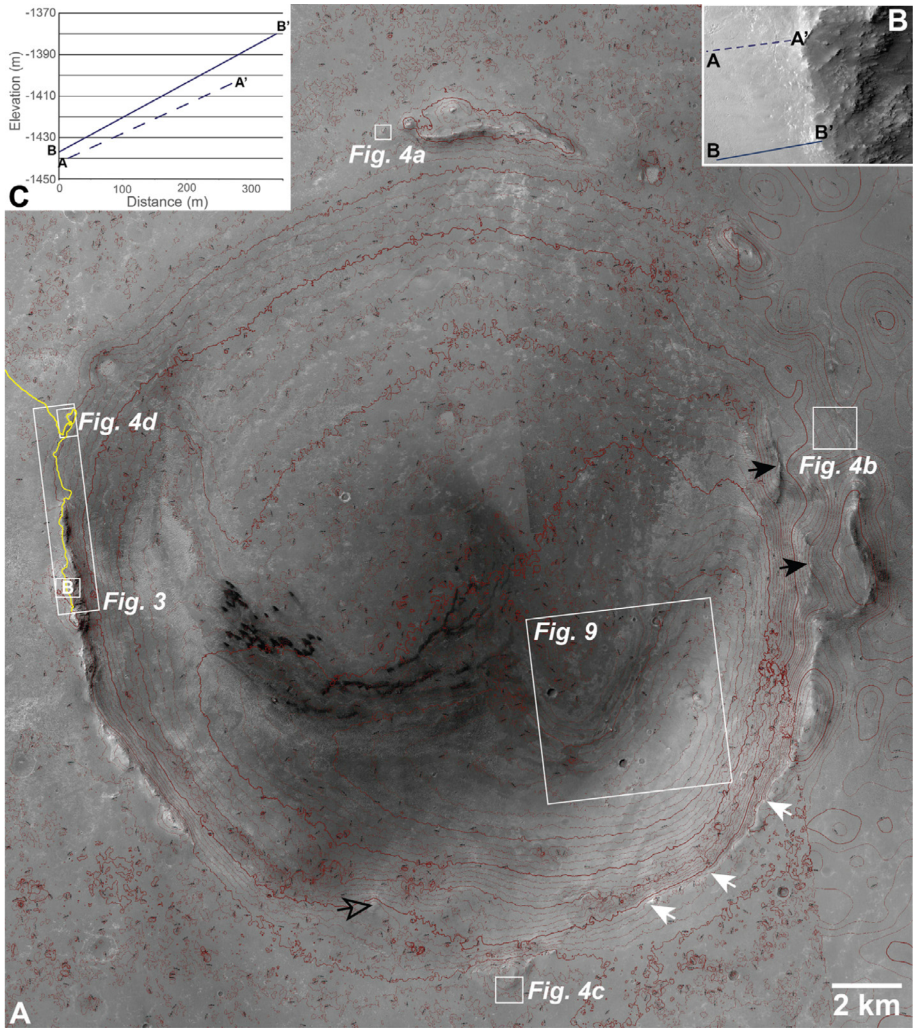

Fig. 2. (A) The 22 km-diameter, complex morphology, Noachian-aged, Endeavour crater in Meridiani Planum (2.3°S, 354.8°E, see Fig. 1 for context). Exposed rim segments are embayed by younger plains rocks that also partially fill the crater interior. The rim outline on the crater wall is broadly scalloped in the southeast (e.g., white arrows) and southwest quadrants and there is a terrace block on eastern rim (e.g., black arrows). The wall around the southern half of the crater typically is exposed over ~300 m. Although additional terrace blocks are not obvious elsewhere around rim, there is a knob inboard of the southern rim at an elevation of −1600 m (black hollow arrow) and isolated blocks in deeper portions of the southeastern interior are apparent (Fig. 9). White boxes show location of Figs. 2B, 3, 4(A–D) and 9. CTX ORR/DEM from CTX G02_018912_1779_XN_02S005W (6 m pixel-scale) and G04_019980_1779_XN_02S005W (6.4 m pixel-scale) with 20 m contours produced by co-author T. Parker using the Ames Stereo Pipeline. Yellow line along western rim indicates the approximate route of the Opportunity rover through sol 4000. North towards the top. (B) Location of transects corresponding to profiles shown in (C). Subframe of HiRISE ESP_035909_1775 (25 cm pixel scale). Image is ~645 m across. (C) The slope of transect A and B is 14% and 16%, respectively, and highlight the low relief on the outer flank of Cape Tribulation.

individual segments. Local relief measured over 100s of metres along the rim crest is as much as 10–20 m, but more commonly only metres.

The Cape York rim segment is about 700 m long and located ~1900 m north of Solander Point, whereas Nobbys Head is located approximately one third of the distance from Cape York to Solander Point (Fig. 3). Cape Tribulation reaches ~100 m higher than the highest point of Cape York and the inner wall of Cape Tribulation is marked by metres of relief over distances of 10–20 m length scales that create a rugged appearance (Fig. 3). By contrast, the exposed outer flank of Cape Tribulation is only thinly covered in sediment (relative to the complete burial of lower surfaces), quite smooth at comparable scales, and the descent from local highs to the plains is characterized by slopes of ~6–16% (in different locations) producing a remarkably smooth profile at the scale of the CTX DTM (Fig. 2).

Wdowiak Ridge is one of several short, superposing ridges along Cape Tribulation oriented southwest-to-northeast (Fig. 3). An exception to the characteristically low relief surfaces observed on the outer flank of the crater, Wdowiak Ridge is ~150 m long and rises 12 m above surrounding surfaces (Fig. 5). Nearby ridges are similar in scale, but Wdowiak Ridge was the only ridge examined by Opportunity. Marathon Valley is ~400 m south of the summit of Cape Tribulation and is oriented orthogonal to the general trend of the rim segment (Figs. 3 and 6). The valley is up to 20–30 deep relative to the bounding rim and is the most prominent local rim relief observed by Opportunity.

2.3. Rocks and deposits around the Endeavour rim

Data from Opportunity permit characterization of the rocks exposed on the western rim of Endeavour crater (Arvidson et al., 2014; Crumpler et al., 2015a). At Cape York (Fig. 7A), the lowest rocks exposed are layered clastic rocks related to an unknown depositional process, but spherules within the rock are either of diagenetic or impact origin and are cut by fractures bearing

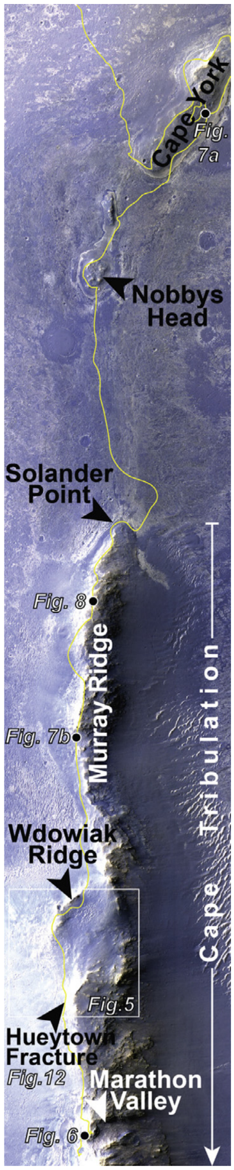

Fig. 3. Western rim segments of Endeavour crater explored by the Opportunity rover (see Fig. 2 for context). The Opportunity rover reached Endeavour at Cape York, traversed past Nobbys Head to Solander Point (at the north end of Cape Tribulation), and then along Murray Ridge to Wdowiak Ridge (yellow line indicates approximate rover path). The summit of Cape Tribulation and Marathon Valley to the south mark the southern extent of the rover's traverse at sol 4000 at the time of manuscript submission. Capes Byron and Dromedary and Point Hicks are located further south. White box indicates location of Fig. 5; black dots indicate locations of Figs. 6, 7A, B, 8, and 12. HiRISE IRB colour image ESP_036753_1775 (27 cm pixel-scale) is 1.2 km across. North towards the top.

Al-rich smectite clays (Arvidson et al., 2014). These rocks are dubbed the Matijevic Formation and are interpreted to pre-date Endeavour crater (Arvidson et al., 2014). Although the Matijevic rocks have only been observed and studied in a section a few metres thick on the eastern side of Cape York, an unknown and potentially much thicker section may be buried beneath these outcrops.

Widespread outcrops of basaltic breccias occur stratigraphically above the Matijevic Formation at Cape York (Squyres et al., 2012) (Fig. 7A) and along the length of Cape Tribulation (Fig. 7B). These breccias, dubbed the Shoemaker Formation, are generally similar in composition (Mittlefehldt et al., 2015) and are interpreted as remnants of the ejecta deposit associated with the impact event that formed Endeavour crater (Squyres et al., 2012). At Cape York, the Shoemaker rocks comprise some 6–7 m of the exposed rim segment. By contrast, Shoemaker breccias make up nearly all outcrops examined along Cape Tribulation (Fig. 7B). The strike and dip of these breccias is difficult to establish given the absence of bedding, but if the deposit has not been tilted much (which could lead to anomalously high estimates of thickness when measured vertically) they could represent up to ~140 m of preserved ejecta along the rim.

