Orbital radar, imagery, and atmospheric modeling reveal an aeolian origin for Abalos Mensa, Mars

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[1] Icy deposits surrounding Planum Boreum, Mars, contain crucial information for deciphering paleoclimate and past geologic processes at the martian north pole. One such deposit, Abalos Mensa, is an enigmatic wedge of material located near the ~1 km high Rupes Tenuis. Its unique location and lobate morphology have fostered formation hypotheses that assume either fluvial or aeolian erosion of a once-larger ice deposit. The aeolian scenario posed previously requires impact shielding of ancient basal unit material to provide an erosional remnant which seeds later deposition, while the fluvial hypotheses invoke cryovolcanism beneath the younger north polar layered deposits (NPLD) and associated outflow to erode the adjacent chasmata. Here we combine newly available radar sounding data, high-resolution imagery, digital elevation models, and atmospheric modeling to examine internal structure and infer both the mechanisms for, and timing of, Abalos Mensa formation. From this integrative approach, we conclude that Abalos Mensa formed as a distinct feature via atmospheric deposition following erosion of Rupes Tenuis and grew concurrently with the rest of Planum Boreum as the NPLD accumulated. The required processes are consistent with those observed today: no exotic phenomena (cryovolcanism, fluvial activity, or impact shielding) appear necessary to explain the formation of Abalos Mensa.
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1. Introduction

[2] Abalos Mensa is a lobate wedge of material near the martian north pole, directly south of Rupes Tenuis at the edge of Planum Boreum (PB) centered on 285°E longitude. This feature measures ~180 km across and is separated from PB by a narrow chasmata on the east and a broad chasmata containing dune fields on the west (Figure 1a). Based on limited visible exposures of its stratigraphy, Abalos Mensa has been assumed to be composed of icy north polar layered deposits (NPLD) strata and both sand-rich members of the "basal unit," a term that combines the rupes and PB cavi units [*Byrne and Murray*, 2002; *Tanaka et al.*, 2008]. The stratigraphic column for this region starts below the ice cap with the regional "basement," Vastitas Borealis Formation, and then begins incorporating icy material. The oldest ice-rich unit is the rupes unit, followed by the PB cavi unit [*Tanaka et al.*, 2008]. These two units comprise what is often referred to as the "basal unit" [*Byrne and Murray*, 2002]. Following the basal unit is the NPLD material. The basal unit material is only visible on the western flank of Abalos Mensa [*Tanaka et al.*, 2008].

[3] Abalos Mensa is unique as an anomalously large, isolated mound proximal to PB. It has a morphology that invoked hypotheses with multiple, distinct processes to explain its formation. Understanding its history is therefore key to evaluating past climate and constraining both the nature and timing of processes that have occurred on Mars.

[4] Prior work on ascertaining the origin of Abalos Mensa can be broken into two dominant hypotheses. The first is based on geomorphology; it ascribes this landform and the surrounding features to cryovolcanism, i.e., interactions of volcanoes/geothermal heat sources with ice [*Fishbaugh and Head*, 2002; *Hovius et al.*, 2008]. Either the mound was deposited as a result of slumping following ice melt, or the mound is in-place but carved from a more extensive deposit via fluvial action, with the chasmata representing former flow channels [*Fishbaugh and Head*, 2002; *Hovius et al.*, 2008]. To support this argument, nearby conical landforms have been compared to terrestrial shield volcanoes [*Garvin et al.*, 2000], streamlined mounds have been identified in the western chasmata [*Hovius et al.*, 2008], and the morphology of channels in the chasmata has been characterized as sinuous [*Fishbaugh and Head*, 2002]. These hypotheses suggest that Abalos Mensa is relatively recent (Middle to Late Amazonian), with *Hovius et al.* [2008] prescribing a maximum age of 20,000 years, since it could have only formed after significant NPLD deposition.

