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Valleys, paleolakes and possible shorelines at the Libya Montes/Isidis boundary: Implications for the hydrologic evolution of Mars

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ABSTRACT

We describe the results of our morphologic, stratigraphic and mineralogic investigations of fluvial landforms, paleolakes and possible shoreline morphologies at the Libya Montes/Isidis Planitia boundary. The landforms are indicative of aqueous activity and standing bodies of water, including lakes, seas and oceans, that are attributed to a complex hydrologic cycle that may have once existed on Mars in the Noachian (>3.7 Ga) and perhaps also in the Hesperian (>3.1 Ga). Our observations of the Libya Montes/Isidis Planitia boundary between 85°/86.5°E and 1.8°/5°N suggest, that (1) the termination of valley networks between roughly −2500 and −2800 m coincide with lake-size ponding in basins within the Libya Montes, (2) an alluvial fan and a possible delta, layered morphologies and associated Al-phyllosilicates identified within bright, polygonally fractured material at the front of the delta deposits are interpreted to be the results of fluvial activity and discharge into a paleolake, (3) the Arabia "shoreline" appears as a series of possible coastal cliffs at about −3600 and −3700 m indicating two distinct still stands and wave-cut action of a paleosea that temporarily filled the Isidis basin the Early Hesperian, and (4) the Deuteronilus "shoreline" appears at −3800 m and is interpreted to be a result of the proposed sublimation residue of a frozen sea that might have filled the Isidis basin, similar to the Vastitas Borealis Formation (VBF) identified in the northern lowlands. We interpret the morphologic–geologic setting and associated mineral assemblages of the Libya Montes/Isidis Planitia boundary as results of fluvial activity, lake-size standing bodies of water and an environmental change over time toward decreasing water availability and a cold and dry climate.

1. Introduction

The hypothesis of ancient martian standing bodies of water, which might have occupied the lowlands of the northern hemisphere and which might have existed in local- to regional-scale paleolakes once in martian history, is one of the most important subjects of ongoing discussion in Mars research (e.g., Parker et al., 1989, 1993, 2010; Baker et al., 1991; Head et al., 1999; Cabrol and Grin, 1999, 2001; Clifford and Parker, 2001; Kreslavsky and Head, 2002; Carr and Head, 2003; Irwin et al., 2005; Ghatan and Zimbelman, 2006; Fassett and Head, 2008a; Di Achille and Hynek, 2010; Mouginot et al., 2012). The case for large standing bodies of liquid water, including lakes, seas and oceans, is attributed to a complex hydrologic cycle that may have once existed on Mars in the Noachian (>3.7 Ga) and perhaps also in the Hesperian (>3.1 Ga). Standing bodies of water are discussed as a result of the discharge of high volumes of liquid water from catastrophic outflow events that formed the outflow channels (e.g., Baker et al., 1992; Carr, 1996; Clifford and Parker, 2001; Burr, 2010), intensive, long-term and repeated fluvial activity, which resulted in the formation of longitudinal valleys (e.g., Carr, 1996; Goldspiel and Squyres, 2000) and widespread dendritic valley networks (e.g., Carr and Chuang, 1997; Mangold et al., 2004; Erkeling et al., 2010). The existence of oceans, seas or lakes is supported by a large variety of morphologic landforms, including ridges, wave-cut platforms and coastal cliffs (e.g., Parker et al., 1993; Head et al., 1999; Webb, 2004; Ghatan and Zimbelman, 2006) and associated delta deposits (e.g., Hauber et al., 2009; Di Achille and Hynek, 2010; Kleinhans et al., 2010). Some of these morphologies appear along two global "paleoshorelines" that represent the two most continuous contacts on Mars and possibly reflect different water levels, i.e., the Arabia "shoreline" and the Deuteronilus "shoreline" (e.g., Parker et al., 1989, 1993; Head et al., 1999; Clifford and Parker, 2001; Carr and Head, 2003; Ghatan and Zimbelman, 2006).

Our study area at the Libya Montes/Isidis Planitia boundary is of particular interest, because local fluvial landforms indicative of standing bodies of water and the landforms of both the global

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Arabia and the Deuteronilus contact appear close to each other within our study area. Therefore, our study area offers an excellent opportunity to provide significant insights into the water-related geologic record of the Libya Montes/Isidis Planitia boundary and possible sea-scale standing bodies of water in the Isidis basin.

In our paper, we present the results of our morphologic, stratigraphic and mineralogic investigations of the Libya Montes/Isidis Planitia boundary. On the basis of high resolution image data, we identified numerous geologic units, which we dated with crater size–frequency distribution measurements to study the history and evolution of our study area at the Libya Montes/Isidis Planitia boundary. We performed hyperspectral image data investigations to study the mineralogy of water-related deposits and landforms. Our results have been integrated into a self-consistent model of the geologic history and evolution of the southern Isidis basin rim.

Our work is focused on morphologic and geologic characteristics of our Libya Montes/Isidis Planitia study area. We critically discuss our observations in the context of the proposed possible primordial global martian ocean ("Oceanus Borealis") and a putative Isidis sea (e.g., Parker et al., 1989, 1993, 2010; Baker et al., 1991; Head et al., 1999; Clifford and Parker, 2001; Kreslavsky and Head, 2002; Carr and Head, 2003; Ghatan and Zimbelman, 2006; Di Achille and Hynek, 2010; Ivanov et al., 2012a; Mouginot et al., 2012). On the basis of our results alternative interpretations other than fluvial activity or ocean-scale standing bodies of water for the formation of identified morphologic contacts appear possible but are inconsistent with the landforms identified in our study area. However, we compare and review our results with the results of previous papers that either support or reject the hypothesis of ancient martian standing bodies of water.

Our work addresses following questions: (1) What are the time limits for the formation of fluvial morphologies and possible shorelines and how do they relate to the geologic history of the Isidis basin, including major episodes of fluvial activity in the Libya Montes and the Syrtis-related volcanic filling of the Isidis basin? (2) Which morphologic evidence supports or contradicts the formation of the Arabia and the Deuteronilus contact by standing bodies of water, such as lakes, seas and oceans? (3) Could the fluvial landforms identified in our study area of the Libya Montes represent the main source for standing bodies of water? (4) Was the putative Isidis sea connected with the proposed primordial ocean that filled the northern lowlands? (5) Are water-related deposits, such as the alluvial fan and the possible delta, witnesses of repeated and long-term occurrence of water in the Libya Montes?

2. Data and methods

The Digital Terrain Model (DTM) of our study area is based on High Resolution Stereo Camera (HRSC) elevation data (Neukum et al., 2004; Jaumann et al., 2007; Gwinner et al., 2009, 2010), in particular of HRSC image h2162_0002 that was used to determine the elevation of possible shorelines, contacts and deposits. Mars Orbiter Laser Altimeter (MOLA) data (Zuber et al., 1992; Smith et al., 2001) were used to make MOLA-based elevations of shorelines (Head et al., 1998) comparable to results shown in this study.

Our morphologic map and the crater size–frequency distribution measurements are based on High Resolution Stereo Camera (HRSC) (Neukum et al., 2004; Jaumann et al., 2007) and Context Camera (CTX) images (Malin et al., 2007). Our morphologic map of the Libya Montes and the Isidis boundary makes use of the unit definitions of Greeley and Guest (1987) and Tanaka et al. (2005). We dated the identified geologic units with crater size–frequency distribution measurements in order to reveal the history of possible shorelines and the evolution of standing bodies of water and possible seas in the Isidis basin. Absolute model ages for the surfaces were derived from the current Mars cratering chronology model of Hartmann and Neukum (2001). A detailed description of the crater size–frequency measurements is provided, for example, by Neukum (1983), Ivanov (2001) and Werner (2005).

In addition, we used data from the Thermal Emission Imaging System (THEMIS) (Christensen et al., 2004) and the Mars Orbiter Camera (MOC) (Malin and Edgett, 2001). Images from the High Resolution Imaging Science Experiment (HiRISE) (McEwen et al., 2007) were used to investigate detailed surface morphologies. Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) (Murchie et al., 2007) data were used to discriminate the mineralogy of the possible delta and the alluvial fan deposits.

We performed CRISM digital image analyses with the Environment for the Visualization of Images (ENVI) (ITT Visual Information Solutions, 2009). Images were pre-processed with the CRISM Analysis Tool (CAT) (e.g., Seelos and the CRISM Team, 2009) and were corrected for instrumental, atmospheric and photometric effects.

3. Regional, geologic and morphologic setting

The Libya Montes represent the southern Isidis basin rim complex and are located along the highland lowland boundary (Fig. 1). The highlands continue to the south (Tyrrhena Terra) and to the east (Amenthes). Plains of volcanic origin from Syrtis Major embay and superimpose the western parts of the Libya Montes highlands. The volcanic province of Hesperia Planum is located to the southeast.

The Libya Montes highlands mainly consist of mountainous massifs and ridges as well as remnants of impact craters, which form the fluvially dissected Isidis basin rim (Fig. 2A and B). The valley networks are in parts dendritic and are categorized as fluvial landforms of highest densities on Mars (Carr and Chuang, 1997; Crumpler and Tanaka, 2003; Erkeling et al., 2010) and partially terminate in deposits similar to terrestrial alluvial fans and deltas (e.g., Gilbert, 1885; Postma, 1990; Leeder, 1999; Adams et al., 2001), the latter indicating lacustrine conditions and deposition into standing water (e.g., Fassett and Head, 2005; Mangold and Ansan, 2006; Ehlmann et al., 2008; Hauber et al., 2009; Di Achille and Hynek, 2010). Volcanic materials appear as intermontane smooth

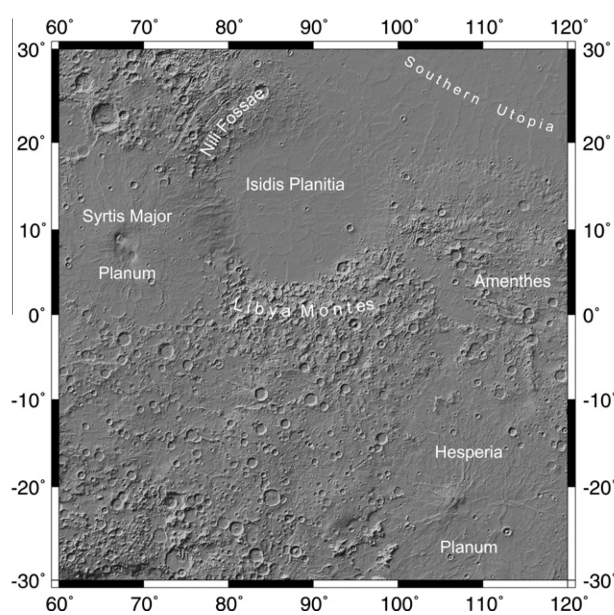

Fig. 1. Mars Orbiter Laser Altimeter (MOLA, Zuber et al., 1992; Smith et al., 2001) shaded relief of the Isidis Planitia region. The Libya Montes highlands build the southern Isidis basin rim complex.

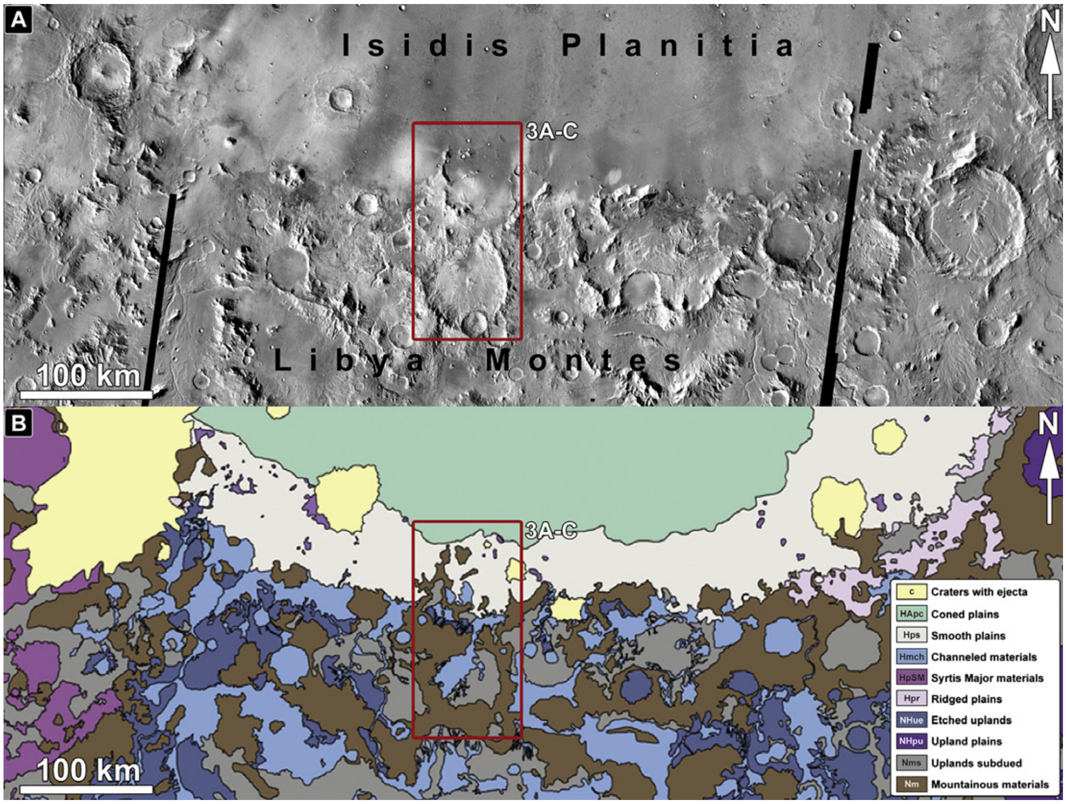

Fig. 2. The southern Isidis basin rim complex. (A) Southern Isidis basin rim complex including the Libya Montes highlands and the Isidis exterior and interior plains (THEMIS IR-Day 100 m mosaic). The red box outlines our study area. (B) Regional scale morphologic map of the southern Isidis basin rim complex (HRSC and THEMIS IR-Day background). The map is based on Fig. 17 of Ivanov et al. (2012a). The Libya Montes are characterized by a heterogeneous mix of mountainous materials, which are degraded mainly by impact cratering and fluvial processes. The Libya Montes are embayed by smooth exterior plains of the Isidis basin (light gray unit). Knobby and coned plains represent the Isidis interior plains (green unit) and occupy the basin floor. The red box outlines our study area.

plains, which are interpreted as results of invading lavas from Syrtis Major (e.g., Crumpler and Tanaka, 2003; Ivanov and Head, 2003; Hiesinger and Head, 2004; Mustard et al., 2007, 2009; Tornabene et al., 2008) or local volcanic sources of Tyrrhena Terra and Amenthes Planum (e.g., Tornabene et al., 2008; Erkeling et al., 2011a).