The Shoemaker Formation at Endeavour is buried by sulphate-rich plains rocks deposited in the Noachian or Early Hesperian (Fig. 1) (e.g., Arvidson et al., 2006, 2011; Crumpler et al., 2015a) and are mostly dirty evaporitic sandstones deposited in aeolian and playa settings with a diagenetic overprint associated with precipitation of hematite concretions and recrystallized materials (Squyres et al., 2004; Grotzinger et al., 2005; McLennan et al., 2005; Squyres and Knoll, 2005; Golombek et al., 2006; Arvidson et al., 2015a). The bulk of the plains rocks correspond to the Burns Formation described by Grotzinger et al. (2005), though a thin section at the base (Arvidson et al., 2014) consisting of thinly bedded sandstones (Squyres et al., 2012) of uncertain depositional setting, is referred to as the Grasberg unit. The Grasberg unit forms a prominent bench or apron explored by Opportunity around Cape York (Arvidson et al., 2014) and Solander Point (Crumpler et al., 2015a) (Fig. 4). Although least prominent in the northeastern and southeastern rim segments, similar benches interpreted to be the Grasberg unit occur at elevations generally corresponding to where other rim segments emerge from the plains rocks (Fig. 4). In the east, the Grasberg apron follows the exposed terrain on the crater wall, descending some 100 m (to −1630 m) over four km as it wraps around the exposed portion of the interior crater wall and terrace block. No occurrence of the Burns Formation or Grasberg unit has been detected on a rim segment at an elevation higher than where the bench occurs. The Burns Formation and Grasberg unit are hereafter referred to collectively as "plains rocks."

More localized occurrences of other rocks include smectite-bearing strata exposed on the floor of Marathon Valley south of the high point along Cape Tribulation (Wray et al., 2009; Arvidson et al., 2015b). The age and origin of the smectite-bearing strata are unknown, but their exposure in a topographic low suggests they may be stratigraphically below the Shoemaker Formation and therefore could be either pre-impact or pre-plains rocks. Local lithologic components younger than the Shoemaker Formation include calcium sulphate veins that cut across both the Matijevic and Shoemaker rocks and are associated with fluids circulating after the formation of Endeavour crater (Arvidson et al., 2014, 2015b). In addition, the stratigraphic position of the relatively more resistant rocks capping Wdowiak Ridge (Fig. 5B) indicates they may be younger than the adjacent Shoemaker Formation. The Wdowiak Ridge rocks are not breccias and are chemically and texturally distinct from both the Matijevic and Shoemaker rocks (Mittlefehldt et al., 2015); the rocks appear less altered than surrounding outcrops when viewed in orbital data and appear to have near pristine Fe/Mn ratios (Mittlefehldt et al., 2015).

Finally, the surface of the plains rocks around and within Endeavour is mostly mantled by a thin (generally less than several metres thick) deposit of basaltic sand and ripples (Golombek et al., 2006). The basaltic sand is of unknown provenance (Golombek et al., 2006) and ripples are covered by a deflationary lag of 1–2 mm diameter hematite spherules eroded from the underlying plains rocks (Arvidson et al., 2004; Soderblom et al., 2004). The crater density on this surface yields an Amazonian age (Lane et al., 2003), thereby implying a long period of erosion followed deposition of the plains rocks.

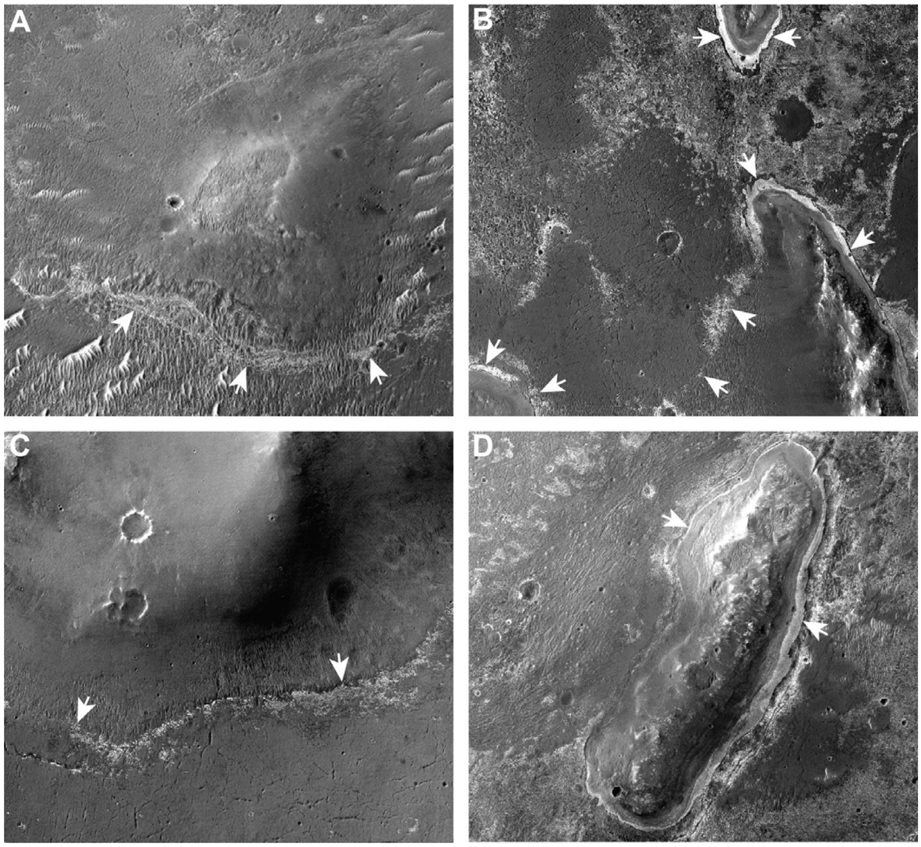

Fig. 4. The orbital expression of the (A) northern, (B) eastern, (C) southern and (D) western rim segments exposed around Endeavour crater is fairly uniform (see Fig. 2 for context). Relief of the rim segments varies from as little as ∼10 m (e.g., along the south and at Cape York on the west) to around ∼100 m (e.g., at Cape Tribulation to the west) to close to 160 m (to the east). All exposed rim segments appear flanked by a bench, presumably of the Grasberg unit (white arrows), though the expression of the bench is more pronounced along the eastern (B) and western (D) rims. (A) Northern rim of Endeavour crater. Subframe of grayscale HiRISE ESP_028670_1780, image is 645 m across (27.2 cm/pixel). (B) Eastern rim of Endeavour crater. Subframe of grayscale HiRISE ESP_030872_1775, image is 1225 m across (26.9 cm/pixel). (C) Southern rim of Endeavour crater. Subframe of grayscale HiRISE PSP_007849_1775, image is 850 m across (27.0 cm/pixel). (D) Western rim of Endeavour crater at Cape York. Subframe of grayscale HiRISE ESP_032573_1775, image is 825 m across (26.9 cm/pixel). North towards the top in all images.

Table 1
Summary of rim elevation and relief for Endeavour crater.

Endeavour rim location	Elevation of contact between plains rocks and rim segment (e.g., Grasberg unit)	Elevation of rim crest	Exposed relief of rim (m)
North	−1460 m (Fig. 4A)	−1430 m	30 m
Northeast	Poorly expressed	−1360 m	∼100 m
East Segments	As high as −1520 m (Fig. 4B)	−1320 to −1350 m	up to ∼160 m
Southeast	Poorly expressed	−1550 m	∼20 m
South	−1460 m (Fig. 4C)	∼−1410 m	∼50 m
West	−1500 m to −1490 (Fig. 4D)	−1380 m at Cape Tribulation	10 m (Cape York) to 100 m (Cape Tribulation)

2.4. The interior of Endeavour crater

The interior of Endeavour is 200–500 m deep (measured from the crest of exposed rim segments to the crater floor), with the lowest elevation (−1980 m relative to MOLA datum) occurring along the southeastern crater floor. Contours surrounding the lowest point in the crater trace a horseshoe shape at successively higher elevations to the north (Figs. 2 and 8). The current depth (d)-to-diameter (D) ratio (d/D) is 0.023. The crater interior is marked by active, dark dunes in some locations, especially in the west-central part of the basin (Chojnacki et al., 2015; Fenton et al., 2015). The floor of the crater exposes fill in the form of numerous layers that can be traced locally for kilometres with orientations generally parallel to topographic contours (Fig. 9A and B). The orbital appearance of these layers and constituent materials appear similar to that associated with the plains materials outside of the crater.

There are several isolated, small blocks of distinctly non-plains rocks material exposed on the southeastern crater floor (Fig. 9C and D) that occur at roughly comparable radii to the terrace block along the east rim (Fig. 2). These smaller blocks are embayed by the layered fill and at least one shows evidence of inclined layers (Fig. 9D). The rim segment adjacent to these blocks is not at increased diameter as would be expected if they were associated with the expression of a terrace block as seen along the eastern crater wall.