[5] The second dominant hypothesis is based on visible stratigraphy, in particular the presence of basal unit beneath NPLD within Abalos Mensa. In this scenario, the rupes unit (the lower member of the "basal unit" as described by [*Byrne and Murray*, 2002]) was more extensive in this region (i.e., a continuous deposit across the location of present-day Abalos Mensa) prior to the widespread erosion that created Rupes Tenuis [*Tanaka et al.*, 2008; *Kneissl et al.*, 2011]. Impact shielding at the location of Abalos Mensa as well as along Rupes Tenuis locally prevented the rupes material from eroding away. Impact shielding causes the material surrounding an impact crater, often covered by ejecta, to become armored and erosionally resistant [*Arvidson et al.*, 1976]. The shielding of Abalos Mensa and additional impact shielding along Rupes Tenuis left an isolated mound and the steep scarp [*Tanaka et al.*, 2008]. Later

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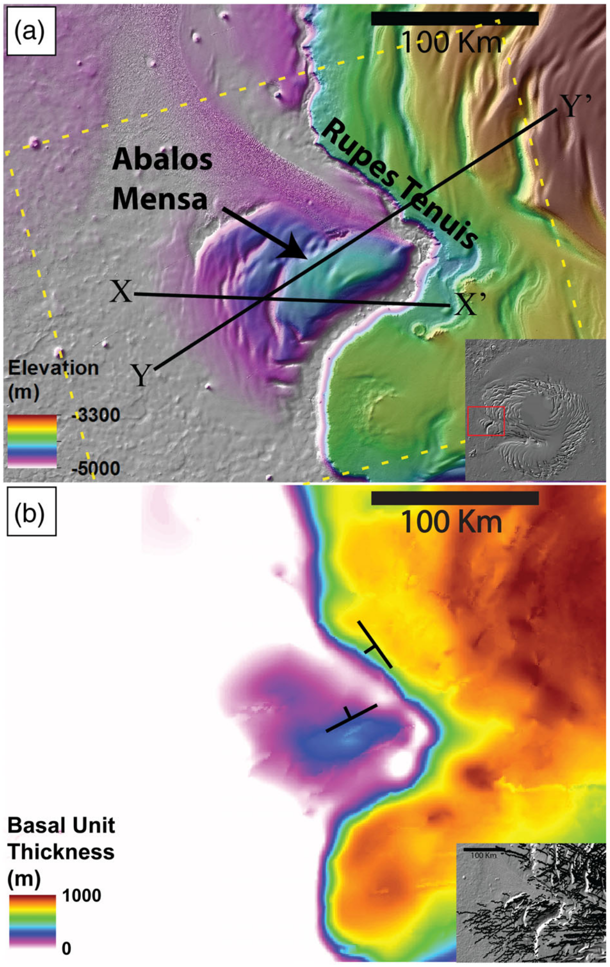

Figure 1. (a) Context map for study area including Abalos Mensa and Rupes Tenuis with the location of radargrams shown in Figure 2. Inset shows position on Planum Boreum. Dashed yellow box is location for Figure 3, the modeling results. (b) Thickness map of basal unit derived from subtracting surrounding plains elevation (−4900m) from a gridded basal unit elevation map. Note the steep scarp and small isolated deposit of basal unit material. Strike and dip symbols show average strike for basal unit layers at both Rupes Tenuis and Abalos Mensa. Inset shows SHARAD data points used in mapping basal unit topography.

deposition of NPLD added to this mound. This implies that the shielded rupes unit should underlie most, if not all, of the deposit [*Tanaka et al.*, 2008] and requires Abalos Mensa to be an Early Amazonian deposit (i.e., much older than assumed in the fluvial hypothesis).

[6] Both hypotheses require a preexisting deposit in order to form Abalos Mensa, yet involve vastly different processes and timing. Melting, fluid flow, and possibly slumping isolate the deposit in the first hypothesis, while impact shielding combined with aeolian erosion is responsible in the second. This work challenges these hypotheses by examining the internal structure and stratigraphy of Abalos Mensa with a combination of high-resolution imagery, orbital radar sounding, digital elevation models (DEMs), and atmospheric modeling. Internal stratigraphy was unavailable in previous studies and gives additional constraints on formation mechanisms. The result is a new hypothesis, based solely on atmospheric processes, for both the timing and mechanism of Abalos Mensa formation. This scenario has important implications for the role played by the atmosphere in the evolution of polar landforms on Mars.