Our study area is located in the northern parts of the Libya Montes rim complex between 85°/86.5°E and 1.8°/5°N and covers the highland/lowland boundary (Fig. 3A–C). An unnamed Noachian 60-km crater (unit Nc) and Noachian highland remnants (unit Nm) cover nearly the entire southern half of the study area (Fig. 3B; darker colors). The mountainous terrain is separated into isolated remnants of highland massifs that extend into the Isidis basin. The northern section of the study area consists of low-lying smooth exterior (unit AHs) and knobby interior plains (unit Ak) of the Isidis basin (Fig. 3B; brighter colors) that embay the older pre-existing Libya Montes highlands. The elevation of the terrain decreases by ~4400 m from the southern edge of the 60-km crater toward the low-lying plains of the Isidis basin (Fig. 3C).

4. Morphologic contacts

At the Libya Montes/Isidis Planitia boundary, we identified series of morphologic landforms at three different elevation levels (Fig. 4A). The morphologies have been associated with intense fluvial activity, standing bodies of water, hydrous alteration, wave-cut action, distinct still stands as well as freezing and sublimation of a cold ocean (e.g., Parker et al., 1993; Head et al., 1999; Kreslavsky and Head, 2002; Carr and Head, 2003; Crumpler and Tanaka, 2003; Webb, 2004; Erkeling et al., 2010). We can distinguish between (1) local occurrences of fluvial and lacustrine landforms of the Libya/Isidis contact between −2500 and −2800 m (Fig. 4B), (2) a series of possible coastal cliffs of the Arabia shoreline at −3600 and −3700 m (Fig. 4C), and (3) the Deuteronilus contact that occurs as an onlap morphology at the boundary between the Isidis interior plains and the Isidis exterior plains (Fig. 4D).

4.1. Libya Montes/Isidis contact (−2500/−2800 m)

The observed morphologic landforms between −2500 and −2800 m elevation bear evidence for intense fluvial activity, valley incision and transport and deposition of materials (Fig. 5A). In particular, the crater materials of an unnamed 60-km crater are incised by a first group of valleys (unit Nd) that trend downstream toward the center of the crater. The valleys incised into the eastern crater materials show mainly degraded morphologies (Fig. 5B), similar to Noachian valleys found in the Libya Montes (Jaumann et al., 2010; Erkeling et al., 2010) and elsewhere on Mars (e.g., Fassett and Head, 2008b). Most of the valleys terminate between −2500 and −2800 m. Deposited materials occur as possible alluvial fan deposits (Fig. 5C) that are superposed on smooth and exhumed intermontane plains (unit Hi) that build parts of the crater floor and are similar to plains found elsewhere in the Libya Montes (Crumpler and Tanaka, 2003; Erkeling et al., 2010). Multiple layered lobes identified in steep and continuously sloped deposits are comparable to terrestrial alluvial fans and indicate that repeated events of fluvial activity, including transport and deposition, were responsible for their formation (Fig. 5D). In addition, a valley in the eastern section of the 60-km crater terminates in a

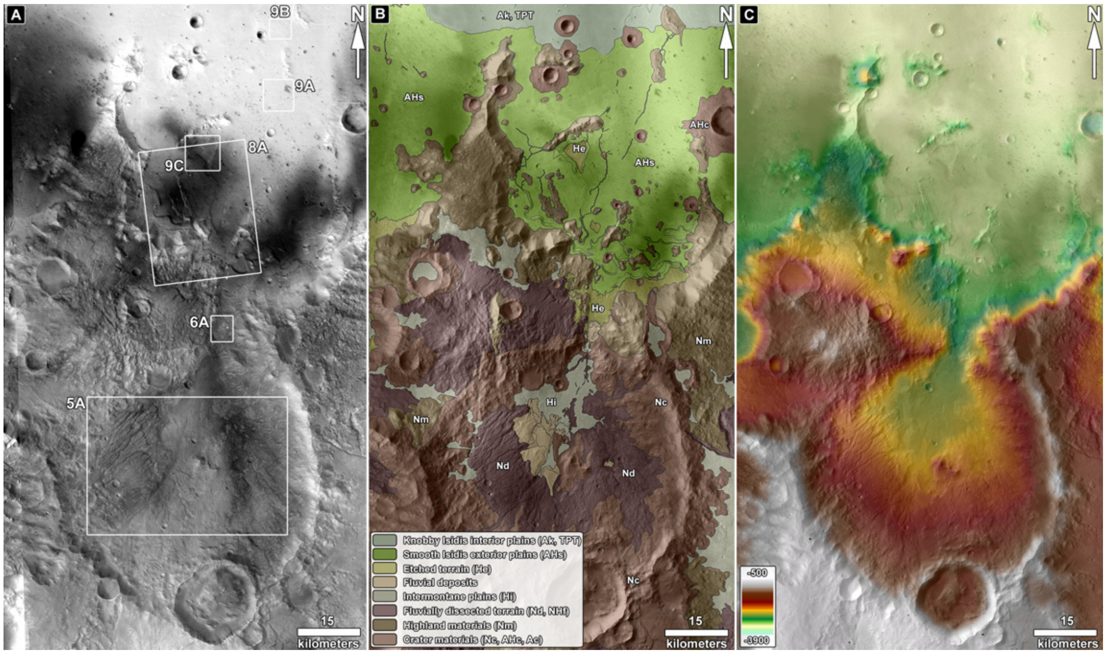

Fig. 3. Image mosaic, morphologic map and color-coded Digital Terrain Model (DTM) of our Libya Montes study area. (A) CTX image mosaic shows our study area that covers the Libya Montes/Isidis Planitia boundary. Locations of close-up images are shown by white boxes. (B) The southern half of our study area consists mainly of a 60-km Noachian crater (unit Nc) and remnants of Noachian mountainous terrain (unit Nm). It should be noted that the remnants of units Nc and Nm show similar morphologies and are difficult to distinguish. Both are dissected and degraded by fluvial landforms (unit Nd) that resulted in deposition of materials in local basins and in the formation of smooth intermontane plains (unit Hi). Materials deposited also appear as possible alluvial fans and in a delta, which are superposed on intermontane basins. Remnants of Noachian craters and highland materials as well as Hesperian etched and exhumed terrains (unit He) extend toward the north and are embayed by smooth Isidis exterior plains (unit AHs). Patches of etched terrains crop out locally within the smooth Isidis exterior plains indicating that these plains represent a thin coverage. The exterior plains, dissected by a few small valleys, represent the northernmost part of our study area and are superposed by the knobby Isidis interior plains (unit Ak) that contain the Isidis thumbprint terrain (TPT). Our morphologic map is based on Context Camera (CTX) and High Resolution Stereo Camera (HRSC) images. The map is superposed on a Context Camera (CTX) mosaic (15 m/px). Morphologic units are adopted from Greeley and Guest (1987) and Tanaka et al. (2005). (C) Digital Terrain Model (DTM) of our study area. The terrain in our study area declines from high-standing surfaces (500 m) shown in white and dark red colors to low-lying areas (−3900 m) shown in light green colors. Color-coded High Resolution Stereo Camera (HRSC) Digital Terrain Model (DTM) h_2162 with a resolution of 50 m/pixel is superposed on Context Camera (CTX) mosaic.

possible open basin paleolake, which shows inlet and outlet morphologies and intra-crater fan deposits on the floor (Fig. 5E).

A second group of fluvial features with different morphologies appears as a drainage pattern of parallel valleys in the western part of the crater (Fig. 5F). The pattern appears topographically higher than the degraded valleys elsewhere in the 60-km crater and displays a terraced morphology. The upper terrace terminates along cliffs at −2500 m, includes the upstream sections of the valleys, and shows preserved morphologies. A smaller lower terrace appears between −2500 and −2800 m and is characterized by degraded downstream sections of the valleys. These valleys terminate along a cliff between −2600 and −2700 m, are possibly truncated by later erosion, and do not show any deposits on the crater floor.

In addition to abundant fluvial morphologies, we also identified viscous flow features (e.g., Baker et al., 1991; Head et al., 2010), near the potential central mound of the 60-km crater, indicating the possible local influence of glacial processes (Fig. 5G).

A third group of valleys is incised into the intermontane plains, trends downstream to the north, and coalesces where the unnamed 60-km crater shows a breach in its northern crater rim. Immediately north of the breach, after the valleys cut through a topographic divide, they terminate within a topographic depression that is filled with layered sedimentary deposits of a possible delta, whose geometry is comparable to terrestrial prograding deltas formed in standing water (e.g., Gilbert, 1885; Postma, 1990; Leeder, 1999; Adams et al., 2001), where delta sediments progressively filled the depression. Numerous inverted distributary channels identified at the shallow sloped topset that is also characteristic for terrestrial deltas, bear evidence for transport and deposition of materials into a standing body of water (Fig. 6A and B). Bright, polygonally fractured materials appear mainly at the steep foreset (front) of the possible delta (Fig. 6C). In particular, the lowest layers consist of bright, polygonally fractured materials (Fig. 6D–F), which are similar to materials identified in possible delta deposits found elsewhere on Mars (e.g., Fassett and Head, 2005; Ehlmann et al., 2008; Grant et al., 2008; Pondrelli et al., 2008). The bright material mainly consists of hydrous minerals and clay, in particular Al-phyllosilicates (e.g., montmorillonite) (Fig. 7A and B). The Al-phyllosilicates are spatially limited to the foreset and to a few sites at the topset where the upper layers have been removed and material of the lowest layers is visible. The possible delta deposits are enclosed by etched and exhumed materials (unit He) that show olivine abundances (e.g., fayalite) and appear topographically above the possible delta deposits (Fig. 7A and C). Fe/Mg-rich phyllosilicates identified in adjacent Noachian highlands indicate hydrous alteration (Fig. 7A and D).

In the northern sections of the topographic depression, the possible delta shows eroded and possibly inverted channels. Numerous meter-sized blocks of the bright, polygonally fractured material are broken off from the steep front of the delta and are covered by dune materials (arrows in Fig. 6E and F). Valleys are absent north of the topographic depression where the terrain slopes slightly upwards and possibly represents remnants of a degraded crater rim.

The surfaces north of the delta also consist of olivine-rich materials and exhumed and etched morphologies. Exhumed terrains extend a few kilometers to the north until they are embayed and covered by the smooth exterior plains of the Isidis basin (unit AHs) that appear spectrally neutral.

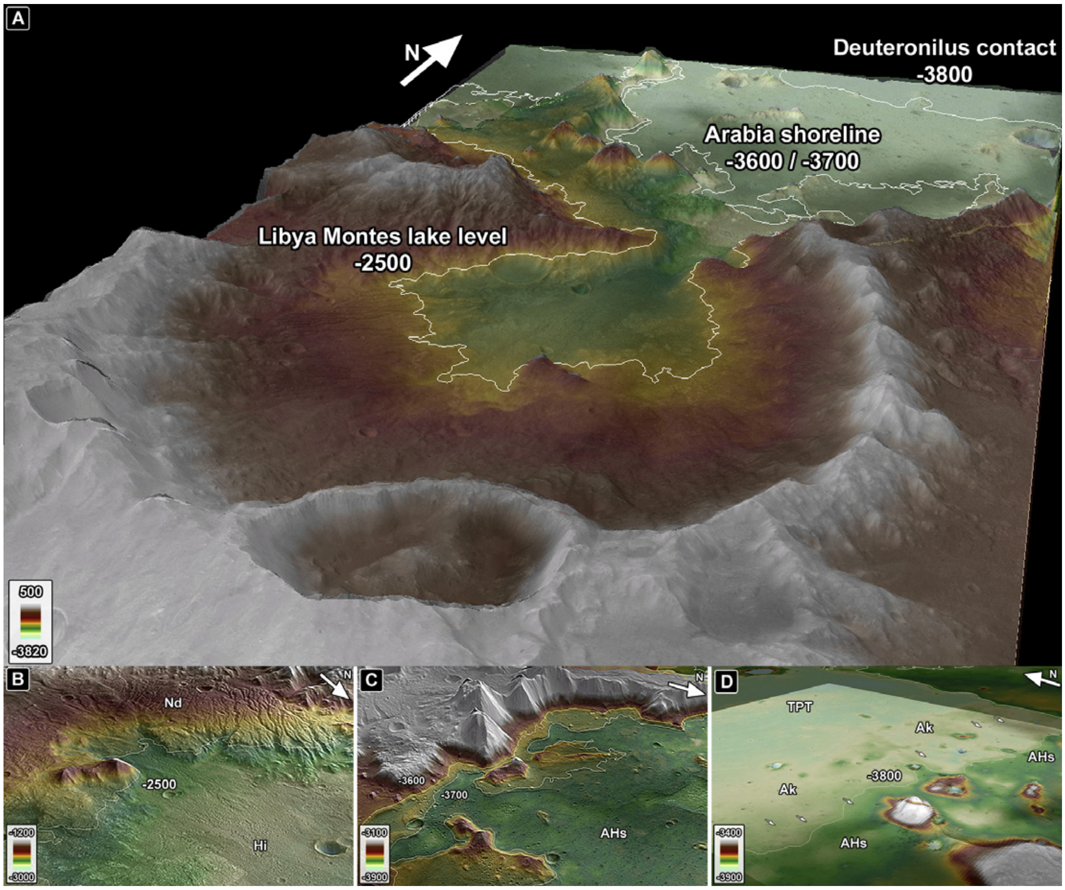

Fig. 4. Perspective views of our study area. The Digital Terrain Models (DTM) are based on High Resolution Stereo Camera (HRSC) image h_2162 and Mars Orbiter Laser Altimeter (MOLA) data. Background based on Context Camera (CTX) image mosaics. (A) Perspective view of the HRSC h_2162 Digital Terrain Model (DTM) of our study area. Morphologic contacts are identified at elevations of −2500 m (Libya Montes fluvial and lacustrine landforms), −3600/−3700 m (Arabia contact) and −3800 m (Deuteronilus contact). (B) Fluvial and depositional landforms associated with elevations between −2500 and −2800 m. Noachian valley networks (unit Nd) originate below the rim of the 60-km crater and terminate near −2500 m. Deposits can be identified on terrains between −2500 and −2800 m. Deposits appear on intermontane plains (Hi) as alluvial fans and as a delta. (C) Landforms associated with the Arabia shoreline. Possible coastal cliffs appear continuously on equipotential surface lines at −3600 and −3700 m indicating two distinct still stands of standing bodies of water. (D) The Deuteronilus contact appears as the boundary between the smooth Isidis exterior plains and the knobby Isidis interior plains. Although the knobby Isidis interior plains (Ak) are superposed on the smooth Isidis exterior plains (AHs), the contact is represented by a drop of elevation shown in the HRSC DTM at −3800 m due to a general decline of the elevation of the terrain to the center of the basin. The first tens of kilometers of the knobby Isidis interior plains (Ak, light green colors) are distinct from surfaces that contain the thumbprint terrain (TPT, light-blue colors) located in the northernmost and low-lying sections.