Although central peaks occur in approximately 70–80% of pristine complex martian craters comparable in size to Endeavour,

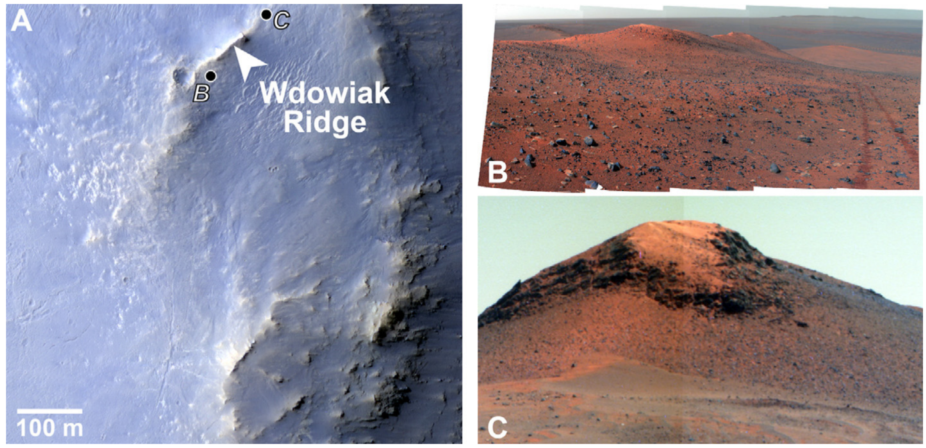

Fig. 5. (A) Wdowiak Ridge on Cape Tribulation (see Fig. 3 for context). Black dots show locations of (B) and (C). Subframe of IRB HIRISE ESP_036753_1775 (27 cm per pixel scale), north to top. (B) False colour mosaic showing view to northeast along the eastern flank of Wdowiak Ridge. The interior and rim of Endeavour crater is seen in the central (NE) and upper left (NW) background, respectively. Wdowiak Ridge is approximately 12 m high and 150 m long and is capped by relatively darker, more resistant rocks of unknown origin that have left the ridge standing in relief as surrounding surfaces were lowered by erosion. Numerous blocks shed from the dark capping unit are visible in the foreground. Pancam mosaic spans about 70 compass degrees from north–northwest on the left to east-northeast on the right and was obtained by Opportunity on sol 3786, filters L2, 5, 7 (432 nm, 535 nm, and 753 nm). For scale, distance between rover tracks visible at right is approximately 1 m. (C) False colour mosaic of the northern end of Wdowiak Ridge (approximately 12 m high) 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 injection of impact melt, exhumation of a megablock of ejecta, a local high on the pre-impact surface, or another origin. Mosaic was obtained by Opportunity on sol 3750, filters L2, 5, 7 (432 nm, 535 nm, and 753 nm).

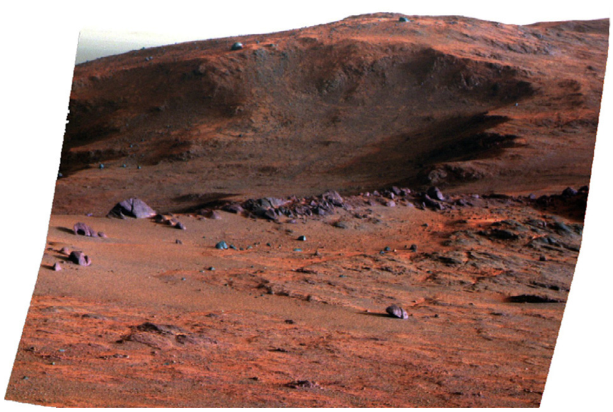

Fig. 6. View of Marathon Valley looking south across the valley (see Fig. 3 for context). The valley varies between ~100 and 140 m across, represents relatively deep radial erosion into the exposed rim, and could reflect local mass-wasting into the crater and/or rim incision whose signatures have been subsequently modified by aeolian 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.

there is no evidence of a central peak within Endeavour. Further, examination of the interior of the crater yields no evidence of fracturing in the layered fill that might be related to differential loading around and over relief associated with a central peak. Hence, if a central peak did form in Endeavour, it was either eroded and/or deeply buried by crater fill and/or plains rocks.

3. Analogues for estimating the pristine form of Endeavour crater

An important factor in evaluating the degradation of Endeavour crater is estimating its initial morphology. Clues to Endeavour's original form may be gleaned from examination of similar sized, pristine, complex craters on Mars, such as craters Bopolu and Tooting (Fig. 10). In addition, numerous studies have focused on characterizing various attributes of complex craters that can provide additional insight into the probable initial form of Endeavour.

3.1. Crater Bopolu on Mars

The relatively pristine 19 km-diameter Bopolu crater (2.95°S 353.67°E, Fig. 10A) is located approximately 65 km to the southwest of Endeavour and postdates emplacement and most subsequent stripping of the younger plains rocks (Fig. 1). The interior wall of Bopolu is characterized by a discontinuous terrace block on the west side that is best developed to the northwest and may be comparable to the terrace block found on the east side of Endeavour (Fig. 2). Although the crest of the terrace block varies in radial position, it corresponds to a diameter of ~16 km, yielding an inner terrace to overall diameter ratio of 0.84 (similar to what is observed at Endeavour). Bopolu's continuous ejecta deposit extends approximately a crater-diameter beyond the rim (Fig. 1), with rays

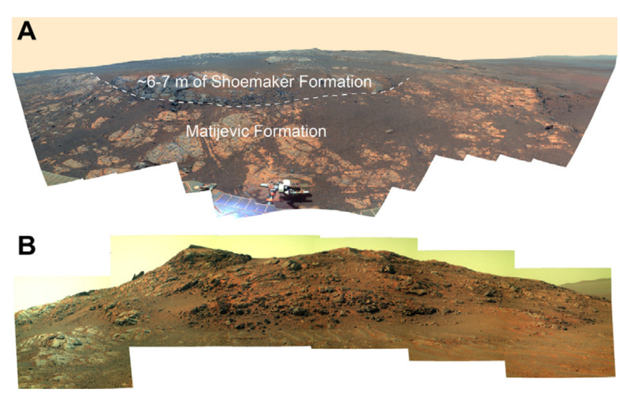

Fig. 7. (A) False colour Matijevic panorama of outcrops on the eastern side of Cape York (see Fig. 3 for context) annotated to show approximate contact between the pre-Endeavour impact Matijevic Formation and the ~6–7 m of overlying impact breccias of the Shoemaker Formation. The darker outcrop in the left centre is dubbed Copper Cliff and is 5–10 long. Pancam mosaic obtained by Opportunity over sols 3137–3150, filters L2, 5, 7 (432 nm, 535 nm, and 753 nm). (B) False colour view of the south end of Murray Ridge along Cape Tribulation (see Fig. 3 for context). The stripped appearance of the Shoemaker Formation breccias and local mantling of surfaces by drift reflects ongoing aeolian modification. Outcrop is 5–6 m high. Pancam mosaic was obtained by Opportunity rover on sol 3720 using filters L2, 5, 7 (432 nm, 535 nm, and 753 nm).

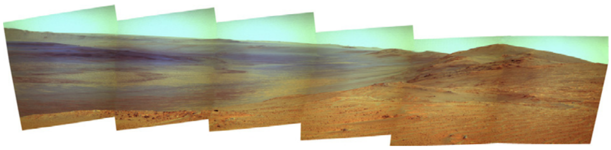

Fig. 8. False colour mosaic of the interior and rim of Endeavour crater from north of the summit of Cape Tribulation (see Fig. 3 for context). Younger, bedded plains rocks (materials of the Burns Formation and perhaps the Grasberg unit) partially fill the crater (left two-thirds of image). The darker (purple-toned) features in the middle left are dunes ~5 km from the rim. Pancam mosaic obtained by Opportunity on sol 3637, filters L2, 5, 7 (432 nm, 535 nm, and 753 nm).

of ejecta and secondaries locally traceable to nearly three crater-diameters away. The morphology of the ejecta deposit surrounding Bopolu can be classified as Type-2 double layered (DLE, see Barlow, 2015). Although there is a field of dark-toned dunes and additional lighter toned material covering a portion of the floor of Bopolu crater, the entirety of the rim, wall, and some of the floor is exposed and can be measured.

Examination of HiRISE, CTX, and individual points along five sections of four MOLA tracks crossing the southern and northern wall of Bopulu enables the contact between the ejecta and pre-impact surface to be identified and the thickness of the ejecta section (E_t) and overall rim height (H_r) to be characterized (Fig. 11). Interpolation between individual MOLA shot points is necessary along some tracks to better match the position of the various contacts expressed on the inner wall of the rim, but results yield reasonable approximations of thickness and relief relative to observed variations in images. The rim varies between 275 m and 480 m in overall height, with an average near 375 m (Table 2).