2. Data and Methods

[7] A relatively new tool in planetary exploration is orbital radar sounding. The Shallow Radar (SHARAD) on Mars Reconnaissance Orbiter provides a detailed subsurface view of PB (see Figure 2) including internal stratigraphy that has provided important new insights into polar cap structure

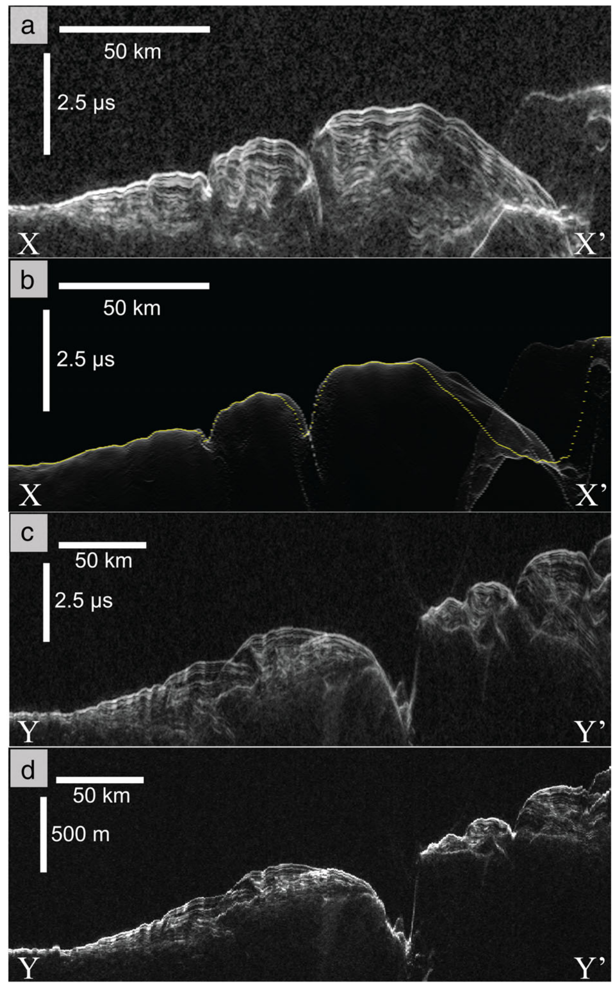

Figure 2. (a) SHARAD observation 1612601000 in time delay. Only NPLD is visible in this radargram. Note reflector downlap onto Vastitas Borealis Formation both near the chasmata and on opposite side. (b) Radar surface clutter simulation for SHARAD track 1612601000. Yellow line shows calculated position of echo from ground track based on MOLA topography. This simulation demonstrates that the reflectors within Abalos Mensa are not generated from off nadir surface echoes. (c) SHARAD observation 622902000 in time delay. This is located very near the thickest part of the mapped basal unit deposit (Figure 1b) within Abalos Mensa. NPLD layers truncate onto the basal unit, and no additional reflectors are visible within the basal unit. (d) SHARAD observation 622902000 in depth using a dielectric constant of 3.15 to convert from time. Note how the reflector geometry is altered when correcting for depth.

Table 1. Optical Basal Unit Bedding Analysis Results[a]

Basal Unit Optical Layer Analysis						
HiRISE Image	Location	MOLA Aspect	HRSC Aspect	MOLA Dip	HRSC Dip	Line Length
009367-1	Abalos Mensa	335	347	18.3	5.5	530 m
009367-2	Abalos Mensa	340	338	14.1	13.5	421 m
009367-3	Abalos Mensa	(*330*)	322	2.3	1.9	2,300 m
010646-1	Rupes Tenuis	223	239	14.2	12.3	597 m
010646-2	Rupes Tenuis	233	225	18.5	8.9	1,710 m

[a]Boundary layer dip and dip direction measurements derived from HiRISE imagery draped on MOLA 512 pixel per degree and HRSC H1264_0000_DA4 DEMs. Parenthetical number indicates low confidence in the measurement, as single pixel changes for elevation points noticeably affect this value.