4.2. Arabia contact (−3600/−3700 m)

A few kilometers north of the exhumed and etched terrains, landforms associated with the Arabia shoreline (Parker et al., 1989, 1993; Head et al., 1999; Clifford and Parker, 2001; Carr and Head, 2003) appear as a series of cliffs and terraces (Figs. 4C and 8A) and represent the southern boundary between the smooth Isidis exterior plains (AHs) and materials of the Libya Montes (Nc, Nd, Hi). The cliffs appear to be mostly continuous within our study area and elsewhere along the boundary between the Libya Montes and the Isidis basin. The Arabia shoreline is not exposed along the eroded western, northern and eastern Isidis basin rim. Most conspicuous are a series of candidate coastal cliffs of the Arabia shoreline that coincide with the −3700 m equipotential surface line (e.g., Head et al., 1999; Carr and Head, 2003). The cliffs show terraces (Fig. 8B) and can be divided into 3–4 distinct terraces (Fig. 8C) tens of meters high and tens of kilometers long. However, the number of cliffs varies and the cliffs also show variations in size and their orientations relative to the Libya Montes high-standing terrain. Highland remnants that either extend hundreds of meters into the Isidis exterior plains or occur isolated within the plains are outlined by possible cliffs of the −3700 m contact (Fig. 8D).

A second series of possible coastal morphologies appears at −3600 m (Fig. 8A). The terracing of the −3600 m contact is less obvious than at the cliffs at −3700 m (Fig. 8A and E). In addition, the contact is considerably more degraded and discontinuous than the contact identified at −3700 m, in particular along the slopes of the Libya Montes massifs (Fig. 8F). Sections with preserved morphologies alternate with sections that are either superposed by materials shed from the Libya Montes or degraded, possibly by later fluvial and/or eolian activity.

North of the cliffs, small valleys that follow the local gradient toward the center of the Isidis basin postdate the formation of the cliffs and are incised into the plains (Fig. 9A). The small valleys originate exclusively north of the possible cliffs and are therefore not connected with the valley networks identified in the Libya Montes. Similar to the possible glacial morphologies we identified near the Libya/Isidis contact at −2500 m (Fig. 5G), the smooth exterior plains of the Isidis basin also show landforms possibly formed by glacial processes. Ridges that appear on the smooth plains and trend mainly toward the basin center (Fig. 9B) were interpreted as eskers (e.g., Grizzaffi and Schultz, 1989; Lockwood and Kargel, 1994; Ivanov et al., 2012a). Local patches of etched terrain, which are similar to etched surfaces farther south crop

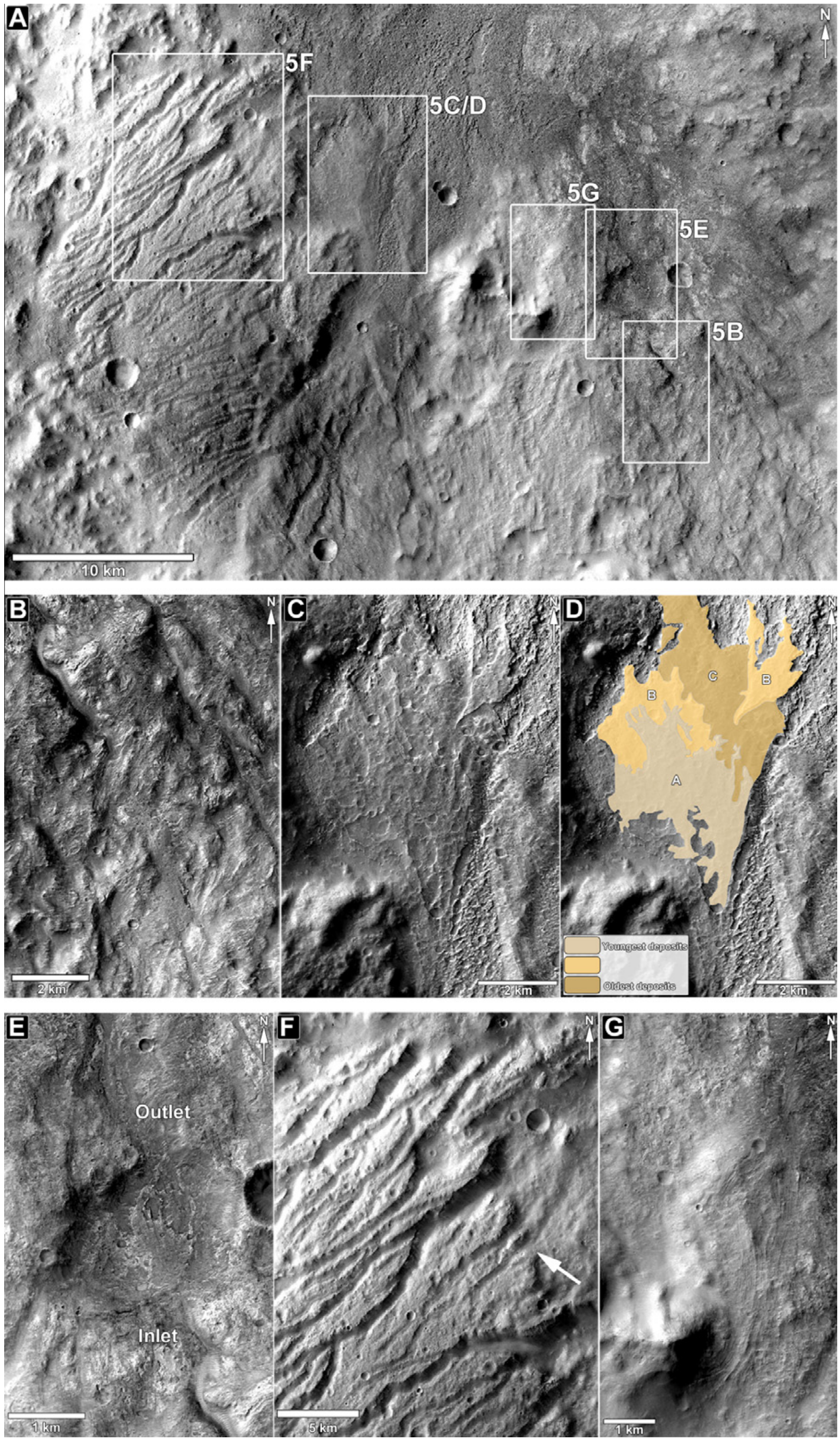

Fig. 5. Fluvial and lacustrine landforms identified in the Libya Montes between −2500 m and −2800 m. (A) Degraded valleys, a pattern of parallel valleys and associated deposits identified in a 60-km crater between −2500 m and −2800 m. Locations of close-up images are shown by white boxes. (B) Degraded valleys that cut surfaces below the rim of the 60-km crater terminate mostly near −2500 m. (C) Possible alluvial fan deposited on the floor of the 60-km crater occurs below −2500 m. The alluvial fan is interpreted to be formed by Noachian fluvial activity and was degraded possibly by eolian activity. (D) Multiple lobes of an alluvial fan and relative stratigraphy of the lobes determined by morphologic mapping. (E) Possible open paleolake site located near −2500 m at the mouth of fluvial valleys. The crater shows an inlet and an outlet channel. Intracrater deposits bear evidence for deposition into standing water. Deposits are degraded possibly by eolian activity. (F) Pattern of parallel valleys shows significantly different morphologies in comparison to degraded valleys shown in (B). They are likely a remnant of a pre-existing layer that filled the 60-km crater. The valleys originate below the crater rim, are incised into the pre-existing layer, a possible cliff and a degraded terrace at −2500 m (white arrow) and terminate along the lower margin of a well-defined but degraded terrace between −2600 and −2700 m. Cross-cut relationships of the valleys and variations in depths suggest repeated formation events and possible use of pre-existing valley paths. Deposits associated with the parallel valleys were not found. (G) Viscous flow features identified east of the central peak of the 60-km crater.

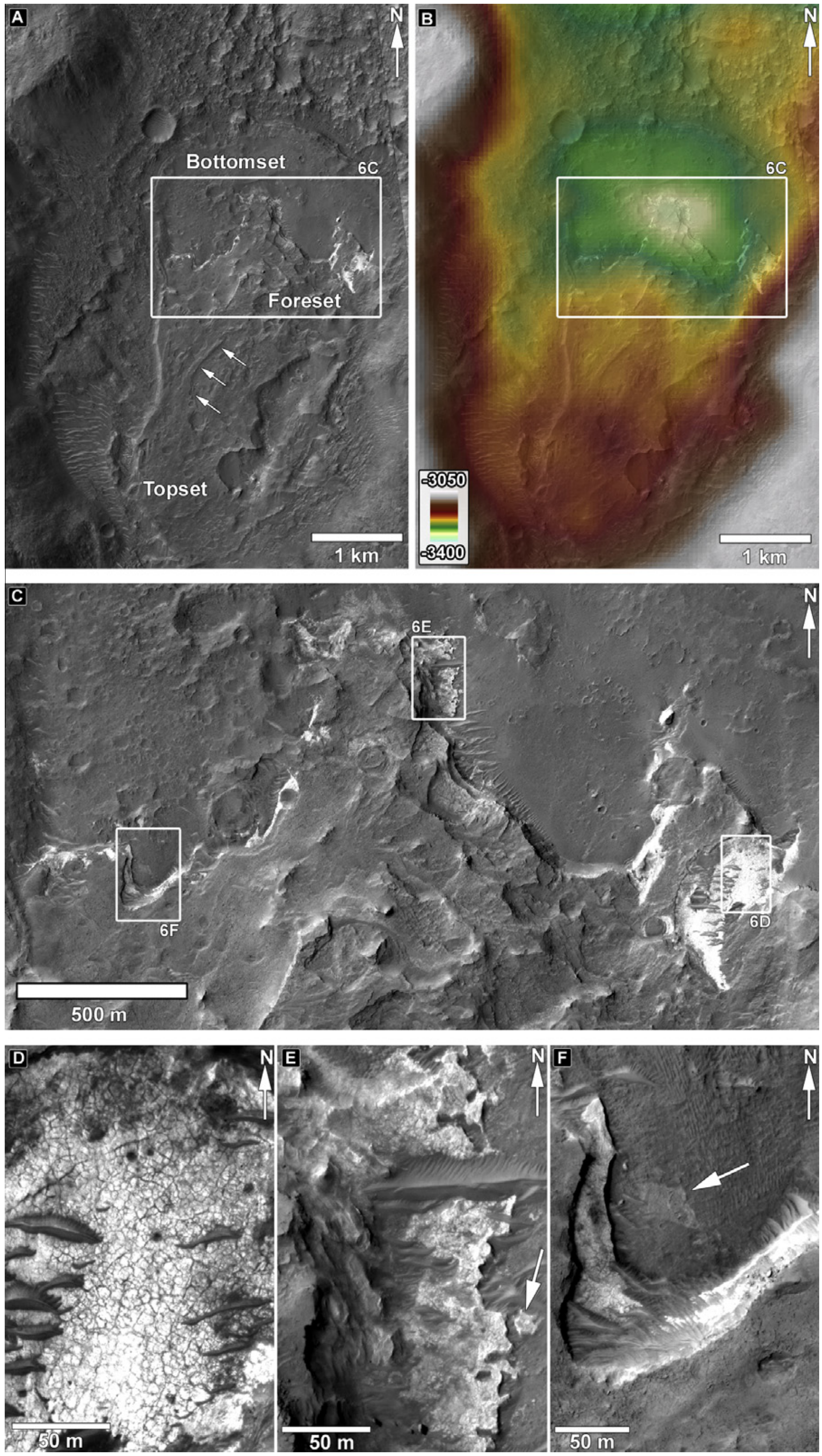

Fig. 6. Morphologies of a possible delta located immediately north of the breach in the rim of the 60-km crater. (A) The delta deposits show a typical sequence of a nearly horizontal topset, a sloped foreset and a low-lying and flat bottomset. Multiple distributary channels (white arrows) bear evidence for repeated deposition of delta sediments. The surrounding topography indicates that the delta was possibly deposited into a crater basin (diameter ~8 km). (CTX_P020_008808_1828). Location of Fig. 6C is outlined by white box. (B) HRSC elevation data show a local minimum (light blue color) of a crater basin that possibly existed before deposition of delta sediments. In addition, the elevation of the terrain increases toward the north (from light-blue colors to yellow) and the surfaces may have served as a topographic barrier for the delta deposits (HRSC DTM h_2162 superposed on CTX_P020_008808_1828). Location of Fig. 6C is shown by white box. (C) Foreset of possible delta shows eroded and exhumed morphologies (HiRISE_PSP008808_1830). Bright, polygonally fractured materials appear in the lowest layers of the foreset. Inverted channel materials are present in the upper layers of the foreset (southern edge of the image) and show eroded morphologies. Surfaces of the bottomset show eroded blocks of bright, polygonally fractured materials, which are partially superposed by dunes. Locations of close-up images are shown by white boxes. (D) Surfaces in the eastern part of the foreset show high abundances of bright, polygonally fractured materials. Numerous dunes are superposed on the bright materials. (E) Bright, polygonally fractured materials appear at the front and represent the lowest layers of the possible delta. Numerous blocks of bright, polygonally fractured materials are broken off from the front (white arrow) and are superposed by dune materials. (F) Remarkable landform at the front that consists of bright, polygonally fractured materials. Numerous blocks of bright, polygonally fractured materials are broken off from the front (white arrow) and are superposed by dune materials.