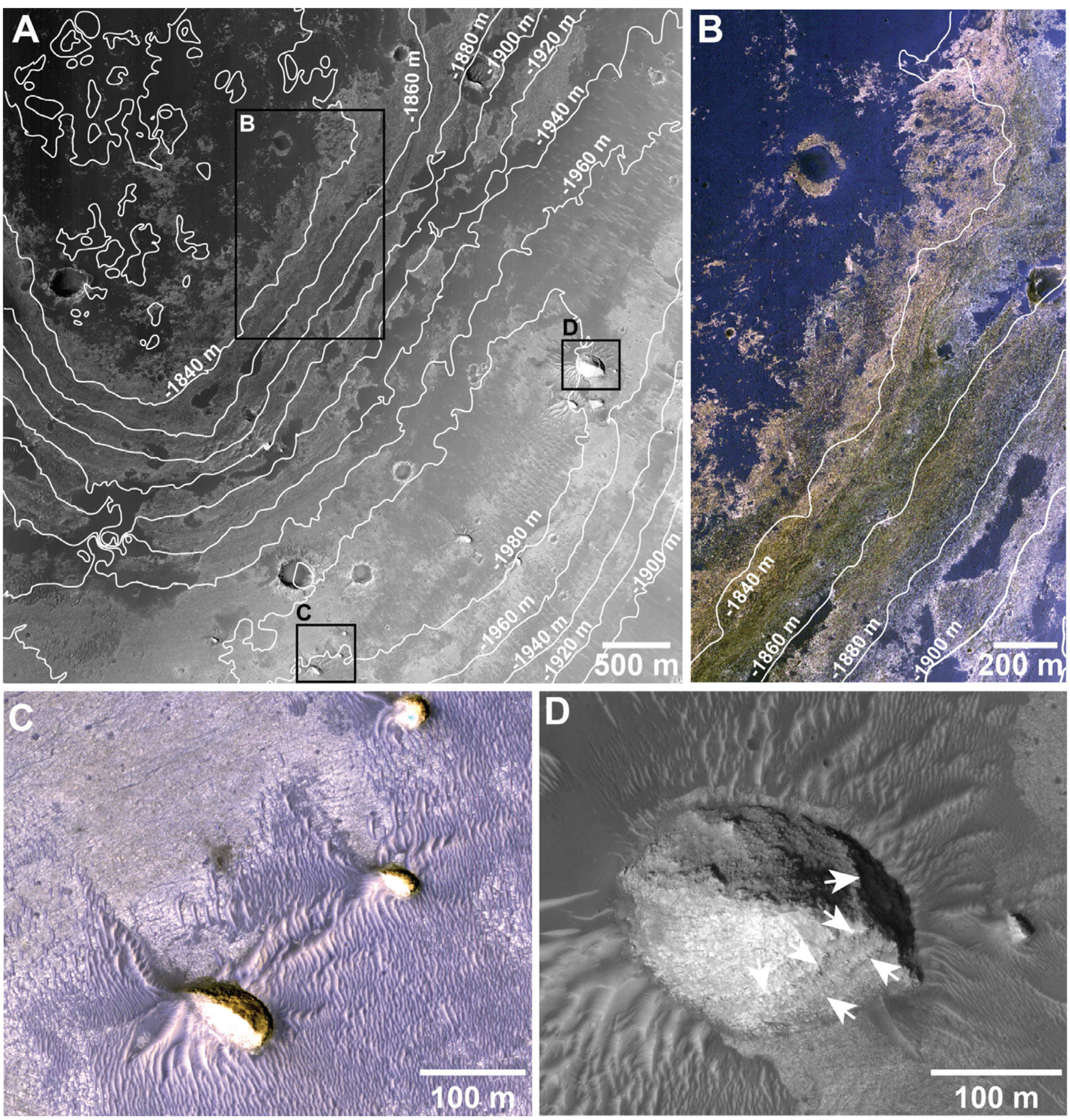

Fig. 9. (A) The deepest part of Endeavour's interior occurs in the southeastern crater floor at an elevation of approximately −1980 m, exposing fill in the form of numerous layers that can locally be traced for several kilometres (see Fig. 2 for context). Subframe of grayscale HiRISE ESP_029738_1775 (27.5 cm per pixel scale) overlain with 20 m contours from Fig. 2. Black boxes show locations of B–D. (B) Detail of the light-toned layers whose orientation is generally parallel to topographic contours. The orbital appearance of these layers and constituent materials is similar to that associated with the plains rocks outside of the crater. Subframe of IRB HiRISE ESP_029738_1775 (27.5 cm per pixel scale) overlain with 20 m contours from Fig. 2. (C) Isolated, presumably exhumed blocks exposed on the southeastern floor of Endeavour near what is currently the deepest part of the crater. Subframe of IRB HiRISE ESP_029738_1775 (27.5 cm per pixel scale). (D) Isolated block near the margin of the −1980 m contour on Endeavour's floor exhibits inclined layers (white arrows). Subframe of grayscale HiRISE ESP_029738_1775 (27.5 cm per pixel scale). North is towards the top in all images.

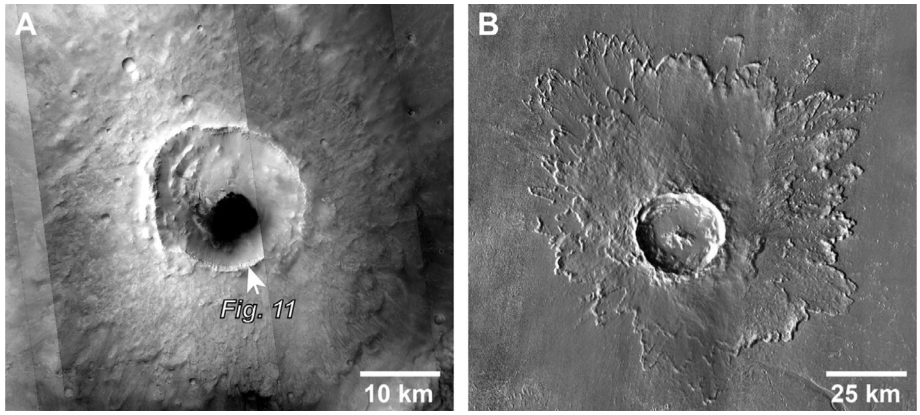

Fig. 10. (A) Bopolu, a 19 km-diameter crater located 65 km southwest of Endeavour (2.95°S, 353.67°E, see Fig. 1 for context). Bopolu post-dates the Meridiani Plains and currently has a 400 m (±100 m) high rim of which ~210 m (±100 m) is ejecta. The crater is currently 1.75 km deep. Note terrace block on NW rim. White arrow indicates location of Fig. 11. CTX images P14_006557_1750, B11_013743_1752, P15_007058_1751, P13_005990_1786, P06_003511_1779 from west to east. Original CTX images 6 m pixel-scale, north is towards the top. (B) Tooting, a 29 km-diameter crater located at 23.1°N, 207.1°E. Tooting is likely <2 Ma and has been studied extensively as an example of a pristine complex crater on Mars (Mouginis-Mark and Garbeil, 2007; Mouginis-Mark, 2014). Tooting has a 484 m high rim (ranges between 400 and 900 m) of which 400 m is ejecta. Tooting is 1.8 km deep. Part of the THEMIS Day IR Global Mosaic in Simple Cylindrical projection, resolution of 256 pixels/degree, and scale of 231.55 m/pixel.

Ejecta thickness measured on the upper wall varies between 110 m and 350 m and averages about 210 m (Table 3). The resultant ratio of average ejecta thickness to crater diameter (E_t/D) is 0.011. Comparable variability in overall thickness is observed at other martian craters (Mouginis-Mark and Garbeil, 2007). Two small knobs rising from the central floor of Bopolu could be remnants of a central peak, but they are partially buried and relief (H_{cp}) cannot accurately be measured (Table 4). Bopolu is 1.75 km deep, as measured from the rim crest to the crater floor, but some fill covering the floor indicates this is a lower bound. Based on this, the current depth-to-diameter (d/D) ratio for the crater is 0.092 (Table 5).

3.2. Crater Tooting on Mars

Tooting (23.1°N, 207.1°E) is a very young (<2 Ma) 29 km-diameter impact crater that has been extensively studied (Mouginis-Mark and Garbeil, 2007; Mouginis-Mark, 2014) and may be a modern analogue for Endeavour. Like Endeavour and Bopolu, Tooting is also characterized by discontinuous terrace blocks that yield an inner diameter of 25.7 km and a ratio to the overall diameter of 0.88, slightly higher than at Endeavour (Fig. 10B). The continuous ejecta form a multi-layer (MLE) deposit around the crater that extends 2–3 crater diameters beyond the rim crest (Mouginis-Mark and Garbeil, 2007).

As summarized in Mouginis-Mark and Garbeil (2007), the average rim height (H_r) at Tooting is 484 m (ranges from 400 m to 900 m, Table 2), of which at least 400 m is ejecta (Table 3). The resultant ratio of average ejecta thickness (E_t) to crater diameter (E_t/D) is 0.014. The prominent central peak (H_{cp}) within Tooting rises some 950 m above the surrounding floor (Table 4) and the base is located an average of 1.8 km below the rim crest (Table 5). This depth is noted to be 1.3–1.4 times what is predicted by Garvin and Frawley (1998) and suggests that some of the craters included in the earlier study incorporated more infilling deposits than observed at Tooting (Table 5).

3.3. Other craters on Mars, the Moon, and Mercury

Metrics for crater properties at many other craters on Mars, the Moon, and Mercury (Tables 2–5) can further constrain the initial appearance of Endeavour crater. For example, observations and methods for estimating rim height (H_r) around complex martian craters are presented in Garvin et al. (2003), Mouginis-Mark and Garbeil (2007), Mouginis-Mark (2014), Sturm et al. (2014) (Table 2). Rim heights (H_r) can also be estimated using relationships measured around complex craters on the Moon (Pike, 1977; Sharpton, 2013) and Mercury (Cintala, 1979) (Table 2). For Mars, these methods yield estimates for the original rim height (H_r) at Endeavour of between ~250 m and nearly 500 m (Table 2), though the lower end of this range may be considered a minimum possible value (Mouginis-Mark and Boyce, 2012). For comparison, estimates of Endeavour's rim height derived from relationships described for the Moon and Mercury are much higher at ~500–800 m and over 900 m, respectively (Table 2). Rim height (H_r) estimates towards the middle-to-upper range for the martian craters may be most realistic, and when scaled to values for Bopolu and Tooting craters, suggests the original rim height (H_r) at Endeavour averaged around 410 m with a range of ±200–300 m around the crater.