[*Phillips et al*., 2008; *Putzig et al*., 2009] and stratigraphy [*Holt et al*., 2010; *Smith and Holt*, 2010]. We used SHARAD data to examine the internal stratigraphy of Abalos Mensa and to map the upper surface of the basal unit across Planum Boreum, including Abalos Mensa. SHARAD is centered at 20 MHz frequency with 10 MHz bandwidth, yielding a theoretical vertical resolution of 8.4 m in pure water ice [*Seu et al*., 2007]. Horizontal resolution is typically 0.3–1 km along track, and 3–6 km across track. SHARAD has dense coverage on the north pole, with more than 1800 SHARAD observations over PB and approximately 100 observations that cross Abalos Mensa. In order to confirm radar reflectors as representing subsurface interfaces, we compared radargrams to forward simulations of surface clutter (Figure 2b) [*Holt et al*., 2006]. These were based on DEMs of the surface derived from the Mars Orbiter Laser Altimeter (MOLA) on Mars Global Surveyor [*Smith et al*., 2001]. To obtain a DEM of the polar paleotopography, mapping results from the SHARAD data were exported, geographically positioned, and then gridded. To convert radar echo time delays to depth below the surface, we assumed a dielectric constant of 3.15, consistent with the water ice composition determined for the bulk NPLD [*Phillips et al*., 2008; *Grima et al*., 2009]. However, changing the dielectric constant will not significantly affect the relative geometries of layers, only their total thickness values (see Auxiliary Information).

[8] While SHARAD detects NPLD stratigraphy and the underlying basal unit topography, it does not typically detect bedding within the basal unit. Therefore, imagery from the High-Resolution Imaging Science Experiment (HiRISE) [*McEwen et al*., 2007] and Context Camera (CTX) [*Malin et al*., 2007] on MRO was used to map basal unit layering. Layers were chosen based on continuity, visibility due to albedo contrast, distance of exposure, and topographic expression. Preference was given to layers with higher albedo contrast and resistance to erosion. Imagery was geo-located and draped on DEMs from both MOLA and the High-Resolution Stereo Camera on Mars Express [*Neukum and Jaumann*, 2004] so that elevation data could be extracted. The extracted data were gridded to calculate bedding attitude for each layer (Table 1).

[9] To complement observational data analysis, the mesoscale atmospheric model of *Spiga and Forget* [2009] was used to qualitatively evaluate winds possibly involved in the formation of Abalos Mensa. We assume that winds are fundamental to the erosion and/or deposition of dust and ice particles at the surface. Recent observations posit this mechanism is at play [*Smith and Holt* 2010; *Appéré et al*., 2011]. Whether the removal process is mechanical erosion or enhanced sublimation is an open question; furthermore, thresholds of wind velocity for either erosion or deposition depend on many unconstrained parameters. Such determinations are beyond the scope of this study; however, the relative magnitude and the spatial pattern of modeled winds provides useful information relevant to those processes. It is certainly clear that with stronger near-surface winds, erosion would be enhanced and deposition less likely.

[10] The mesoscale model simulates atmospheric circulation with a horizontal resolution of approximately 5–10 km, suitable to assess typical regional wind regimes in the vicinity of Abalos Mensa. The model was run over a domain encompassing the north polar region (see section 7.2 in *Spiga et al*., 2011). Present-day obliquity and conditions were assumed, except that modern topography was replaced with the ancient SHARAD derived basal unit topography (see Auxiliary Information). No spurious effects in model predictions arise from this change, given the method employed to produce a high-resolution initial state from low-resolution global climate runs (cf. section 2.3.4 in *Spiga and Forget* 2009). Running a polar mesoscale model in present-day conditions except for the topography is a simple approach, closer to idealized modeling than real-case numerical weather prediction. However, it allows us to obtain results quantitative to the first order and to model, for the first time, paleo-wind conditions from a geophysically derived paleo-surface on Mars. This is possible because near-surface regional winds in polar regions are primarily controlled by slope-induced acceleration and Coriolis forcing, as shown both by mesoscale modeling and frost streak mapping [*Howard*, 2000; *Massé et al*., 2012].