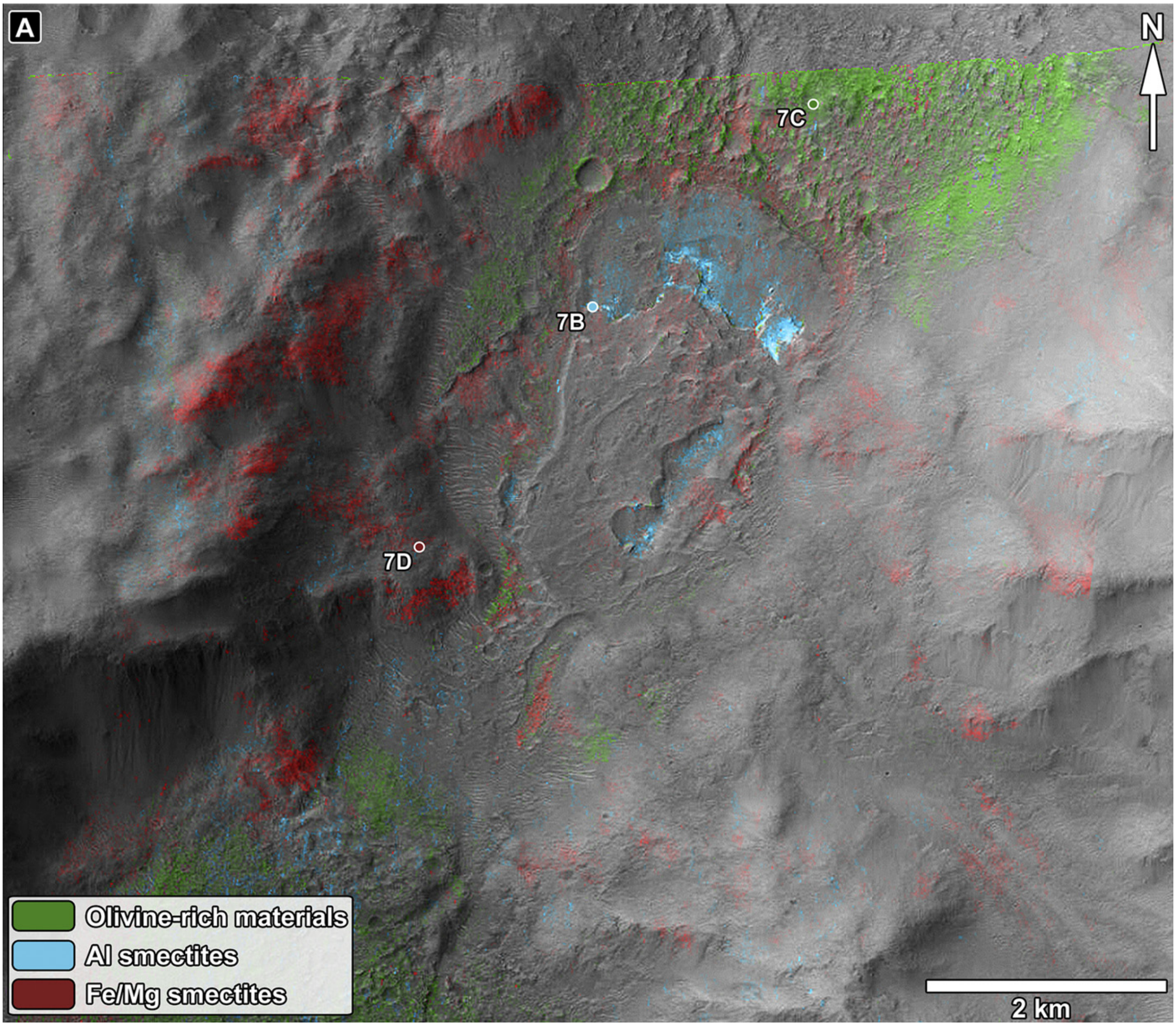

Fig. 7. Mineralogy of the possible delta and the surrounding terrain as observed in CRISM image FRTB0CB. (A) Appearances of bright, polygonally fractured materials at the front of the possible delta are identified as Al-smectites (blue color). Al-smectites appear also in local outcrops at the topset, where the lowest layers are excavated by erosion. Al-smectites indicate lacustrine environments and hydrous alteration of deposited materials, possibly as a result of fluvial activity and transport into standing water. However, materials of the possible delta also show weak appearances of Fe/Mg-smectites (red colors). They are eroded from surrounding Noachian highlands of the Libya Montes, where Fe/Mg-smectites are abundant. Additionally, olivine-rich (green) surface units south and north of delta deposits are mixed with Fe/Mg-smectites from the highlands. CRISM image FRTB0CB is superposed on CTX_P020_008808_1828. The CRISM spectra were taken from three distinct sites characteristic of Al-smectites, Fe/Mg-smectites and olivine-rich materials, respectively. Vertical lines, in particular in blue and red color in the western part of the CRISM image, are related to camera artifacts and do not represent mineral appearances. (B) Comparison of ratioed CRISM reflectance spectrum of Al-smectites (grayscale) with laboratory spectrum of montmorillonite (blue). The spectrum shows typical absorption bands at 1.41, 1.91 and 2.2 μm. Spectrum was taken from the western front of the delta (location is shown in (A). (C) Comparison of ratioed CRISM reflectance spectrum of olivine- and pyroxene-rich plains materials (grayscale) with laboratory spectra of lizardite (dark green), olivine_fayalite (green) and siderite (light green). The CRISM spectrum shows a long slope from ~1.4 to 1.9 μm indicating the presence of olivine. Pyroxene is likely present due to the broad absorption at ~2.0 μm. The spectrum was taken from etched terrains north of the possible delta (location is shown in (A)). (D) Comparison of ratioed CRISM reflectance spectrum of Fe/Mg-smectites (grayscale) with spectra of Fe/Mg-rich clays vermiculite (red and dark-red) and saponite (magenta) from spectral library. The CRISM spectrum shows absorption bands at 1.41, 1.93 and 2.31 μm, which are also present in the laboratory spectra.

out within the smooth plains and appear stratigraphically lower than the plains (Fig. 9C). The contact between the smooth Isidis exterior and the knobby Isidis interior plains, both occupying the basin floor, is located some tens of kilometers to the north and appears as a circumferential onlap morphology that coincides with the proposed Deuteronilus contact (see next section below).

4.3. Deuteronilus contact (−3800 m)

The Deuteronilus contact (e.g., Parker et al., 1989, 1993; Clifford and Parker, 2001; Carr and Head, 2003) appears in the northernmost part of our study area (e.g., Figs. 4A, D and 10A) and represents a well-defined and sharp boundary (Fig. 10B) that shows significantly different morphologies in comparison to landforms identi-

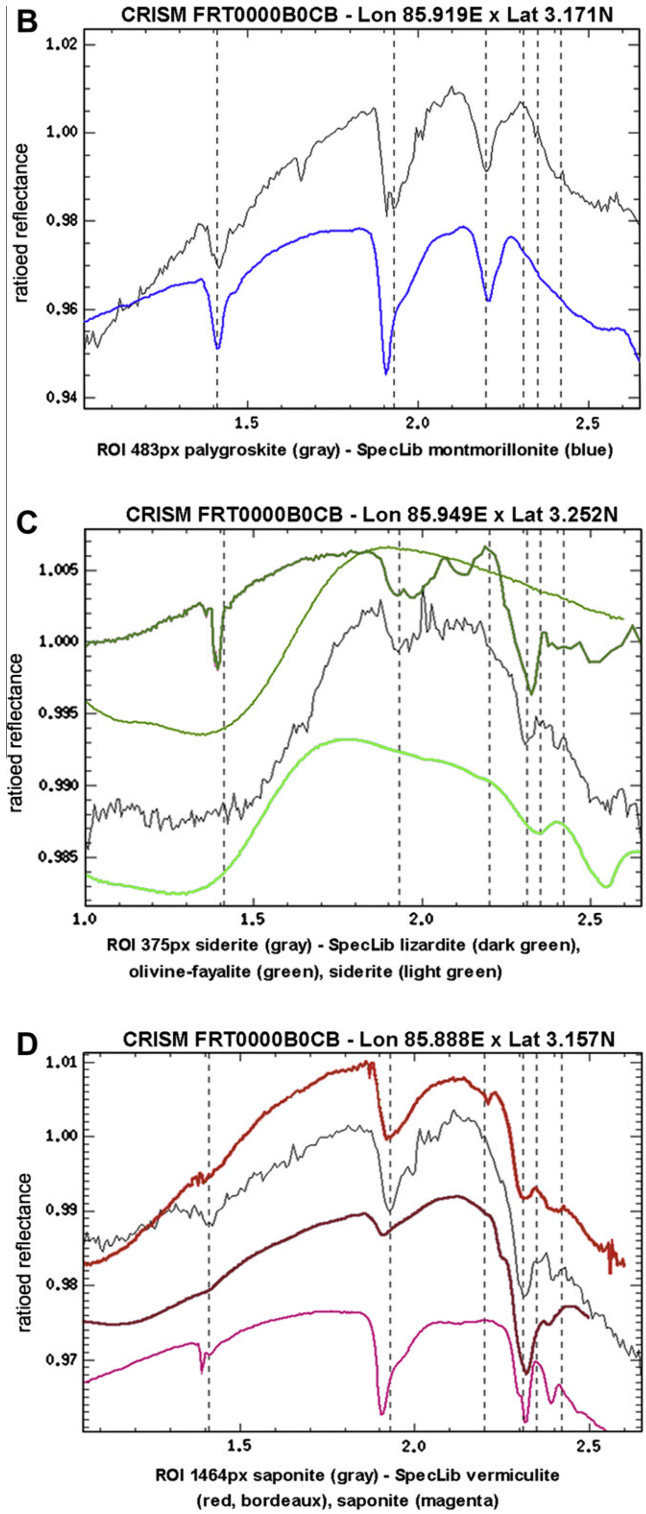

Fig. 7 (*continued*)

fied both at the valleys and fan deposits between −2500 and −2800 m and at the Arabia shoreline at −3600/−3700 m. The Deuteronilus contact represents the boundary between the smooth Isidis exterior plains (AHs, Ht) (Greeley and Guest, 1987; Tanaka et al., 2005) and the coned and knobby Isidis interior plains (Ak) (Greeley and Guest, 1987; Tanaka et al., 2005), which also contain the thumbprint terrain (hereafter TPT; Fig. 10C; e.g., Grizzaffi and Schultz, 1989; Hiesinger and Head, 2003; Ivanov and Head, 2003; Komatsu et al., 2011; Ghent et al., 2012; Ivanov et al., 2012a). The contact is characterized by an onlap geometry (Fig. 10B) where the Isidis exterior plains are superposed by materials of the Isidis interior plains that are stratigraphically higher (Ivanov et al., 2012a). In our study area, as well as elsewhere along the boundary between Isidis Planitia and Libya Montes, the Deuteronilus contact is more continuous in appearance than the Arabia contact. As the floor of the Isidis basin is tilted to the southwest, the Deuteronilus contact does not follow an equipotential line at −3800 m elsewhere in the Isidis basin, in particular in the northeastern section, where the contact appears between −3600 and −3700 m.

Although the Deuteronilus contact separates both plain units, they show similar morphologies, because typical TPT morphologies (Fig. 10C), including individual knobs and chains of cones, initially occur a few kilometers north of the contact, but not along the Deuteronilus contact (Fig. 10A and B). However, small valleys incised into the smooth Isidis exterior plains (Fig. 9A), as well as ridges (Fig. 9B) that trend toward the center of the Isidis basin, are superposed and embayed by the knobby interior plains of Isidis.

5. Surface ages and stratigraphy

The crater size–frequency distribution measurements for our study area are based on the definitions and the current Mars cratering chronology model of Hartmann and Neukum (2001) and are consistent with results of previous studies (e.g., Greeley and Guest, 1987; Crumpler and Tanaka, 2003; Erkeling et al., 2010, 2011a; Jaumann et al., 2010; Ivanov et al., 2012a). Particularly, the remnants of the Libya Montes were formed in the Noachian and are embayed by Hesperian and Early Amazonian surface units of the Isidis basin. Consequently, the ages of our morphologic surface units in our study area generally decrease from the southern regions, which consist of mountainous terrain of the Libya Montes, toward the low-lying Isidis plains in the northern parts of the study area.

Mountainous massifs (Nm) and the 60-km crater (Nc) are stratigraphically the oldest surface units in our study area and were likely to be formed in the Noachian earlier than ∼3.9 Ga. Both units were almost certainly formed at the time of the formation of the Isidis impact basin (e.g., Mustard et al., 2007, 2009), but predate the formation of fluvial morphologies identified in our study area and elsewhere in the Libya Montes (Crumpler and Tanaka, 2003; Jaumann et al., 2010; Erkeling et al., 2010). The pattern with parallel valleys in the western part of the 60-km crater is older than ∼3.8 Ga (Fig. 11A) and was formed earlier than the degraded valleys elsewhere in the 60-km crater, which show ages between ∼3.8 and ∼3.5 Ga. A 19-km crater that was formed at ∼3.7 Ga (Fig. 11B) at the southern rim of the 60-km crater is possibly responsible for the resurfacing of the degraded valleys that show slightly younger model ages. Fluvial activity likely occurred in repeated events in the Noachian and Early Hesperian and resulted in the formation of deposits in the center of the 60-km crater. Olivine-rich plains units that fill the lowest parts in the center of the 60-km crater are ∼3.7 Ga old. The plains postdate the formation of both the degraded and the parallel valleys. However, possible late-stage fluvial activity resulted in the formation of the alluvial fan that was formed later than ∼3.7 Ga ago and post-dates the formation of the olivine-rich plains. It should be noted that erosional processes resulted in exhumed morphologies that show a significantly younger model age of ∼3.3 Ga (Fig. 11A). Therefore, our model ages might represent the time when exhumation of the plains units occurred, but not the initial formation age.