Estimates of the thickness of the ejecta deposit (E_t) contributing to rim relief can be derived using direct measurements in images and relationships for martian craters (Mouginis-Mark and Garbeil, 2007; Mouginis-Mark and Boyce, 2012; Mouginis-Mark, 2014; Sturm et al., 2014) and lunar craters (Sharpton, 2013). For Mars, based on a likely range in total rim relief (Table 2) where the ejecta contributes between 40% and 70% of the total rim, these relationships suggest that between ~90 m and 430 m of ejecta was originally present (Table 3). Relationships from the Moon (Sharpton, 2013) predict a lesser section of only ~60–160 m was present at Endeavour. The wide range in estimates for Mars is likely a reflection of natural variation in ejecta thickness around martian craters (i.e., due to variable enlargement via late stage collapse and the location where a measurement is made relative to normal variations around the rim). Direct scaling to Bopolu and Tooting suggests there was originally 250–275 m of ejecta (E_t) present at Endeavour, a value that gives an E_t/D of 0.012 and is in the mid-range of predictions from studies of these and other martian craters. Small differences in the E_t/D at Bopolu and Tooting suggest this value for Endeavour is likely accurate to within about 20%, or about ±50–60 m.

Although Endeavour lacks evidence of a central peak, the height of central peaks associated with other craters (H_{cp}) have been characterized using relationships defined for Mars (Garvin et al., 2003; Mouginis-Mark and Garbeil, 2007) and the Moon (Hale and Grieve, 1982; Kalynn et al., 2013) and could provide some indirect evidence of the minimum amount of infilling/erosion that has occurred within Endeavour. When the relationships for martian

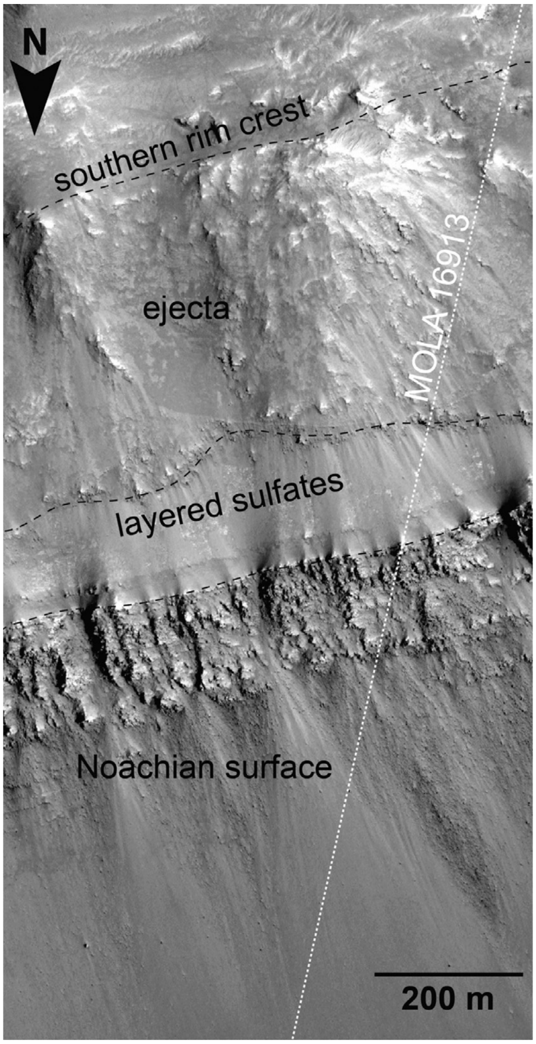

Fig. 11. View of the south wall of Bopolu crater (see Fig. 10 for context) showing the Noachian rocks beneath the layered sulphate rocks forming the Meridiani "plains rocks" and Bopolu ejecta. Location of one of the MOLA tracks used to derive the rim height and thickness of rocks forming the rim is shown. The thickness of the Meridiani plains rocks varies around the rim and ranges between 75 and 260 m thick. Subframe of HiRISE ESP_029092_1770 (50 cm pixel-scale). North is towards the bottom.

Table 2
Rim heights (H_r) for Bopolu, Tooting, and estimates for Endeavour.[a]

Rim height (m)	Relationship	Reference	Planet/ satellite	Notes
∼375 m	Bopolu crater	This study	Mars	Measured using MOLA data, range is 275–480 m
484 m	Tooting crater	Mouginis-Mark and Garbeil (2007)	Mars	Measured using MOLA data, range is 400–900 m
Endeavour rim height (m)	**Relationship**	**Reference**	**Planet/ satellite**	**Notes**
268	$H_r = 0.02D^{0.84}$	Garvin et al. (2003)	Mars	May be minimum estimate based on Tooting crater comparison (Mouginis-Mark and Boyce, 2012)
484	$H_r = 0.022D$	Mouginis-Mark and Garbeil (2007)	Mars	Average measured at Tooting crater
∼240–310	See note	Mouginis-Mark (2014)	Mars	Analogy with $D \sim 10$ km Pangboche and Zunil craters
∼350–400	See note	Sturm et al. (2014)	Mars	Analogy with $D \sim 16$ km unnamed crater
810	$H_r = 0.236D^{0.399}$	Pike (1977)	Moon	For comparison only, also in Melosh (1989)
∼500–600	See note	Sharpton (2013)	Moon	For comparison only, study used craters 17–30 km in diameter
960	$H_r = 0.043D^{1.005}$	Cintala (1979)	Mercury	For comparison only

The shaded cells are for comparisons to the Moon and/or Mercury rather than Mars.
[a] H_r = height of rim; D = crater diameter.

craters are applied to Endeavour, they suggest that if a central peak was present, H_{cp} should reach between ∼200 and 500 m above the adjacent crater floor (Table 4). Similar estimates for H_{cp} of between ∼250 and 500 m are obtained for a possible central peak height using relationships for craters on the Moon (Table 4). However, such relief would still be buried beneath the younger plains based on estimates of the original versus present depth of the crater.

One of the morestudied aspects of complex crater morphology on Mars is the original depth (d) relative to the diameter (D), or d/D ratio (e.g., Garvin and Frawley, 1998; Garvin et al., 2003; Boyce et al., 2006; Boyce and Garbeil, 2007; Mouginis-Mark and Garbeil, 2007; Hsu and Barlow, 2013; Tornabene et al., 2013; Mouginis-Mark, 2014). With the exception of Boyce et al. (2006) the depth is measured from the rim crest to the crater floor as has been done at Endeavour. In Boyce et al. (2006), anomalously deep craters were characterized using the depth measured from the elevation of the surrounding plains to the crater floor. Similar studies (using depth measured from the rim crest to the crater floor) have been done for lunar craters (e.g., Pike, 1977). The martian studies yield relationships for crater d/D that can be applied to Endeavour crater and produce estimates of the original crater depth of between ∼1.1 km and 3.2 km (Table 5). The lunar study gives an estimate of just over 2.6 km depth. The extreme low and high end of the martian estimates is probably not realistic, as the associated relationships may include, respectively, some partially infilled craters and anomalously deep craters (Boyce et al., 2006). This is especially true when considering that crater depth estimates in Boyce et al. (2006) would be even greater had they been measured from the rim crest rather than the level of the surrounding plains. Hence, a more realistic range of estimates for the original crater depth at Endeavour excludes the maximum and minimum values for Mars and is 1.5–2.2 km (Table 5) which gives a d/D of 0.07–0.10 for the crater, where depth is measured from the crater rim crest to the bottom of the crater floor.

In summary, despite uncertainties associated with various methods of estimating the pristine form of Endeavour, there is reasonable convergence between properties estimated from measurements at likely analogue craters and from estimates made using metrics for broader studies of martian craters (Tables 2–5). Hence, a pristine Endeavour crater was likely characterized by a rim (H_r) averaging 410 m in elevation, but that varied on order of about ±200 m around the rim. The ejecta deposit (E_t) was likely 250–275 m thick (±50–60 m) and would have comprised a significant fraction of the rim height. If there was a central peak, it was probably between 200 and 500 m high (H_{cp}). The original crater depth (d) was likely between 1.5 km and 2.2 km.

Table 3
Thickness estimates (E_t) of Endeavour ejecta at the crater rim.[a]

Ejecta thickness (m)	Relationship	Reference	Planet/satellite	Notes
210	Bopolu crater	This study	Mars	Measured using MOLA data, range 110–350 m
>400	Tooting crater	Mouginis-Mark and Garbeil (2007)	Mars	Measured using MOLA data, E_t > 400 m
Endeavour ejecta thickness (m)	Relationship	Reference	Planet/satellite	Notes
∼150–430	$E_t = 0.7H_r$	Mouginis-Mark and Boyce (2012)	Mars	Based on Tooting, uses Endeavour estimated $H_r \sim 210–610$ m
∼90–255	$E_t = 0.42H_r$	Mouginis-Mark (2014)	Mars	Based on Pangboche, uses Endeavour estimated $H_r \sim 210–610$ m
∼90–255	$E_t = 0.42H_r$	Sturm et al. (2014)	Mars	For unnamed $D \sim 16$ km crater, uses Endeavour estimated $H_r \sim 210–610$ m
∼63–163	$E_t = 0.25H_r$	Sharpton (2013)	Moon	For comparison only, uses Endeavour estimated $H_r \sim 250–650$ m

The shaded cells are for comparisons to the Moon and/or Mercury rather than Mars.
[a] E_t = thickness of ejecta; H_r = height of rim; D = crater diameter.