3. Results

[11] The radar analysis of Abalos Mensa, and PB in general, provides a clear and unprecedented demarcation of basal unit extent beneath the overlying NPLD. The radar returns in the NPLD show distinct, bright, laterally continuous reflectors with very little echo power between reflectors [*Phillips et al*., 2008]. Where basal unit underlies NPLD, there is generally a sharp transition to diffuse scattering at the base of the NPLD, presumably due to increased complexity at the wavelengths of SHARAD (Figure 2) [*Putzig et al*., 2009].

[12] The NPLD radar reflectors within Abalos Mensa exhibit clear downlap onto the underlying Vastitas Borealis Formation (Figure 2a). Radar layers have maximum thickness near the center of Abalos Mensa and gradually thin as they downlap onto either the Vastitas Borealis Formation or the basal unit. Abalos Mensa radargrams show NPLD downlap directly onto Vastitas Borealis Formation both near the chasmata and at the southernmost edge; this is most apparent in radargrams lacking basal unit (Figure 2).

[13] SHARAD mapping also shows that basal unit extent beneath Abalos Mensa is much more limited than was hypothesized in prior work [*Tanaka et al*., 2008] and found primarily beneath the north-western half of Abalos Mensa (Figure 1b). The only basal unit identified in imagery at

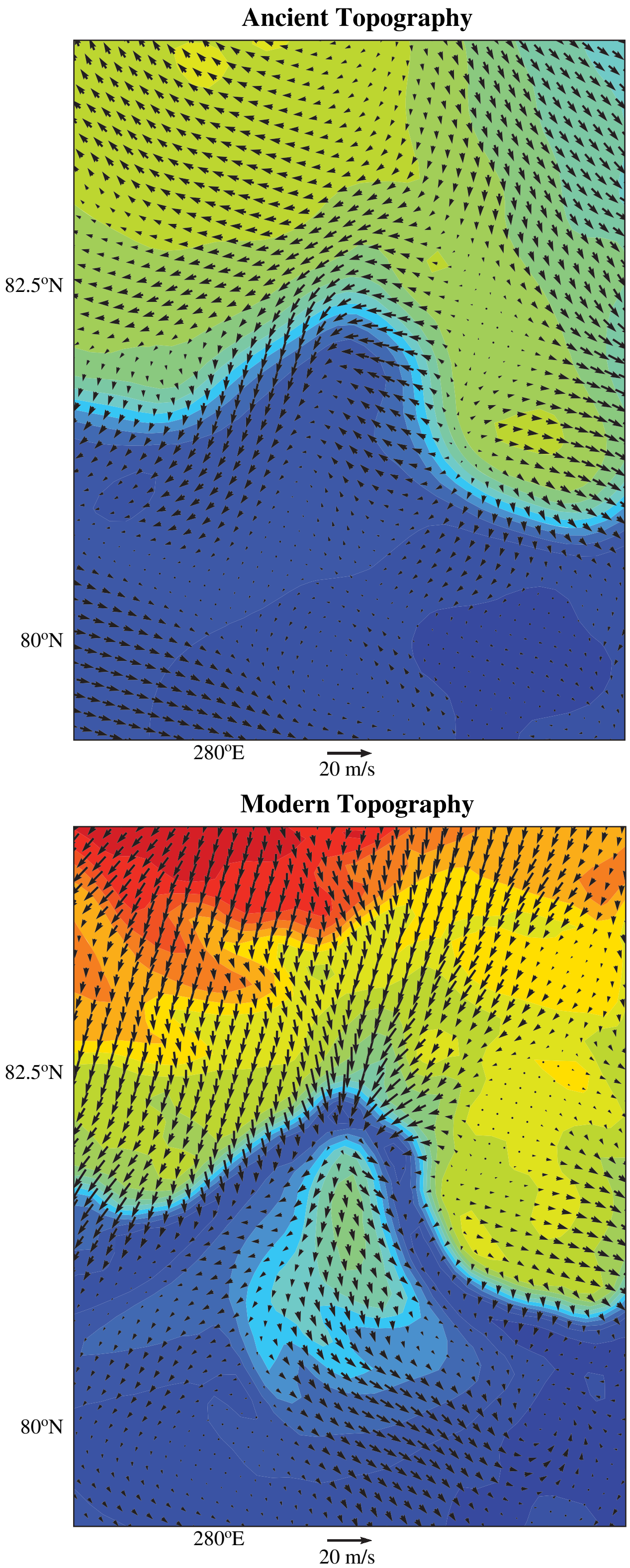

Figure 3. (a) Wind modeling results from paleotopography showing local winds descending across Rupes Tenuis, before slowing down where the modern Abalos Mensa is located. The displayed area is a zoom on the Rupes Tenuis/Abalos Mensa region; the simulation domain encompasses the northern polar region with a horizontal resolution of approximately 7 km. (b) Identical wind simulation but with modern topography instead of the SHARAD-derived paleotopography.

Abalos Mensa is a small deposit on the western half [*Tanaka et al*., 2008]. The basal unit is near maximum thickness here based on the radar data. At this location, the exposed basal unit has been identified as cavi using optical data [*Tanaka et al*., 2008]. Within PSP_009367_2620, there are clear examples of cross bedding and preserved bedforms in the basal unit deposit (see Auxiliary Information). This stratigraphy is consistent with the cavi unit and inconsistent with the rupes unit [*Tanaka et al*., 2008].

[14] Our analysis of HiRISE and CTX data shows that bedding attitudes of bounding surfaces within the basal unit dip outward from scarp exposures at both Rupes Tenuis and Abalos Mensa (Figure 1b and Table 1). This attitude is consistent with the overlying NPLD, which clearly downlap onto the Vastitas Borealis Formation. Additionally, the dip directions of basal unit layering in the western edge of Abalos Mensa are offset as compared with those exposed across the chasmata within the rupes unit exposed by Rupes Tenuis. This indicates that deposition was influenced by localized processes rather than continuous across the region prior to a hypothesized erosion event.