Small valleys, which trend toward the breach in the northern crater rim and which are incised into the ∼3.7 Ga old olivine-

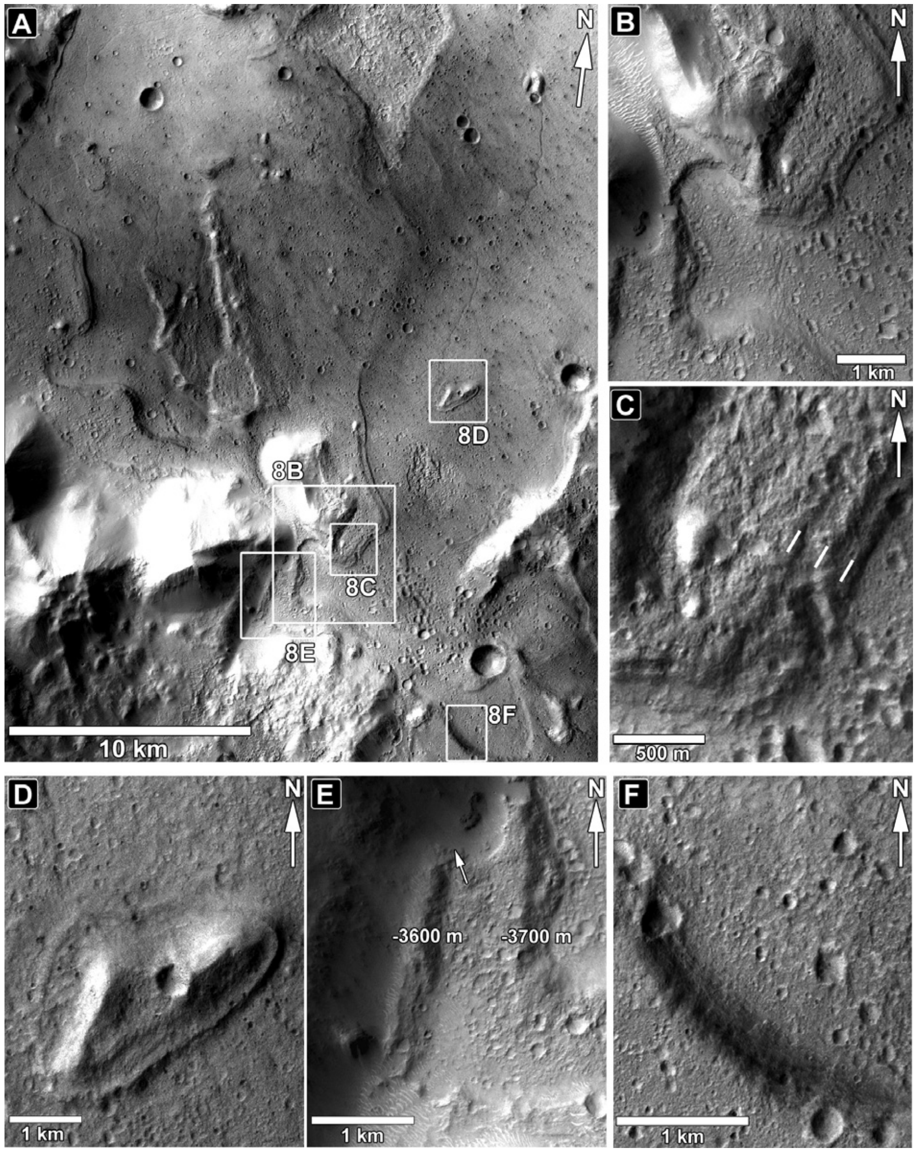

Fig. 8. Morphologies of the Arabia shoreline. (A) The boundary between the highlands and the Isidis exterior plains shows the most continuous occurrence of the Arabia shoreline in our study area (CTX_P20_008808_1828). Locations of close-up images are shown by white boxes. (B) Possible coastal cliffs of the Arabia shoreline. (C) Close-up of possible coastal cliffs that consist of a series of terraces and slopes indicating wave-cut action (e.g., wave erosion). (D) Remnants of highland materials that appear in the smooth Isidis exterior plains are enclosed by possible cliff morphologies. (E) Due to their proximity to the steep sloped highland remnants of the Libya Montes, sections of the coastal morphologies between −3600 and −3700 m are superposed by mass wasting processes (arrow shows interruption of cliff at −3600 m by highland materials). (F) Possible coastal cliffs show also layered morphologies that are distinct from the series of terraces and slopes shown in (C).

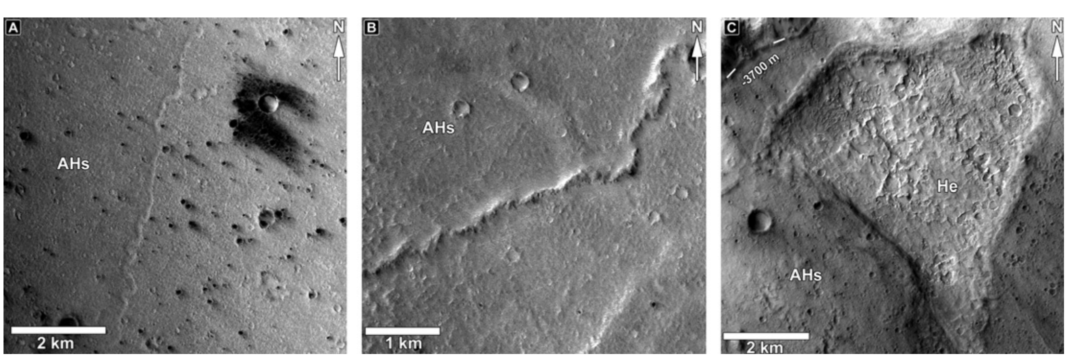

Fig. 9. Morphologies of smooth Isidis exterior plains (unit AHs). (A) Small valleys are incised into the plains materials and trend toward the center of the Isidis basin. (B) Ridges with sinuous sections appear in the northernmost parts of the Isidis exterior plains and in the Isidis interior plains. The ridges have been interpreted as possible eskers (e.g., Ivanov et al., 2012a). (C) Patches of etched terrains (He) appear locally within the smooth Isidis exterior plains (AHs) indicating that the latter represent a thin layer that is superposed on older (fluvially eroded) and (subsequently) degraded Libya Montes highland materials.

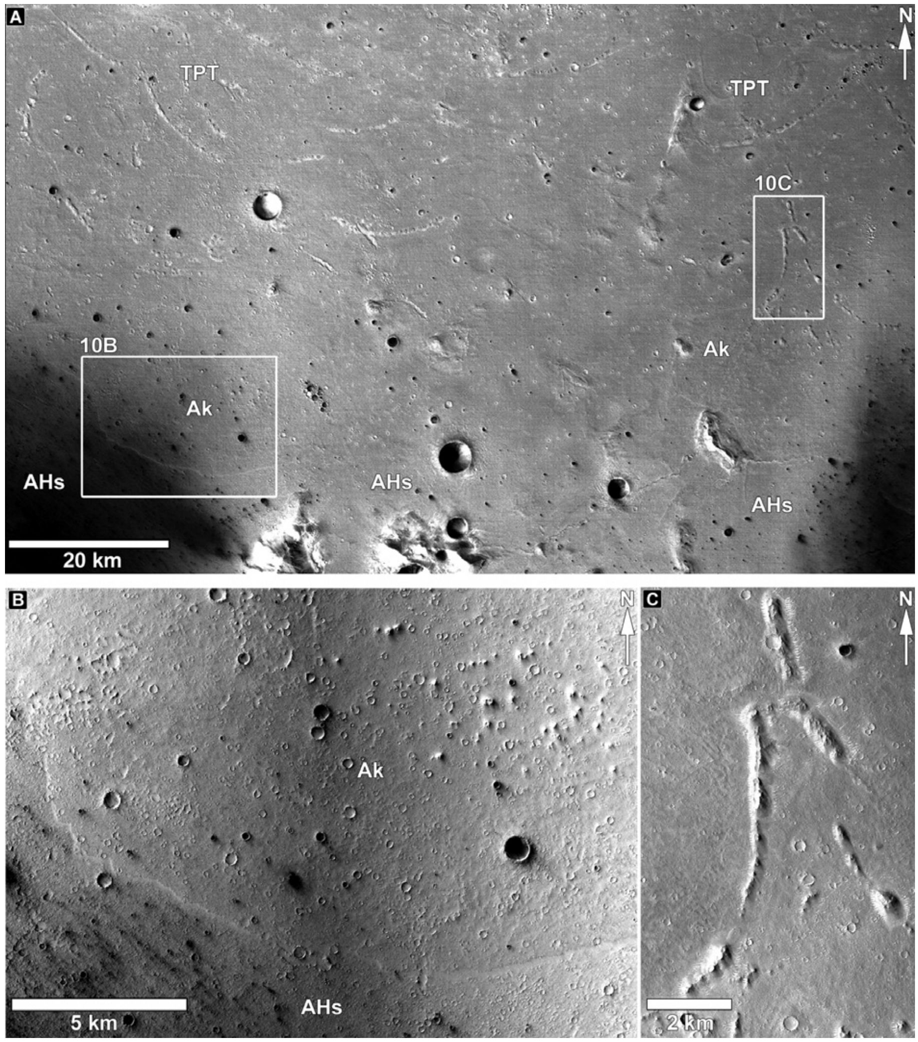

Fig. 10. Morphologies in the northernmost part of our study area near the Deuteronilus contact (HRSC h_2162). (A) Morphologies of the Deuteronilus contact. The knobby and coned terrain of the TPT appears in the northernmost part of the image with close proximity to the Libya Montes. (B) Onlap morphology of the Deuteronilus contact. The TPT occurs only a few kilometers north of the Deuteronilus contact. Therefore, the terrains, both of the Isidis interior plains and the Isidis exterior plains close to the Deuteronilus contact, have nearly identical morphologies. (C) Example of coned ridges of the TPT.

rich materials are possibly also related to the latest fluvial activity in this area. The possible delta, located immediately north of the breached rim of the 60-km crater and at the termini of the small valleys, was formed at the same time (~3.7 Ga) and likely by the same Late Noachian–Early Hesperian fluvial events. Although we could not derive absolute model ages for the flat topset of the possible phyllosilicate-rich delta, morphologic relationships suggest that it is stratigraphically younger than the ~3.7 Ga old surfaces located directly to the north. Olivine-rich terrains with etched and eroded morphologies mostly postdate the Noachian and Early Hesperian surfaces formed by fluvial activity and are associated either with an early impact melt veneer eroded and transported to form sediments (e.g., Mustard et al., 2007, 2009) or with the volcanic flooding and filling of the Isidis basin in the Hesperian (e.g., Tanaka et al., 2000; Head et al., 2002; Ivanov and Head, 2003; Hiesinger and Head, 2004; Tornabene et al., 2008). Landforms associated with the Arabia shoreline were formed at ~3.5 Ga ago and are younger compared to previous studies that show ages of “at least” ~4.0 Ga (Clifford and Parker, 2001). In addition, the cliffs of the Arabia shoreline in our study area are interpreted to have formed after the last fluvial activity in the Libya Montes highlands ceased ~3.7 Ga ago. The smooth Isidis exterior plains that occur a few kilometers farther north are slightly younger than the eroded and stratigraphically older terrain to the south. The model ages vary between ~3.6 and ~3.2 Ga (Fig. 11C) although we could not identify any systematic variations of ages with location of the count areas, i.e., when craters were counted on surface units close to the boundary to the etched terrain, near the cliffs of the Arabia contact or near the Deuteronilus contact farther north. As previously stated for the exhumed surfaces, resurfacing events including erosional processes as well as mass wasting and deposition of materials from adjacent mountain massifs onto the smooth Isidis exterior plains may result in significantly younger model ages of the plains as derived from crater counting (Fig. 11C; ~2.7 Ga).

Local patches of etched and eroded terrain that crop out within the smooth Isidis exterior plains are stratigraphically lower (~3.7 Ga). Although we could not derive model ages because of the relative small size of isolated highland remnants enclosed by the smooth Isidis exterior plains, they are interpreted to be older because they are associated with Noachian mountainous ridges of Libya Montes. The minimum age of the smooth Isidis exterior plains is defined by impact craters, which are superposed onto the plains and therefore postdate them. Crater counting on the ejecta materials of those craters show Late Hesperian and Early Amazonian model ages between ∼3.3 (Fig. 11D) and ∼2.7 Ga. Also the small valleys, which are incised into the plains, postdate the formation of the smooth Isidis exterior plains, indicating late-stage fluvial activity north of the mountainous terrains of the Libya Montes and after the latest emplacement of volcanic plains materials.

Farther north, the Isidis interior plains located north of the Deuteronilus contact are stratigraphically younger than the Isidis exterior plains. Crater size–frequency distribution measurements show

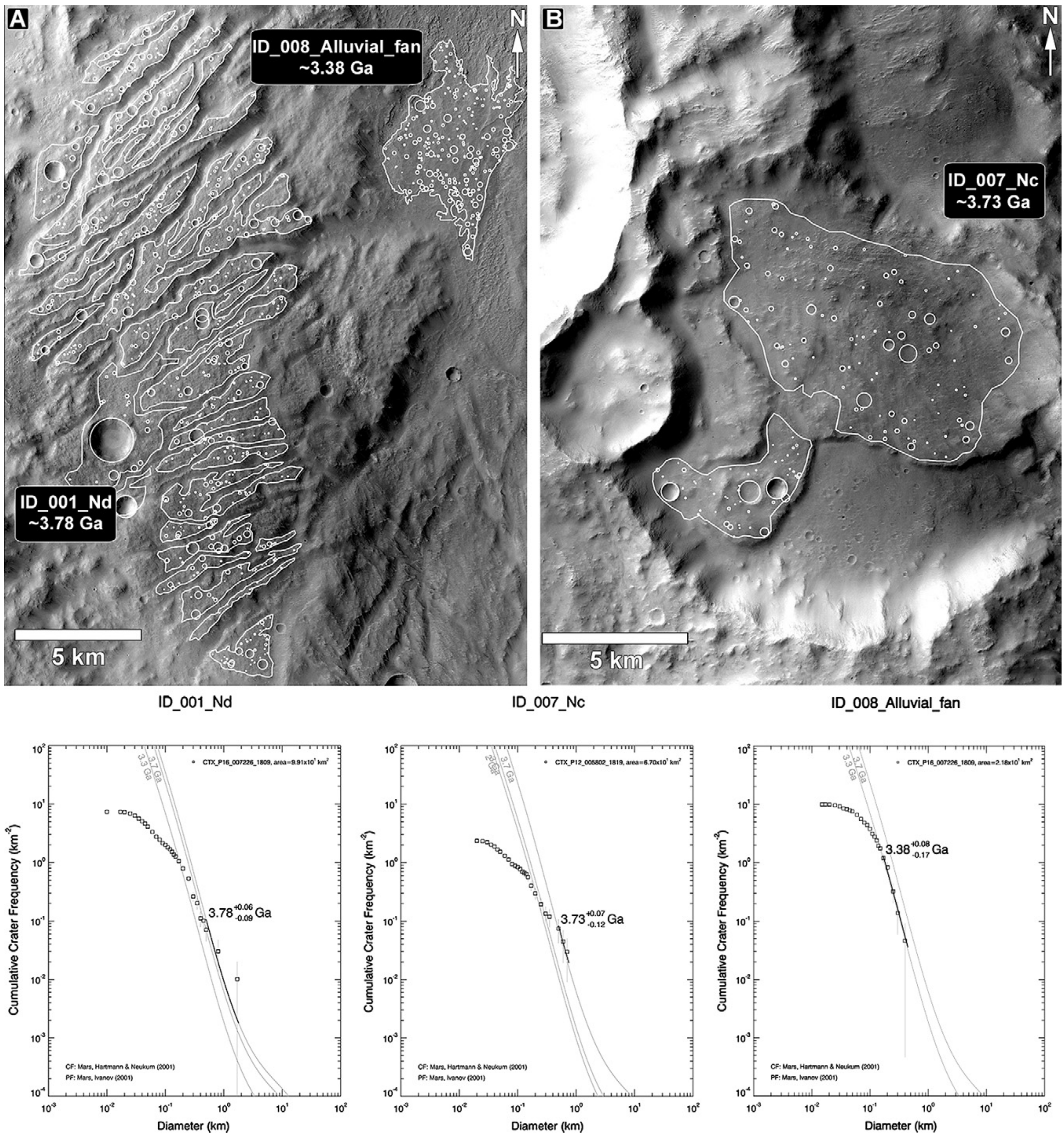

Fig. 11. Stratigraphic interpretation of fluvial morphologies near the Libya Montes/Isidis contact at −2500 m and associated crater statistics for selected surface units. Morphologic units are adopted from Greeley and Guest (1987) and Tanaka et al. (2005) (see Fig. 3). Craters counted and areas (morphologic units) outlined are shown in white color. The model ages shown in the statistics contain two decimal places and may not necessarily represent the model ages of units discussed in the manuscript. Patterns with secondary craters were excluded from counting. (A) Pattern of parallel valleys, which are incised into a remnant of a pre-existing layer that filled the 60-km crater. The valleys were formed ∼3.8 Ga ago. However, both the valleys and the alluvial fan deposits were likely to be formed earlier, because resurfacing events (valleys are exhumed and degraded) may have resulted in younger model ages. (B) The ejecta layer of a 19-km crater (Fig. 4A) was formed ∼3.7 Ga ago, but shows also resurfacing. The crater could have contributed to the removal of the initial valley unit. (C) The smooth Isidis exterior plains show model ages between ∼3.6 and ∼2.7 Ga (possible resurfacing). Patterns with secondary craters were excluded from the counting and led to the fragmentation of crater count areas. (D) Late Hesperian/Early Amazonian crater is superposed on the smooth Isidis exterior plains and was formed ∼3.3 Ga ago.