Table 4
Central peak heights (H_{cp}) for Bopolu, Tooting, and estimates for Endeavour crater.[a]

Central peak height (m)	Relationship	Reference	Planet/satellite	Notes
Unknown	Bopolu crater	This study	Mars	Partially buried
950	Tooting crater	Mouginis-Mark and Garbeil (2007)	Mars	Measured using MOLA data
Endeavour central peak height (m)	Relationship	Reference	Planet/satellite	Notes
540	$H_{cp}/D_{cp} = 0.106$	Mouginis-Mark and Garbeil (2007)	Mars	Diameter CP from $D_{cp} = 0.24D^{0.99}$ (Hale, 1983)
∼200	$H_{cp} = 0.014D^{0.51}$	Garvin et al. (2003)	Mars	For 7–100 km-diameter craters, various units
265	$H_{cp} = 0.0006D^{1.97}$	Hale and Grieve (1982)	Moon	For comparison only
∼500	From plot in Fig. 2	Kalynn et al. (2013)	Moon	For comparison only, data for craters > Endeavour

(See above-mentioned reference for further information.)
The shaded cells are for comparisons to the Moon and/or Mercury rather than Mars.
[a] H_{cp} = height of central peak; D_{cp} = diameter of central peak; D = crater diameter.

4. Comparing the present versus pristine form of Endeavour crater

Despite the range in values estimated for the pristine rim height, rim ejecta thickness, and depth, it is clear that the original

Table 5
Estimates of original depth (d) of Endeavour crater.[a]

Endeavour depth (km)	Complex crater relationship	Reference	Planet/satellite	Notes
∼2.0	$d/D = 0.092$ measured	This study	Mars	Bopolu crater ($D = 19$ km), depth range is ∼1.7–1.8 km
1.1	$d = 0.25D^{0.49}$	Garvin and Frawley (1998)	Mars	
1.6	$d = 0.36D^{0.49}$	Garvin et al. (2003)	Mars	
3.2	$d = 0.25D^{0.82}$	Boyce et al. (2006)[b]	Mars	For anomalously deep craters[b]
1.9	$d = 0.381D^{0.52}$	Boyce and Garbeil (2007)	Mars	
1.5–1.6	1.3–1.4× value from Garvin and Frawley (1998)	Mouginis-Mark and Garbeil (2007)	Mars	Tooting crater ($D = 27$ km)
1.4–1.7	(1) $d = 0.0377D^{0.6671}$ (2) $d = 0.0527D^{0.6129}$	Hsu and Barlow (2013)	Mars	Relation varies with region on Mars: (1) Chryse and (2) Amazonis
∼1.5	$d = 0.357D^{0.52}$	Tornabene et al. (2013)	Mars	For pitted impact melt-bearing craters
∼2.2	$d/D = 0.1$	Mouginis-Mark (2014)	Mars	For Pangboche and Zunil craters
2.6	$d = 1.044D^{0.301}$	Pike (1977)	Moon	For comparison only

The shaded cells are for comparisons to the Moon and/or Mercury rather than Mars.
[a] d = crater depth measured from rim crest to crater floor except where noted; D = crater diameter measured from rim crest to rim crest;
[b] d for Boyce et al. (2006) measured from level of surrounding plain to crater floor and use of relation results in estimates of exaggerated depths when compared to those derived using depths measured from the rim crest to the crater floor.

morphology of Endeavour crater differed significantly from the current degraded form of the crater. Some of the degradation is due to the partial burial by younger plains rocks, whereas other aspects relate to past and ongoing erosion of the crater. Careful consideration of the geology and form of the exposed rim segments yields insight into the relative importance and timing of various geomorphic processes.

For example, given the predicted original variation in rim relief of up to 400 m around Endeavour crater, it is tempting to ascribe differences in the relief of exposed rim segments and the cause of intervening gaps to burial of varying topography around the original rim. However, variations in rim relief at Tooting crater do not occur at the complete expense of the thickness of the ejecta which is >400 m everywhere. In addition, a significant, albeit varying, section of ejecta occurs everywhere around Bopolu as well. Hence, the very thin exposure of Shoemaker Formation (<10 m) and outcrop of Matijevic Formation pre-impact rocks at Cape York relative to the ∼140 m section of Shoemaker Formation at Cape Tribulation (and no exposure of Matijevic Formation) indicates variable relief of rim segments is not simply due to variations in original rim relief.

Vertical offset between rim segments is also a possible cause of differences in elevation between rim segments and could relate to faulting during late stage crater modification. For example, there appears to be a ∼150 m offset of beds across a fault exposed in the wall Bopolu crater. Such fractures may be similar to those around smaller terrestrial impacts (Kumar and Kring, 2008) and large fractures (e.g., Hueytown linear feature, Figs. 3 and 12) are

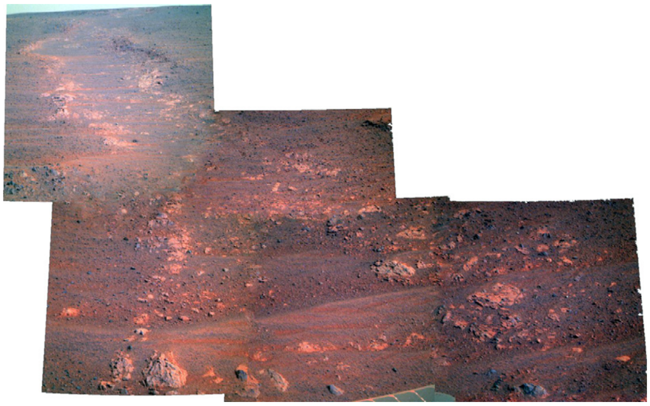

Fig. 12. False colour mosaic of Hueytown fracture zone extending to the east-southeast from the rover and located along the Endeavour rim south of Wdowiak Ridge (see Fig. 3 for context). The fracture zone is generally ∼1–2 m across and continues to the west of the rover as well. The fractures are locally filled by sulphate materials and likely confirm the structural influence of the formation of Endeavour crater on local rocks during and shortly after impact. No obvious offset is observed in the rocks across the fracture at Endeavour. Pancam mosaic was obtained by the Opportunity rover on sol 3861 using filters L2, 5, 7 (432 nm, 535 nm, and 753 nm).

observed at Cape Tribulation. However, there is no significant variation in rim relief on either side of the offset in beds in the rim of Bopolu and there is no obvious offset in beds or surface relief across the Hueytown or other linear fractures at Cape Tribulation.

5. Estimating the amount and timing of degradation at Endeavour crater

The occurrence of variable amounts of degradation and vertical lowering of the rim around Endeavour appears most consistent with the overall form and stratigraphy as measured *in situ* by Opportunity. If the original ejecta section emplaced around the crater averaged between 250 m and 275 m, then 200 m or more ejecta has likely been eroded at Cape York. The total thickness of the section preserved at Cape Tribulation is unknown, because the contact with the underlying Matijevic Formation (or alternate pre-impact country rock) has not been detected by the rover (Crumpler et al., 2015a) and is not identifiable in orbital images. However, the presence of up to ∼140 + m of ejecta at Cape Tribulation indicates significantly less erosion has occurred there relative to Cape York.

Another clue related to the amount of degradation at Endeavour comes from expected versus observed rim relief. Although variable, average rim relief at Endeavour is predicted to be on order of 400 m, but the current relief of Cape Tribulation above the surrounding plains is close to 100 m. The plains rocks bury additional rim relief and knowledge of their thickness would enable better constraint of the total rim relief that remains. The plains rocks well to the east and north of Endeavour are estimated to be 800–900 m thick (Hynek and Phillips, 2001; Griffes et al., 2007; Watters et al., 2014), but the plains rocks at Endeavour must be considerably thinner for there to be any exposure of the rim.

Endeavour is located within ∼40 km of the margin of the plains rocks (Fig. 1). At nearby Bopolu crater, the pre-impact surface and overlying plains rocks can be distinguished in the wall below the ejecta and their thickness ranges between 75 and 260 m (Fig. 11). Bopolu is relatively closer to the margin of the plains rocks, but Endeavour sits along the northeastern flank of Miyamoto crater, so the thickness of the plains rocks at Bopolu may be more representative. Ada crater (2.2 km-diameter, 3.0°S, 356.8°E, Fig. 1) is ∼150 km east-southeast of Endeavour, approximately the same distance from the edge of the plains rocks, and reveals a comparably thin section of plains rocks (Golombek et al., 2010; Arvidson et al., 2015a). A fresh, unnamed 0.84 km diameter crater 40 km west of Endeavour crater also has exposures of light-toned layered deposits (likely Burns Formation) in its interior that are at least tens of metres thick (Golombek et al., 2010). Hence, the thickness of the plains rocks at Endeavour, to first order, is estimated at ∼100–200 m.