[15] The wind modeling results (Figure 3) show sustained katabatic winds flowing downward across Rupes Tenuis, changing to low velocity in the region where Abalos Mensa now exists. The change in wind velocity is sudden, with winds leaving the scarp at ~ 10 m/s then slowing to only a few m/s where Abalos Mensa is located. These wind patterns are typical of those taking place during the whole day throughout the year at the edges of Martian polar caps; their amplitudes could however vary with large-scale weather conditions and surface ice cover.

4. Discussion

[16] Based on these new observations, the previous hypotheses do not adequately explain Abalos Mensa formation and evolution. Under the impact-shielding hypothesis, the majority of the deposit should be underlain with rupes basal unit material. However, along the basal unit exposure on the western side of Abalos Mensa, no rupes was identified, only the younger basal unit member, PB cavi unit. Furthermore, the SHARAD-detected basal unit is nearly at maximum thickness at that location, and its areal extent is small relative to the entire Abalos Mensa formation. While we cannot exclude the possibility of any rupes unit existing beneath Abalos Mensa, we have confidence that if it does exist there, it must be very thin, likely below the resolution of SHARAD. This suggests that the entire basal unit deposit beneath Abalos Mensa is likely PB cavi unit. If no rupes unit is present beneath Abalos Mensa, then the formation is not contemporaneous with the rupes unit exposed in Rupes Tenuis, and the impact-shielding hypothesis is therefore insufficient.

[17] The geometry of bedding, as indicated by HiRISE analysis of the cavi unit and SHARAD for the NPLD, is inconsistent with both the fluid flow and impact-shielding hypotheses. Both of these hypotheses assume that layers were once continuous across Rupes Tenuis and should therefore have very similar bedding attitudes. However, layers within basal unit material on each side of Rupes Tenuis are significantly offset rather than parallel or subparallel. While a melt scenario may explain a difference in dip and perhaps a small difference in strike, it does not

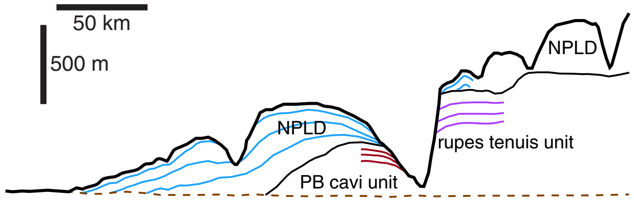

Figure 4. Interpretative cross section based on SHARAD observation 622902000 and basal unit layer attitudes derived from HiRISE imagery draped on HRSC DEM (see Table 1). Layers within both basal unit exposures dip away from their scarps and the thickest region of basal unit, indicating in-place deposition.