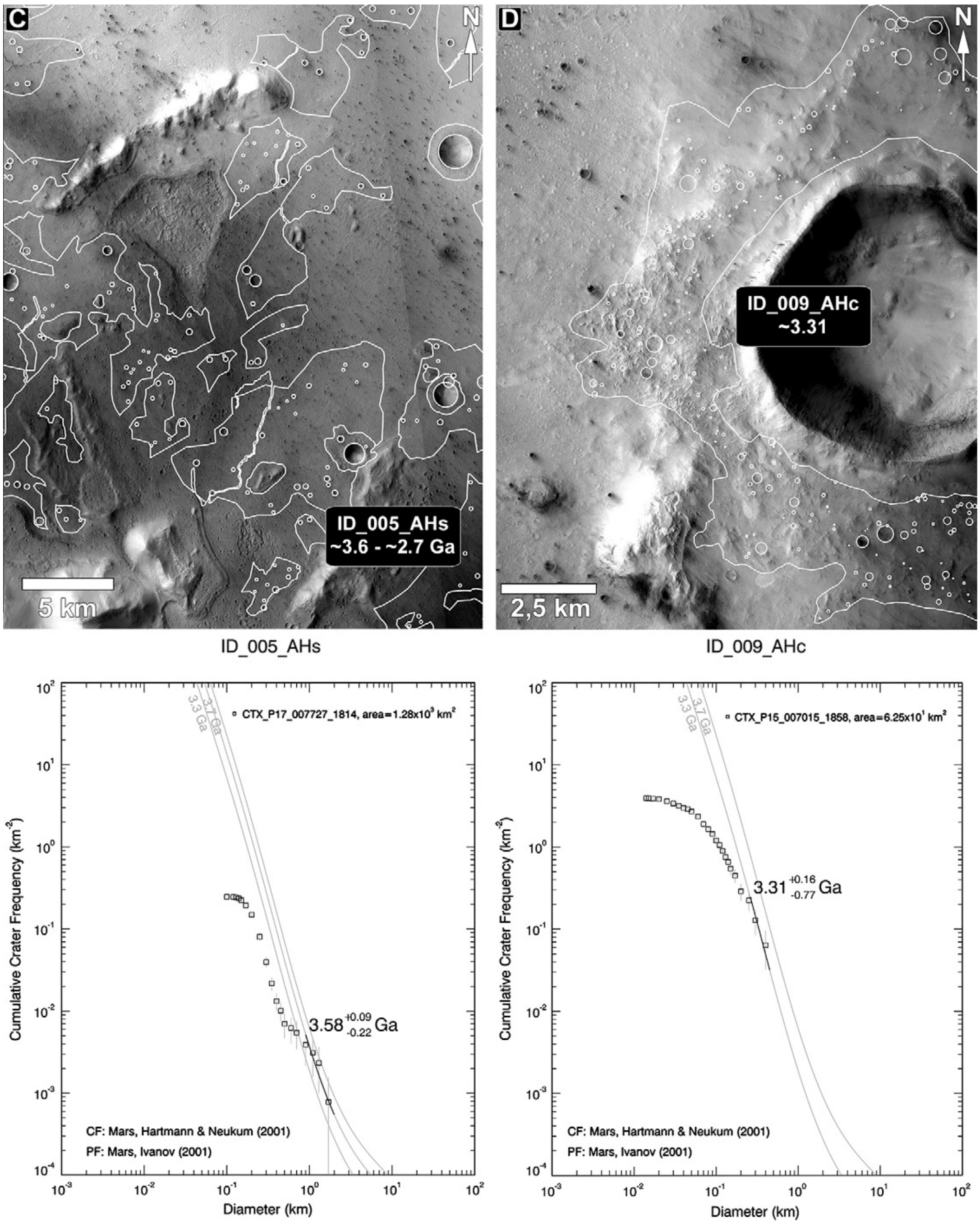

Fig. 11 (*continued*)

model ages between ~3.2 and ~2.7 Ga and are consistent with previous investigations that resulted in a model age of ~3.1 Ga (Ivanov et al., 2012a). The Isidis interior plains also postdate the formation of small valleys and ridges that originate in the southern Isidis exterior plains and cross the Deuteronilus contact. Several impact craters with preserved ejecta layers superposed onto the knobby Isidis interior plains show ages between ~2.8 and ~2.5 Ga and are interpreted to represent the youngest surface units in our study area. They also define the minimum age of the Isidis TPT.

6. Discussion

Hypotheses for the presence of standing bodies of water in the geological past of Mars have been proposed and tested by numerous investigators over the last two decades (e.g., Parker et al., 1989, 1993, 2010; Baker et al., 1991; Scott et al., 1995; Head et al., 1998, 1999; Cabrol and Grin, 1999, 2001; Clifford and Parker, 2001; Carr and Head, 2003; Webb, 2004; Ghatan and Zimbelman, 2006; Di Achille and Hynek, 2010; Mouginot et al., 2012). The past existence of standing water, i.e., of oceans or lakes has been proposed on the basis of various lines of morphological evidence. However, because morphologic features can form from a variety of processes, the existence of such standing bodies of water remains heavily debated. Strong arguments that support the ponding of water in the northern lowlands and in regional- to local-scale crater lakes are valley networks and outflow channels that terminate in those depressions and delta deposits (e.g., Baker et al., 1992; Carr, 1996; Fassett and Head, 2008a). Outflow channels likely contrib-

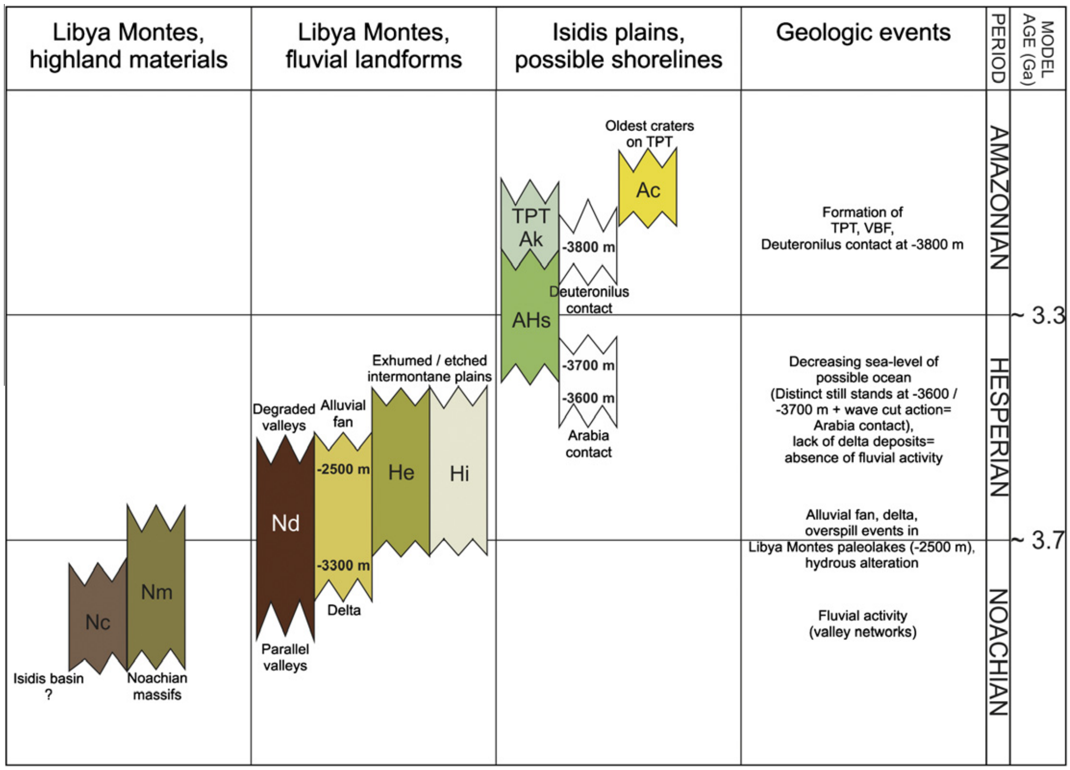

Fig. 12. Stratigraphy of the Libya Montes/Isidis Planitia boundary region. The stratigraphic table is subdivided into Libya Montes highland materials, Libya Montes fluvial landforms, Isidis plains and possible shorelines and geologic (column). The Noachian, Hesperian and Amazonian periods, as well as the model ages that define the boundaries between them are shown in rows. Morphologic units are adopted from Greeley and Guest (1987) and Tanaka et al. (2005).

uted substantially to a possible filling of the northern lowlands with water, because they drain predominantly into the northern lowlands, i.e., the channels of Chryse, Amazonis and Elysium (e.g., Baker et al., 1992; Ivanov and Head, 2001). There is a general consensus that the outflow channels were most likely formed by water (Baker et al., 1992; Carr, 1996; Tanaka, 1997; Nelson and Greeley, 1999; Leask et al., 2007; Harrison and Grimm, 2008), although other liquids or ice might also have been involved in their formation (e.g., Hoffman, 2000; Lucchitta, 2001; Leverington, 2004, 2009). However, morphologies associated with outflow channels bear evidence for a formation by significant amounts of water and deposition of sediments that were emplaced over a geologically short period of time (e.g., Tanaka, 1997).

The contribution of valley networks to the possible filling of the northern lowlands or crater lakes with water remains elusive. They are widespread on the surface of Mars and are interpreted to be formed by fluvial activity in the Noachian. Today they appear, together with large-scale outflow channels and the presence of hydrated minerals, as the strongest evidence for a wet ancient Mars (e.g., Baker et al., 1992; Carr, 1995; Carr and Chuang, 1997; Mangold et al., 2004; Erkeling et al., 2010). Although most authors prefer liquid water as the major valley network forming medium, uncertainties remain about how much water was necessary to form the valley networks (e.g., Jaumann et al., 2005; Hoke et al., 2011), because valley densities are significantly lower than those found in terrestrial drainage basins (e.g., Carr and Chuang, 1997; Mangold et al., 2004; Erkeling et al., 2010; Hynek et al., 2010). In addition, valleys are commonly degraded or filled, and deposits that can be associated with valley dimensions are very rare (Di Achille et al., 2009; Hoke et al., 2011). However, standing bodies of water should have formed considering the amount and density of valley networks identified on the surface of Mars, as an inevitable result of the amount of water available in the Noachian (e.g., Clifford and Parker, 2001).

In general, environmental and hydraulic conditions in the Noachian and Hesperian, including high quantities of water, high sediment volumes and repeated discharge events responsible both for the formation of outflow channels and dense valley networks are interpreted to support the existence of standing bodies of water, i.e., lakes, seas and oceans (Baker et al., 1992; Parker et al., 1993, 2010; Carr, 1995, 1996; Scott et al., 1995; Forsythe and Blackwelder, 1998; Cabrol and Grin, 1999, 2001; Clifford and Parker, 2001; Irwin et al., 2005; Di Achille and Hynek, 2010; Mouginot et al., 2012).

In addition to fluvial landforms like valley networks and outflow channels that might have resulted in the formation of standing bodies of water, geologic characteristics of the surfaces of the northern lowlands and possible paleolake sites bear evidence for ponding of water. To a large extent the plains of the northern lowlands show surface morphologies associated with the Vastitas Borealis Formation (VBF) (e.g., Tanaka and Scott, 1987; Hiesinger and Head, 2000; Head et al., 2002; Kreslavsky and Head, 2002; Tanaka et al., 2005). Significant parts of the VBF are interpreted as a sublimation residual from a frozen standing body of water that was formed in the (Late-) Hesperian and is possibly related to the formation of the outflow channels and their debouching into the northern lowlands (Head et al., 2002; Kreslavsky and Head, 2002; Carr and Head, 2003; Ivanov and Head, 2003). The most compelling argument is that estimates of material eroded by the outflow channels coincide with estimates of the volume of the VBF (Ivanov and Head, 2001; Kreslavsky and Head, 2002). Recently, the Mars Express radar (MARSIS), which was designed to probe the martian subsurface, has shown that the subsurface materials of the VBF consist of low-density sedimentary deposits with a low dielectric constant compared to typical volcanic materials, therefore providing strong evidence for a former Mars ocean (Mouginot et al., 2012). In addition, the similar formation time of the VBF, the location of the VBF near the termini of most of the outflow channels (e.g., Tanaka, 1997) and morphologies such as ridges, knobs and grooved and mottled facies, which are interpreted as results of freezing of outflow channel effluents and sublimation of a global-scale body of ice (e.g., Kreslavsky and Head, 2002) bear evidence for ponding in the northern lowlands. Knobby and coned plains of the TPT that occupy the floor of the Isidis basin show similar morphologies (Ivanov et al., 2012a). The TPT is likely to be formed at the same time (e.g., Crumpler and Tanaka, 2003; Erkeling et al., 2011a; Ivanov et al., 2012a) and by the same processes, i.e., glacio-lacustrine and periglacial processes (Grizzaffi and Schultz, 1989; Ivanov et al., 2012a,b), as significant parts of the VBF.