If the rim of Endeavour is buried by ∼200 m of the plains rocks, then the observed 100 m relief at Cape Tribulation represents a reduction in elevation of ∼100 m from the average expected initial rim height. By contrast, a 200 m thick section of plains rocks implies the rim at Cape York has been lowered by an order of 200 m, roughly consistent with the presumed amount of erosion of the Shoemaker Formation ejecta. If the thickness of the plains rocks around Endeavour is significantly less, then vertical lowering could approach 200 m at Cape Tribulation and over 300 m at Cape York, though this would be difficult to reconcile with the preservation of a thick section of ejecta at Cape Tribulation and persistence of any ejecta at Cape York (unless the ejecta were originally considerably thicker than estimated here). Hence, based on expected original rim height (H_r) and variability, thickness and variability of the ejecta deposit (E_t), and plains thickness relative to observations, it appears the variable relief of rim segments and intervening gaps are due to variations in both original rim relief/thickness of ejecta and differing amounts of degradation and vertical lowering. Although somewhat uncertain, degradation and vertical lowering of the western rim segments of between 100 m and 200 m is most consistent with the geology exposed at Capes York and Tribulation and expectations of the original form of the crater rim.

Degradation of western rim segments is probably typical of that occurring at other crater rim segments rising above the nearly flat-lying plains. Comparison between the detailed morphology observed by the rover on the western rim segments and their expression in orbital data reveals other rim segments around the crater are quite similar in appearance. Moreover, the preservation of the light scalloping of the rim outline (Fig. 2) and the terrace block along the eastern wall (Fig. 2) indicates that overall crater degradation cannot have been significantly greater than amounts inferred here.

Wdowiak Ridge (Fig. 5) is of uncertain origin (Grant et al., 2015; Mittlefehldt et al., 2015), but all models for its formation call for significant erosion to produce the landform. For example, the chemically and texturally distinct rocks capping the ridge could be (1) exhumed impact melt injected into the ejecta during Endeavour's formation (Grant et al., 2015), (2) an exhumed mega-block of ejecta or relief on the pre-impact surface (Mittlefehldt et al., 2015), (3) an exhumed fault block created during impact, or (4) ancient valley fill of resistant materials left standing in relief after lowering of surrounding, less competent surfaces (Crumpler et al., 2015b). Each of these models calls for considerably more degradation of the Cape Tribulation rim segment than is accounted for in current relief of Wdowiak ridge and indirectly support our estimates of degradation.

If the estimated 1.5–2.2 km original depth of Endeavour is correct, then on order of 1–1.5 km of infilling material is present and it would represent up to an order of magnitude more material than is estimated to bury the exterior of the crater. However, it may be reasonable to expect such differences in burial as the crater would more efficiently trap sediments. For example, examination of nearby Bopolu crater reveals little in the way of mantling outside the crater, but light-toned materials and darker dunes and fill cover an appreciable portion of the crater floor. The absence of any expression of a central peak within Endeavour is consistent with significant infilling, though does not require it since it would likely be less than 500 m high. The absence of any signature at the centre of the crater implies any central peak is either deeply buried or was largely eroded prior to burial by erosional debris shed from the rim and plains rocks.

Debris shed off the eroding wall and rim of Endeavour and infilling by plains materials must both contribute to crater infilling. However, there is very little debris associated with the Shoemaker Formation or Matijevic or other non-plains rocks around rim segments and crater interior. A possible exception is the isolated blocks exposed in the lowest southeast part of the crater (Fig. 9C and D). Hence, emplacement of the plains rocks post-dates major contributions to infilling as the result of rim erosion. The scattered blocks exposed in the southeast portion of the crater (Fig. 9) could represent exhumation of large blocks shed from the rim, but may also be the limited expression of a lower terrace block (similar to what is observed downslope of the terrace block on the northwest wall of Bopolu crater, see Fig. 10A). Erosional debris from the Shoemaker and Matijevic Formations is also absent around the exterior of the crater and must be buried by the plains. Hence, the vast majority of the predicted rim degradation and associated lowering must have occurred prior to emplacement of the plains rocks in the Late Noachian to Early Hesperian, consistent with prior models for the amount and timing of erosion in the region (e.g., Hynek and Phillips, 2001).

6. Degradation processes

A variety of landforms at Endeavour enable speculation regarding the processes responsible for the degradation of the crater. It is clear that aeolian processes dominate ongoing modification of Endeavour's rim segments (e.g., Arvidson et al., 2015a) and the resulting surface has been lowered over time. Most rim outcrops appear stripped and some outcrops appear fluted and/or marked by lineations created by wind erosion (Fig. 7B). The scale of these features, however, implies aeolian erosion is responsible for modification of the rim form rather than wholesale development of existing rim morphology.

The weaker plains rocks are more easily eroded (e.g., Grant et al., 2006; Golombek et al., 2006) and their ongoing stripping by aeolian processes in and around Endeavour crater is manifested in the plains surface (e.g., Fig. 9A and B) and associated basaltic sand and granule covered ripples (Grant et al., 2006, 2008; Golombek et al., 2006, 2014; Arvidson et al., 2015a). Moreover, the dark dunes in the interior of Endeavour (Fig. 2) appear to move over time and indicate active sediment transport (Chojnacki et al., 2015).

The partial burial by the plains rocks dominates the expression of the crater and represents the most obvious contribution to the crater's appearance. The sandstones comprising the plains rocks were deposited in aeolian and playa settings (Grotzinger et al., 2005; Squyres and Knoll, 2005; Arvidson et al., 2015a) and are susceptible to aeolian stripping (Grant et al., 2006; Golombek et al., 2006). Evidence of this is highlighted by the expression of the plains rocks inside Endeavour where the approximate horseshoe-shaped interior depression (Figs. 2 and 9) may reflect aeolian stripping enhanced by interactions with the southern crater rim. Present winds are predominantly from the northwest and southeast (Sullivan et al., 2005; Grant et al., 2008; Fenton et al., 2015), but were likely more north–south prior to 200 ka (Fenton et al., 2015). Hence, winds entering the crater from the north would accelerate over and be deflected laterally by the more resistant rocks forming the southern rim, thereby leading to enhanced erosion of the weaker plains rocks (e.g., Grant et al., 2006; Golombek et al., 2006) consistent with the current relief on the crater floor.

While rover-based imaging does not yield any evidence of plains rocks anywhere above the current elevation of the plains, orbital data indicate plains rocks elsewhere in Meridiani (e.g., in Miyamoto crater, Fig. 1) were partially stripped without leaving traces of their former extent (e.g., Malin and Edgett, 2000). Removal of some section of plains rocks at Endeavour is required by the occurrence of Ca-sulphate veins in outcrops of both the Grasberg unit and Shoemaker Formation (Arvidson et al., 2015b), which must have formed while they were previously buried.

The missing Hesperian cratering record from the plains indicates ~80 m of plains rocks has been eroded over time (Golombek et al., 2006) in the vicinity of Endeavour. The Hueytown fracture (Fig. 12) is close to 100 m above the present level of the plains and, if deposits in the fracture were emplaced when the surface was buried by plains rocks, implies roughly comparable erosion of the plains rocks. Hence, plains rocks probably onlapped ~80–100 m higher on the rim of Endeavour, but it is uncertain if they could have been even thicker or whether the rim segments were once completely buried. There is no break in slope on the exposed rim (Fig. 2C) as might be expected if the level of the plains rocks was stable for an extended period at a higher elevation while significant erosion occurred on exposed surfaces above.

Mass wasting has likely contributed to slope processes and development of colluvial deposits around Endeavour's rim and may also be important in slow backwasting of the crater wall that produces the relatively rough spur and gully/debris chute relief. However, there are no significant offsets in the rim position (except for the terrace block on the east rim) that would be expected if there was wholesale collapse of rim segments long after crater formation. Hence, mass wasting cannot account for observed differences in rim segment geology, relief, or gaps in the rim outline.

Identifying additional signatures of pre-plains degradation remains elusive, but evidence for modification by fluvial erosion is evident in older craters and surfaces to the south beyond the extent of the plains rocks (Hynek and Phillips, 2001). Many crater rims on these Noachian surfaces are dissected by extensive valley networks that drain towards the north until buried by the plains rocks (Fig. 1). Several of the larger valleys drain towards Endeavour and come within 40–70 km of the crater before disappearing beneath the plains rocks (Fig. 1). In addition, the rims of some craters are breached by valleys (Fig. 13A) and the rim of nearby Miyamoto crater is incised (Fig. 1). These valleys are consistent with the wider view of Noachian surfaces around Meridiani Planum that indicates fluvial activity was important in shaping the Noachian landscape (e.g., Grant, 1987, 2000; Grant et al., 2009; Hynek and Phillips, 2001). Although the absolute age of Endeavour is not known with precision, it is Noachian in age (Hynek et al., 2002; Arvidson et al., 2014) and there are a number of characteristics of the crater suggesting it may have been subjected to significant fluvial dissection/incision.