account for large offset in layer strike. This further supports our contention that these are not the same units. Additionally, the NPLD is downlapping onto either Vastitas Borealis Formation or basal unit material. In an erosional scenario, one would expect visible SHARAD reflector truncation along the chasmata, yet the relationship is clearly dominated by depositional downlap. Therefore, as neither hypothesis is consistent with these new data, a new formation hypothesis appears necessary. We first review the critical observations.

[18] The stratigraphy in Abalos Mensa from the NPLD and into the basal unit is consistent with localized deposition. Within the NPLD, the radar data show clear downlap onto Vastitas Borealis, indicating in-place deposition. The underlying cavi unit has this same bedding attitude, indicating it formed in place as well. In general, the cavi unit exhibits a gradational contact with the NPLD [*Tanaka et al.*, 2008], and therefore deposition was likely continuous across this boundary. The consistent bedding attitudes within Abalos Mensa support this relationship.

[19] The mesoscale atmospheric model results, using the ancient basal unit topography and modern atmospheric conditions, are also qualitatively consistent with in-place formation and deposition of material in Abalos Mensa. The model shows katabatic winds, capable of material transport, descending across Rupes Tenuis toward modern Abalos Mensa where a significant drop in wind velocity occurs. The drop in velocity would reduce the wind's carrying capacity at the location of Abalos Mensa, making deposition feasible. Interestingly, mesoscale simulations with modern topography (section 7.2 of *Spiga et al.*, 2011) show that, once the deposit reaches sufficient altitude above the surrounding surface, Abalos Mensa itself influences the local wind regime, which tends to mitigate the effects of atmospheric deposition that could have given birth to it.

[20] This integration of new observational data from SHARAD, HiRISE, and HRSC combined with atmospheric modeling suggests an alternative explanation (Figure 4). We hypothesize that Abalos Mensa formed in place, essentially as it appears today, following the construction of Rupes Tenuis. As hypothesized in previous work, widespread erosion of rupes caused hundreds of kilometers of polar cap retreat [*Tanaka et al.*, 2008; *Kneisssl et al.*, 2011]. However, erosion was inhibited along Rupes Tenuis due to impact shielding there, a hypothesis supported by the presence of partially buried impact craters [*Tanaka et al.*, 2008]. This scarp locally amplified katabatic winds as they flowed down and away from the center of PB. However, once in the Abalos region, the winds lost velocity, and thus their ability to carry ice/sediment. This caused deposition of cavi unit material, some of which may have been eroded directly from Rupes Tenuis. Rupes Tenuis and the Abalos chasmata are actively scoured by these katabatic winds keeping the chasmata open. As described by others [*Herkenhoff et al.*, 2007; *Tanaka et al.*, 2008], the cavi unit locally exhibits a gradational contact with NPLD. Hence, the entire deposit was likely formed in an essentially continuous manner when climate changed following widespread erosion of the rupes unit. This hypothesis will require further examination and atmospheric modeling to account for atmospheric compositions and obliquities in Mars' past, yet this explanation is consistent with a recent finding that nearby Chasma Boreale is a constructional feature that formed after regional basal unit erosion, rather than being created from the erosion of NPLD [*Holt et al.*, 2010].

[21] Based on our results, the geological processes required for the formation of Abalos Mensa are essentially the same as those recently active at Mars' north pole: deposition, erosion, and atmospheric transport of material. No exotic processes are necessary to explain the formation of Abalos Mensa. This also indicates that at least since the time of widespread rupes erosion and subsequent cavi and NPLD deposition, estimated at ~1 Ga [*Tanaka et al.*, 2008], climate-related processes and resulting landform evolution at the north pole of Mars have likely undergone little change, at least for this region on Planum Boreum. The present is therefore likely the key to the past, and we can learn much about paleoclimate and the long-term evolution of Mars landforms by further examining the processes active today.

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