The extent, both of the VBF and the TPT, and their contacts to adjacent geologic units are the most important morphologic characteristics that led investigators to interpret the VBF as evidence for a standing body of water (Parker et al., 1989, 1993, 2010; Clifford and Parker, 2001; Carr and Head, 2003; Kreslavsky and Head, 2002). Both units show a well-defined morphologic contact that represents onlapping onto adjacent surface units (e.g., Crumpler and Tanaka, 2003; Komatsu et al., 2011; Ivanov et al., 2012a; this work, Fig. 10B). The contact appears almost continuous and was identified by Parker et al. (1989, 1993) as global "Contact 2", and redefined by Clifford and Parker (2001) as the Deuteronilus shoreline, which is one of two most continuous global putative paleoshorelines. Landforms recently identified at the Deuteronilus contact in southern Isidis, where valleys incised into the exterior plains of Isidis continue across the Deuteronilus contact and occur then as ridges, show similar morphologies to terrestrial subaqueous eskers and bear evidence for the existence of a standing body of water that filled the Isidis basin, subsequently froze and sublimed (Erkeling et al., 2012). Additional support for a former body of standing water is given by the fact that the Deuteronilus shoreline approximates an equipotential line surface line, potentially indicating past sea levels, and shows only slight differences in elevation (e.g., Hiesinger and Head, 1999; Head et al., 1999; Carr and Head, 2003; Webb, 2004), although there is agreement that other morphologies not associated with a shoreline, for example debris flows, also result in morphologies that follow equipotential surfaces (e.g., Carr and Head, 2003; Kreslavsky and Head, 2002; Ghatan and Zimbelman, 2006). If the Deuteronilus contact is indeed the result of subsequent sublimation of a frozen ocean, it was influenced by only minor isostatic movement (Parker et al., 1989, 1993; Head et al., 1999; Carr and Head, 2003; Leverington and Ghent, 2004).

However, different interpretations for the evolution of the VBF exist (Hiesinger and Head, 2000; Kreslavsky and Head, 2002), in particular for morphologies and processes that possibly build the TPT, including pseudocraters (Frey and Jarosewich, 1982), pyroclastic flows (Ghent et al., 2012), tuff cones (e.g., Bridges et al., 2003), cinder cones (e.g., Plescia, 1980), phreatomagmatic rootless cones (Fagents et al., 2002; Bruno et al., 2004) and mud volcanoes (e.g., Davis and Tanaka, 1995; McGowan, 2011). Additionally, the morphologies of the VBF, in particular the absence of light-toned layered deposits are difficult to reconcile with the assumption that the VBF consists of depositional effluents of an ocean (McEwen et al., 2007). Also the distribution of boulders in the VBF might exclude the formation by flowing water (McEwen et al., 2007), although their occurrence on the surface of the VBF can be explained by clustering and size-sorting processes (Orloff et al., 2011). However, Mars Express radar data indicate that if any remnants of a possible standing body of water that filled the northern lowlands still survive, they should exist in the deep subsurface (Mouginot et al., 2012) and the almost complete absence of altered surface materials (e.g., Poulet et al., 2007; Carter et al., 2010; Salvatore et al., 2010) may not represent a restriction on the existence of a former ocean.

In general, uncertainties remain about possible coastal landforms as evidence for an ocean, including different interpretations for the same morphologies associated with the Deuteronilus contact (e.g., Parker et al., 1993; Clifford and Parker, 2001; Carr and Head, 2003; Webb, 2004; Ghatan and Zimbelman, 2006; Erkeling et al., 2012). Further arguments against the ocean scenario are the occurrence of the VBF near ridged plains (e.g., Greeley and Guest, 1987; Kreslavsky and Head, 2002), which are generally considered as volcanic in origin (e.g., Head et al., 2002) and multiple occurrences of ridges and escarpments parallel to the contact (Kreslavsky and Head, 2002; Carr and Head, 2003; Ghatan and Zimbelman, 2006).

In addition, the nature and origin of the longest global paleoshoreline, the Arabia shoreline (Parker et al., 1989, 1993; Clifford and Parker, 2001), labeled as "Contact 1" by Parker et al. (1989, 1993), remain unresolved. Although some morphologies of the Arabia shoreline appear to be very similar to terrestrial coastal landforms (e.g., Bradley and Griggs, 1976; McKenna et al., 1992; Adams and Wesnousky, 1998), numerous alternative interpretations cannot be excluded. Ghatan and Zimbelman (2006) concluded that most of the morphologic landforms identified near both the Arabia and the Deuteronilus shorelines can be dismissed as wrinkle ridges, lobate flow fronts and margins of lava flows formed by volcanic processes (e.g., Schultz, 2000), remnants of impact craters, inverted channels and tectonic and eolian constructs. In addition, the morphologies associated with the Arabia shoreline do not appear at constant elevations as demonstrated for the Deuteronilus contact (Hiesinger and Head, 1999; Head et al., 1999; Carr and Head, 2003) although local lateral modifications by isostatic readjustment and deformation by crustal movement associated with true polar wander are possible (e.g., Tanaka et al., 2000; Leverington and Ghent, 2004; McGowan and McGill, 2006). Although terrestrial shorelines are younger than the cliffs identified on Mars, they show significant variations in elevation and are displaced as a result of isostatic rebound, for example the cliffs of Lake Bonneville (Currey, 1980). However, the Deuteronilus contact does not follow an equipotential surface and appears ~200 m higher in the northeastern part of the Isidis basin (the Arabia shoreline is absent), although this can be explained by the Syrtis-related tilt of the Isidis basin (e.g., Tanaka et al., 2000; McGowan and McGill, 2006), which is interpreted to have occurred later than the formation of the Arabia contact and earlier than the formation of the Deuteronilus contact.

Taken together the landforms identified in our study area at the Libya Montes/Isidis boundary are difficult to explain by volcanic, eolian and mass wasting processes. The landforms are similar to those interpreted by Ghatan and Zimbelman (2006) as having most likely formed by standing water and wave cut action. We interpret the morphologies identified in our study area as reasonable candidate coastal landforms indicative of Noachian Libya Montes lacustrine environments (−2800 m), Late Noachian and Early Hesperian standing bodies of water with wave-cut action intense enough to form coastal cliffs as the result of distinct still stands (−3600/−3700 m) and, a Late-Hesperian short lived stationary ice sheet that sublimed and resulted in a depositional residue (−3800 m). The morphologies identified are not necessarily the results of a standing body of water that was part of the proposed northern ocean, but there is evidence such as the depositional residues in the center of the Isidis basin (Ivanov et al., 2012a; Mouginot et al., 2012) for a sea-scale standing body of water that might have filled the Isidis basin (Isidis sea) and also for local ponding in km-sized crater basins in the Libya Montes.

Based on our morphologic, mineralogic and stratigraphic results, we have produced a stratigraphic correlation chart (Fig. 12) and we propose the following scenarios for possible contacts identified in our study area at the southern Isidis basin rim between −2500 and −2800 m (Libya/Isidis contact), at −3600/−3700 m (Arabia contact) and at −3800 m (Deuteronilus contact), which are possibly associated with fluvial activity and standing bodies of water, i.e., lakes and a putative Isidis sea.

6.1. Geologic history of the Libya Montes/Isidis contact (−2500/−2800m)

The morphologies found in the 60-km crater suggest repeated fluvio-lacustrine activity in the Noachian and Early Hesperian. Noachian fluvial activity resulted in the formation of fluvial valleys that were incised into large parts of the 60-km crater. The pattern of parallel valleys in the western section of the crater (Fig. 5A and F) possibly represents a remnant of a pre-existing valley unit that has covered parts of the crater interior. Fluvial activity likely led to local-scale ponding of water in the crater as suggested in craters elsewhere on Mars (Cabrol and Grin, 1999, 2001; Irwin et al., 2005; Fassett and Head, 2008a; Hauber et al., 2009). The valleys terminate along a cliff at −2800 m, which possibly represents an erosional landform that was the result of an initial standing body of water that filled the 60-km crater. In the Noachian, erosional processes driven by fluvial activity led to the removal of the initial valley unit from the southern and eastern parts of the crater. Also the cliff at −2800 m was eroded except at the termini of the parallel valleys. Intense fluvial activity increased the water level in the crater to −2800 m and resulted in the formation of the lower terrace that shows degraded valley morphologies, which in some cases are completely eroded. The lower terrace became flooded after the water level increased above −2800 m. The continuation of the valley paths from the upper to the lower terrace (Fig. 5F) indicates that the parallel valleys existed already before the formation of the lower terrace. Eolian processes were involved in the modification of materials in the crater but are unlikely to be responsible for the formation of the cliffs that show heights of tens of meters. The upper terrace, which possibly represents the only remnant of the pre-existing valley unit, is located above −2500 m and was unlikely flooded by a standing body of water. However, intra-crater deposits located in the eastern parts of the 60-km crater appear at −2450 m and bear evidence for a paleolake in a 3-km crater that also shows an inlet and an outlet (Fig. 5A and E) and is similar to open basin paleolakes found elsewhere on Mars (e.g., Cabrol and Grin, 2001; Fassett and Head, 2008a). The crater is likely associated with a degraded valley, which is cut into crater materials and that was formed later than the parallel valleys.

The possible ponding of water in the Libya Montes up to −2500 m likely resulted in multiple overspill events and in the formation of a breach in the northern crater rim of the 60-km crater. After the formation of the breach between the Late Noachian and Early Hesperian, the 60-km crater was no longer filled by a standing body of water. However, fluvial activity continued from the Late Noachian to the Early Hesperian and resulted in transport of materials from the high-standing Libya Montes to the low lying plains of the Isidis basin as seen elsewhere at the southern Isidis basin rim (Crumpler and Tanaka, 2003; Erkeling et al., 2010; Jaumann et al., 2010; Ivanov et al., 2012a).

In most cases, fluvial landforms pre-date exhumed and etched olivine-rich surface units identified on the floor of the 60-km crater. The olivine-rich surfaces are associated either with the impact event that formed the Isidis basin in the Noachian and subsequent transport and deposition (e.g., Mustard et al., 2007) or with the volcanic flooding of the Isidis basin in the Hesperian (e.g., Tornabene et al., 2008). Local volcanic sources are unlikely and were not identified in the Libya Montes (e.g., Crumpler and Tanaka, 2003; Tornabene et al., 2008; Ivanov et al., 2012a; this work, Fig. 2) except in the western Libya Montes near the boundary to Syrtis Major (Jaumann et al., 2010; Ivanov et al., 2012a). Although some olivine-rich surfaces occur at higher elevations than the lavas from Syrtis Major could have reached, we identified olivine-rich materials only in low-lying areas and not in the Libya Montes mountainous terrains, which were formed as a result of the Isidis impact. Our Early Hesperian model ages for olivine-rich plains support both the early impact melt formation (Mustard et al., 2007) and subsequent erosion and transport as well as a Syrtis-related post impact formation proposed for example by Tornabene et al. (2008).

Materials were also transported and deposited into a 4-km basin immediately north of the 60-km crater, where layered clay minerals and distributary channels of a delta indicate local, but also fluvial activity and possible standing water. The presence of Al-phyllosilicates in the fan instead of Fe/Mg-smectites is nevertheless in favor of authigenic formation processes (Story et al., 2010).

Late Noachian fluvial activity in the areas around the Isidis basin could have resulted also in the collection and accumulation of water within the basin and in the formation of an Isidis sea, similar to the proposed primordial ocean that filled the northern lowlands in the Noachian and the Hesperian (e.g., Parker et al., 1993, 2010; Clifford and Parker, 2001; Di Achille and Hynek, 2010). Although the highstand of a possible primordial ocean has been postulated at −2500 m (Di Achille and Hynek, 2010), the landforms identified in the 60-km crater suggest local standing water and are unlikely the result of a possible Late Noachian Isidis sea as possible cliffs and terraces appear locally in our study area and in only few places elsewhere in the Libya Montes.

No matter whether lacustrine or sea-size standing bodies of water were involved in the formation of the cliffs and terraces we identified in the 60-km crater, fluvial activity ceased around the Noachian/Hesperian boundary and resulted in multiple, steep sloped alluvial fan deposits, which unlikely formed in standing water. The alluvial fan is spatially limited only to the 60-km crater and is indication for decreased water availability and material transport. The alluvial fan is located at the termini of Early Hesperian valleys that either cut through the Noachian pattern of parallel valleys or re-incise the paths of the parallel valleys (Fig. 5A, C, and E). Moreover, the orientation of the alluvial fan perpendicular to the parallel valleys indicates that these valleys are not the source of material constituting the alluvial fan (Fig. 5A). The most plausible source region is located somewhere upstream of a Hesperian valley that is cut into the southern parts of the pattern of parallel valleys. However, fluvial activity responsible for the formation of the alluvial fan was likely active several times (Fig. 5D), but spatially limited and not intense enough to produce long-term standing bodies of water. In addition, as fluvial activity in the Hesperian was decreasing, olivine-rich surface units were only selectively removed and the olivine was possibly altered only locally (Tornabene et al., 2008). Therefore, Early Hesperian fluvial activity most likely represents the late stage end of valley formation and deposition in the mountainous terrains of the Libya Montes.

6.2. Geologic history of the Arabia contact (−3600/−3700 m)

A series of possible coastal cliffs of the Arabia shoreline were identified immediately north of the steep highland remnants of the Libya Montes. The smooth exterior plains of Isidis Planitia were formed significantly later than the fluvial and lacustrine morphologies between −2500 and −2800 m. The landforms associated with the Arabia shoreline located at −3600/−3700 m show model ages between ∼3.5 and ∼3.2 Ga and morphologic characteristics comparable to terrestrial coastal erosional landforms (e.g., Bradley and Griggs, 1976; Adams and Wesnousky, 1998; Ghatan and Zimbelman, 2006). Therefore, we interpret these landforms at −3600 and −3700 m as the results of distinct still stands and wave erosion of a putative Isidis sea that possibly existed in the Hesperian. The cliff morphologies possibly resemble terrestrial sea cliffs eroded by wave-cut action and were formed during sea level variations of the Isidis sea, in particular during the retreat of the Isidis sea as a result of decreasing water availability and reduced fluvial activity. The possible coastal cliffs at −3600 m are slightly older than the cliffs ~100 m below, although our model ages do not show significant differences.