Fluvial incision of Endeavour's rim would focus erosion in some locales and could account for removal of nearly all Shoemaker Formation rocks at Cape York while leaving a thicker section preserved at Cape Tribulation. Even greater incision of portions of the rim is consistent with the evolution of some of the gaps around the crater. Formation of Marathon Valley and features of a similar scale via incision is consistent with their general form and, in the instance of Marathon Valley, the strong detection of smectites along the valley floor may point towards sustained interaction with water relative to adjacent rim surfaces. Significant fluvial degradation is also consistent with the relatively low relief, smooth profile, and thin sediment cover of the outer flank, suggesting it evolved as a pediment. Under such a model, fluvial erosion on higher surfaces yields sediment that is transported across the outer rim and deposited on more distal surfaces now buried by the plains. Collectively, these attributes suggest Endeavour was modified by fluvial degradation in the Noachian on a par with

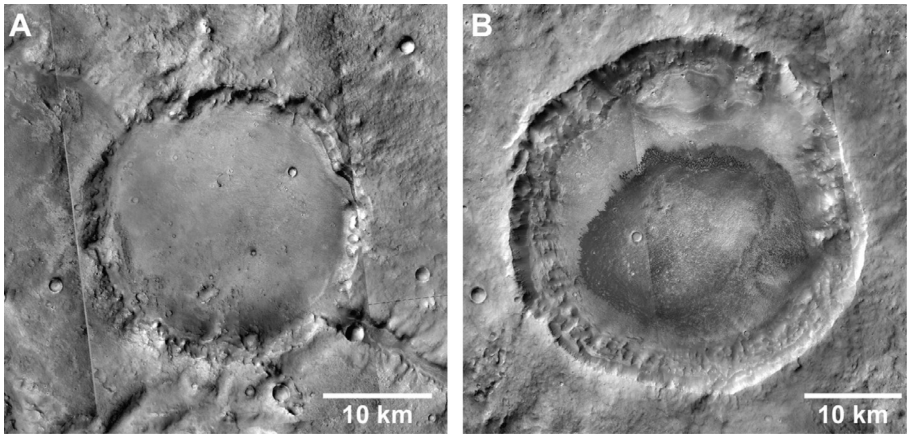

Fig. 13. Unnamed craters south of Meridiani Planum used as comparisons to predict the degradation state of Endeavour. (A) Unnamed 27 km-diameter crater at 5.5°S, 354.7°E. The *d*/*D* for the crater is 0.022 or close to that at Endeavour (depth measured from crater rim crest to floor). However, the rim is likely considerably more degraded than Endeavour, with a much more irregular outline that results in broad alcoves and promontories not seen at Endeavour. Moreover, the crater is wholly breached by a valley network (trending northwest–southeast). Subframe of CTX images B16_016077_1753, P06_00330_1738, B05_011620_1747, G03_019268_1741, G22_026771_1729. (B) Unnamed 37 km-diameter crater at 4.7°S, 357.4°E. The *d*/*D* for the crater is 0.032 (depth measured from crater rim crest to floor) and may be similar to what would characterize Endeavour if the plains rocks were removed. The rim outline preserves minor scallops and measured elevations vary over a range of ˜250 m: some of this variability in elevation appears related to original rim relief, whereas some appears to be the result of degradation (e.g., along the southwest portion of the rim). Based on comparison of observed and predicted morphology, Endeavour may be comparably or slightly more degraded than this crater. Subframe of CTX images CTXP16_007137_1748, CTX B01_009998_1758 and B02_010565_1748. North towards the top in both images.

other craters on nearby Noachian-aged surfaces. Moreover, the absence of significant erosional debris from the Matijevic and Shoemaker Formations coupled with survival of features like Marathon Valley, if fluvial in origin, implies most modification of Endeavour occurred in the Noachian with subsequent modification limited to a few 10s of metres or less.

Examination of Noachian craters south of Meridiani provides clues to what Endeavour might look like if not mostly buried by plains rocks. One unnamed crater (5.46°S, 354.7°E) that is 25 km in diameter is highly degraded and shows abundant evidence for fluvial modification (Fig. 13A). The rim outline is much more irregular than Endeavour's and is marked by deep incision in multiple locations. Recessive alcoves have developed (especially to north) and sections of the rim do not appear elevated above the surrounding plains that are separated by remnant rim spurs that reach hundreds of metres into the crater. The crater has been breached by a large inlet valley on the southeastern rim and an outlet valley on the northwestern rim, where the elevation of the surface crossing the rim is about the same as the crater floor. Although total crater infilling is proportional to Endeavour and yields a *d*/*D* of 0.022 (depth measured from rim crest to crater floor), plains rocks contribute significantly to infilling at Endeavour. The unnamed crater in Fig. 13A appears to have been filled mostly by deposits eroded from the crater wall and carried in by the large valley network. Hence, the unnamed crater is considerably more degraded than Endeavour (not including degradation associated with the plains rocks at Endeavour).

A larger, 37 km-diameter unnamed crater (4.66°S, 357.38°E) may be a better analogue for an Endeavour-like crater not buried by plains rocks (Fig. 13B). The rim of the larger unnamed crater is slightly scalloped in places and shows local evidence for incision on a scale roughly comparable to Endeavour (Fig. 13B). Relief around the rim varies by ~250 m, some of which is due to local incision (e.g., on the west side) and some appears to be the result of original topography around the rim. Hence, burial of the crater rim in Fig. 13B would result in a rim characterized by discontinuous segments of varying relief much like what is seen at Endeavour. Although the wall of the unnamed crater in Fig. 13B does not include a terrace block, there is higher local relief compared to the outer flank that likely reflects the increased importance of mass-wasting on the steeper walls. The unnamed crater floor is partially filled by material of unknown origin, but that includes a large dune field covering much of the southern two thirds of the crater. Finally, the unnamed crater is 1.35 km deep (measured from rim crest to crater floor) and yields a *d*/*D* of 0.037 that may be similar to Endeavour if the plains rocks were not present. Based on all of the above, the unnamed crater in Fig. 13B shares many of the attributes predicted and observed on the rim segments at Endeavour, including those suggestive of an important role played by fluvial processes in degradation.

7. Summary and conclusions

Endeavour crater is a 22 km-diameter Noachian-aged impact structure that possesses a complex morphology characteristic of similar sized craters on Mars. The present form and structure of Endeavour has been evaluated *in situ* by the Opportunity rover and remotely using high resolution HiRISE and CTX images from MRO.

Multiple exposed rim segments are sometimes slightly scalloped along their circumference, separated by gaps, and range in elevation from ~10 m to over 100 m above the level of the surrounding Meridiani plains (Fig. 2). The interior wall around the southern half of the crater is exposed over ~300 m relief and reveal a terrace block along the eastern quadrant whose diameter is ~0.8 that of Endeavour. Slopes of 6–16% flank separate locations on the exterior flank of Cape Tribulation before being embayed by the plains rocks and appear representative of other higher relief rim segments assessed from orbit. Both pre-impact rocks (Matijevic Formation) and Endeavour ejecta (Shoemaker Formation) are present at Cape York, but only the Shoemaker Formation (up to ~150 m section) outcrops at locations examined by Opportunity at Cape Tribulation. The crater is ~200–500 m deep and mostly filled with plains rocks that probably overlie pre-plains erosional debris shed from the rim. There is no evidence of a central peak within Endeavour.

Study of pristine complex craters Bopolu and Tooting as well as the use of morphometrics derived for describing morphometry of other martian complex craters enables the pristine form of

Endeavour to be approximated. The original rim of Endeavour likely averaged 410 m in elevation, but relief varied ±200 m around the circumference. A 250–275 m section of ejecta (±50–60 m) would have comprised a significant fraction of the rim height. The original crater depth was likely between 1.5 km and 2.2 km and if there was a central peak, it was probably between 200 and 500 m high.

Comparison between the predicted original and current form of Endeavour suggests on order of 100–200 m of degradation and vertical lowering of the crater rim that varied such that almost the entire ejecta section was removed in some locales (e.g., Cape York) while thick sections remain preserved elsewhere (e.g., Cape Tribulation). Differences in rim relief and where rim segments are exposed versus where there are gaps are not simply the result of variations in the original rim relief and (or) due to offsets along faults radial to the rim. Although the origin of features such as Wdowiak Ridge and Marathon Valley remain uncertain, most interpretations coupled with the scale and character of the features broadly support our estimates of erosion. The paucity of exposed debris shed from the rim indicates that most rim degradation occurred prior to embayment by the plains rocks. The plains rocks are likely ~100–200 m thick outside the crater, but much thicker on the interior where the closed depression of the crater formed an efficient sediment trap.

Deposition in aeolian and evaporitic playa settings dominated emplacement of the plains rocks (Squyres et al., 2004; Grotzinger et al., 2005; McLennan et al., 2005; Squyres and Knoll, 2005; Golombek et al., 2006; Arvidson et al., 2015a) and interaction between the prevailing winds and the crater is clearly important in the ongoing stripping of the plains rocks. Aeolian modification of the exposed rim is also apparent in the form of streamlined/fluted outcrops and local drift deposits. Pre-plains rocks erosion, however, must account for varying amounts of degradation around the rim. Analogy with degradational morphologies associated with Noachian-aged craters exposed south of Endeavour and the Meridiani Plains suggests early fluvial incision played an important role in rim degradation (Fig. 13) and was likely followed by only a few 10s of metres modification by alternate processes. This is consistent with (1) the interpretation of a pediment on the rim flanks at Endeavour, (2) the formation of features such as Marathon Valley, (3) the nearly complete removal of ejecta at Cape York, (4) preservation of a thicker section of ejecta at Cape Tribulation and perhaps, and (5) the origin of some gaps in the rim around the crater. A large unnamed, Noachian-aged crater south of Meridiani shares many of the attributes described at Endeavour (Fig. 13B), including signatures associated with fluvial modification, and suggest the unnamed crater may be a reasonable analogue for the general appearance of Endeavour crater if it were not buried by plains rocks.

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