The cliffs are not continuous along the Isidis basin rim and occur only along the Libya Montes that form the southern Isidis basin rim. Cliff morphologies similar to those identified in our study area and elsewhere at the Libya Montes/Isidis Planitia boundary are absent along the western basin rim, where cliff morphologies were possibly superposed by Syrtis Major lavas (Ivanov and Head, 2003). Cliffs are also absent along the northeastern rim, where the barrier toward Utopia Planitia was eroded. Similar cliff morphologies occur only discontinuously at the edges of the southwestern Amenthes trough near the eastern basin rim. These findings are consistent with the mapped occurrence of possible shoreline morphologies near Amenthes (e.g., Fig. 6 in Clifford and Parker (2001); Fig. 4 in Carr and Head (2003); Fig. 4d in Ghatan and Zimbelman (2006)), although some sections of the shorelines are based on interpolations.

In addition, uncertainties remain about the source of the water that possibly filled the Isidis basin. Valleys formed by fluvial activity that cross the boundary between the Libya Montes and the Isidis basin and associated deposits do not exist in our study area and along the Isidis basin rim complex (Crumpler and Tanaka, 2003; Erkeling et al., 2010; Jaumann et al., 2010). The majority of Noachian valleys and associated deposits that drained into the Isidis basin were likely superposed by the lavas that filled the Isidis basin in the Hesperian including lavas invading from Syrtis Major (Head et al., 2002; Mustard et al., 2007; Tornabene et al., 2008) and Amenthes Planum (Tornabene et al., 2008; Erkeling et al., 2011a). The lack of valleys incised into the possible cliffs and also the lack of associated deposits indicates that fluvial activity had ceased before the formation of the Arabia shoreline. Therefore, the source for standing bodies of water that filled the Isidis basin and that resulted in the formation of the coastal cliffs of the Arabia shoreline was likely active in the Hesperian. While possible Noachian standing bodies of water that filled the Isidis basin were the result of intense fluvial activity and drainage through dense and complex valley networks (e.g., Carr and Chuang, 1997; Mangold et al., 2004; Erkeling et al., 2010; Hynek et al., 2010), Hesperian standing bodies of water were likely the result of repeated catastrophic water release events that resulted in the formation of the outflow channels (Baker et al., 1992; Carr, 1996; Tanaka, 1997; Nelson and Greeley, 1999; Leask et al., 2007; Harrison and Grimm, 2008). A possible Isidis sea that might have existed in the Hesperian could have been the result of similar fluvial events and processes that formed the outflow channels elsewhere on Mars. However, the majority of outflow channels on Mars only drained into the northern lowlands. Although the Isidis basin is possibly connected via gaps at −3500 m at its northeastern basin rim with the Utopia basin (Carr and Head, 2003; Ivanov et al., 2012a), it remains unclear if the water level of a putative northern ocean reached the −3500 height and has spilled over the barrier. Carr and Head (2003) concluded that the divide between the basins does not show any morphologic evidence for water flowing from one basin into the other.

In addition, outflow channels that drain into the Isidis basin were not identified except the Palos crater outflow channel, which is located hundreds of kilometers farther east in Amenthes Planum (Erkeling et al., 2011a) and has much smaller dimensions than outflow channels elsewhere on Mars. Although the Palos crater outflow channel postdates the volcanic flooding of Amenthes Planum and the Isidis basin and was formed in the Hesperian at the same time as the cliffs of the Arabia shoreline, the morphologies suggest that the water and materials transported by the Palos crater outflow channel terminate on the smooth plains of Amenthes Planum and did not drain into the Isidis basin (Erkeling et al., 2011a).

Therefore, based on uncertainties about the sources for the water, alternative interpretations for the formation of the cliffs of the Arabia shoreline need to be considered. Some authors argued that volcanic processes and flowing lava could result in morphologies similar to those formed by standing water (e.g., Ivanov and Head, 2003; Ghatan and Zimbelman, 2006). Most of the candidate coastal landforms discussed in previous studies, such as cliffs and ridges, are interpreted as wrinkle ridges, eolian landforms, remnants of crater rims, scarps or lobate flow fronts (e.g., Webb, 2004; Ghatan and Zimbelman, 2006). However, this is unlikely for the morphologies and dimensions of the cliffs, terraces and platforms in our study area, especially when compared with analogous terrestrial oceanic coastal cliffs (e.g., Bradley and Griggs, 1976; Adams and Wesnousky, 1998). In particular, the ridges and cliffs interpreted by Ghatan and Zimbelman (2006, Figs. 15e and 17b) as reasonable candidates for coastal landforms are similar to landforms identified in our study area.

Surfaces of intermontane plains, etched terrains and the Isidis exterior plains located a few kilometers north of the Libya Montes mountainous terrain and south of the possible coastal cliffs show high olivine abundances, which likely could not persist in long-term contact with flowing or standing water. If these plains are indeed lavas, they likely filled the Isidis basin in the Early Hesperian (Head et al., 2002; Tanaka et al., 2002; Mustard et al., 2007) and therefore later than the proposed intense Noachian fluvial activity, which should have resulted in alteration. However, we interpret the olivine-rich plains as results of the erosion of early impact melts and following deposition as intermontane plains, although the transport by fluvial processes was possibly too short to result in alteration of the olivine. The olivine-rich lavas were subsequently superposed by younger olivine-poor lavas (e.g., Tornabene et al., 2008) that represent the majority of the Isidis exterior plains. Therefore, they do not exclude the existence of a standing body of water that filled the Isidis basin. Possible hydrated minerals deposited in the Isidis basin are likely obscured by younger mafic minerals similar to those found in the plains of the northern lowlands (Poulet et al., 2007; Salvatore et al., 2010). However, even standing bodies of water, such as a proposed cold glacial ocean (Fairén et al., 2011), did not necessarily result in the alteration of olivine-rich lavas to clay minerals such as the Fe/Mg-phyllosilicates identified in our study area. Although the model results of Fairén et al. (2011) are expected for the Noachian period and standing bodies of water that appeared poleward 30°N, the scenario of a cold ocean that would preclude the alteration of olivine-rich lavas to clays, is even more likely in the Hesperian, when environmental conditions supported only short-lived and rapidly freezing standing bodies of water as for example proposed by Kreslavsky and Head (2002), even near the equator as in the case of the Isidis basin.

Olivine-rich surface units in our study area and elsewhere in the Libya Montes are considered to be related either to old Isidis impact melt deposits or to Syrtis Major because of their proximity to the volcanic province and similarities in their morphology to Syrtis lavas (Mustard et al., 2007). However, some of the olivine-rich units appear at topographically higher terrain of the Libya Montes, difficult to be reached by lavas from Syrtis Major or Hesperian Planum (Tornabene et al., 2008). Therefore, in our study area, olivine-rich surfaces occur at higher elevations than the proposed Isidis sea could have reached. Although a possible sea that filled the Isidis basin led to alteration of olivine-rich lavas, occurrences of olivine north of the Arabia shoreline and at lower elevations can be explained by eolian activity. Channeled winds from the Libya Montes valleys (Christensen et al., 2005; Tornabene et al., 2008) likely eroded plains materials and were responsible for excavation of the underlying olivine-rich materials and the formation of the etched terrains. The continuation of winds from the Libya Montes until today resulted in the redistribution of olivine-rich materials from topographically higher terrain to the low-lying Isidis exterior plains, long after a putative standing body of water ceased to exist.

6.3. Geologic history of the Deuteronilus contact (−3800 m)

Farther north, the landforms associated with the Deuteronilus contact are explained by numerous authors as the result of standing water that filled the northern lowlands of Mars and readily froze during the proposed Hesperian environmental change (e.g., Kreslavsky and Head, 2002; Webb, 2004; Ghatan and Zimbelman, 2006). Based on comparable morphologies identified at the VBF (e.g., Kreslavsky and Head, 2002), the Deuteronilus contact at the boundary between the Isidis exterior and the Isidis interior plains, which also contain the TPT, may represent the maximum extent of a standing body of water or a stationary ice sheet. Therefore, depositional landforms, including onlap morphologies identified in our study area could represent the margin of a hypothesized Isidis sea. The onlap might also indicate the absence of wave erosion and supports that liquid standing water was short-lived and did not result in coastal erosional landforms. Further support comes from our model ages of the Isidis interior plains, which show that the Deuteronilus contact in our study area was formed in the Late Hesperian and is unlikely the result of Early Hesperian standing water that resulted in the formation of the Arabia shoreline. Based on the proposed martian climate change in the Hesperian toward cold conditions and limited availability of liquid water on the surface (e.g., Bibring et al., 2006; Ehlmann et al., 2011), the Late Hesperian Isidis sea likely represented a late phase of standing water on the surface of Mars that existed only for a geologically short timespan (Kreslavsky and Head, 2002; Carr and Head, 2003).

However, alternative interpretations exist for the formation of the Deuteronilus contact and for the origin of the VBF (e.g., Ghatan and Zimbelman, 2006). Those authors interpreted both landforms as results of volcanic processes. In particular, the evolution of the TPT is possibly related to the existence of mud volcanoes (e.g., Davis and Tanaka, 1995; Komatsu et al., 2011) or the mobilization of pyroclastic surge deposits (Ghent et al., 2012), which both could have resulted in the formation of the Isidis interior plains and the TPT, respectively.

The identification of mafic minerals in the northern plains also supports a volcanic origin (Poulet et al., 2007; Salvatore et al., 2010), at least for significant areas of the stratigraphically younger deposits that likely obscure possible hydrated minerals as recently revealed by the Mars Express radar data (Mouginot et al., 2012). Detections of phyllosilicates in the northern lowlands are rare and associated with crater peaks and crater ejecta materials corresponding to Noachian crustal rocks (Carter et al., 2010). These findings are likely consistent with investigations of crater ejecta materials in the southern Isidis basin (Tornabene et al., 2008). In the case of volcanic flooding of the Isidis basin, the Deuteronilus contact, whose landforms are comparable to lobate flow fronts (e.g., Ivanov and Head, 2003), would represent the maximum extent of lavas that originated in the center of the basin, where coned landforms occur frequently. As sources for Late Hesperian volcanic activity are numerous around Isidis, including the volcanic province of Syrtis Major and Amenthes Planum, they could have also contributed to the formation of the Deuteronilus contact. However, the surfaces of the Isidis interior plains are spatially not connected with volcanic plains of Syrtis Major or Amenthes Planum.

Also the lack of Hesperian aqueous sources that could result in standing water in the Isidis basin is difficult to reconcile with the interpretation of the formation of the Deuteronilus contact as the result of an Isidis sea. Although most of the outflow channels were formed in the Hesperian (e.g., Baker et al., 1992; Carr, 1996; Tanaka, 1997; Nelson and Greeley, 1999; Ivanov and Head, 2001; Leask et al., 2007), a significantly smaller number of possible aqueous sources existed during formation of the Deuteronilus contact compared to the Early Hesperian. The water that formed the outflow channels probably did not reach −3500 m and did not overspill the northeastern Isidis rim as it might happened during formation of the Arabia shoreline (Carr and Head, 2003). Sources other than the northern ocean are uncertain (Erkeling et al., 2011a) and possibly could not provide the amount of water to fill the Isidis basin. In summary, our observations and results, including the Late Hesperian model ages and the onlap morphologies, are consistent with the assumption that the Deuteronilus contact in the Isidis basin represents a shoreline of the proposed Isidis sea, but do not necessarily prove its existence.

7. Conclusions

Based on the morphology, stratigraphy and mineralogy, we propose that Noachian long-term aqueous activity resulted in the erosion of the Libya Montes cratered terrains and in the formation of fluvial morphologies in a 60-km crater, including valley networks and associated deposits. Intense fluvial activity resulted in a lake-size standing body of water in the 60-km crater with a maximum highstand between −2500 and −2800 m. Delta deposits and associated phyllosilicates bear evidence for discharge into a paleolake and indicate transportation and alteration of minerals by liquid water.

A series of cliffs at −3600 and −3700 m possibly indicate two distinct still stands and wave-cut action of a Hesperian paleosea in the Isidis basin, which was, at least temporarily, connected with the northern lowlands via the eroded northeastern basin rim. The cliffs and terraces are difficult to explain by alternative volcanic or mass wasting processes and are reasonable candidates for coastal erosional landforms similar to those identified on Earth. However, fluvial morphologies and deposits are absent and indicate that the valleys of the Libya Montes were probably not the source of the water in the putative Isidis sea. In addition, the lack of fluvial landforms that cross cut the Arabia shoreline indicates that fluvial activity had ceased during formation of the possible coastal cliffs. In conclusion, the lack of possible sources for the water that could have filled the Isidis basin as well as the occurrence of the Arabia landforms at different elevations and the absence of possible coastal cliffs elsewhere in the Isidis basin raise considerable doubts about the existence of an Isidis sea. However, the cliffs of the Arabia shoreline bear striking evidence for ponding of water in the Isidis basin long enough to erode the shoreline, although the valleys of the Libya Montes were unlikely the source for the water and that the fill must have come from somewhere else.

The onlap morphologies of the Deuteronilus contact at about −3800 m were formed between the Late Hesperian and Early Amazonian and might be explained by an Isidis sea, although they do not prove its existence. Outflow events might have led to the formation of a proposed ocean that froze under cold and dry environmental conditions, which were similar to those on recent Mars. The Deuteronilus contact therefore could represent the margin of a hypothesized Isidis sea that readily froze and sublimed. Although small valleys trend toward the Deuteronilus contact it is unlikely that they provided the amount of water to form depositional effluents similar to the extent of the Isidis interior plains.

However, the geologic setting and chronostratigraphic sequence, that indicates Late Noachian landforms at the Libya/Isidis contact, Hesperian landforms at the Arabia shoreline and Early Amazonian landforms at the Deuteronilus contact, are consistent with the proposed Hesperian climate change from warm and wet to cold and dry conditions. Therefore, we propose this site as a new candidate landing site for potential future missions after MSL Curiosity (Erkeling et al., 2011b). As our study area provides significant insights into the water-related geologic record of the Libya Montes/Isidis boundary it will help to reconstruct the climatic evolution of Mars, in particular the proposed climate change at the Noachian/Hesperian boundary. In addition, our proposed candidate landing site ellipses on the smooth plains of the 60-km crater near the alluvial fan deposits and on the smooth Isidis exterior plains near the cliffs of the Arabia shoreline allow morphologic and mineralogic in situ investigations directly at the landing site.

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