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Evidence for paleolakes in Erythraea Fossa, Mars: Implications for an ancient hydrological cycle

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ABSTRACT

There is now widespread agreement that the surface of Mars underwent some degree of fluvial modification, but there is not yet full understanding of its surface hydrological cycle and the nature of standing bodies of water, rivers, and precipitation that affected its surface. In this paper we explore Erythraea Fossa (31.5 W, 27.3 S), a graben adjacent to Holden crater, which exhibits strong evidence that it once housed a chain of three lakes, had overland water flow, and was subject to precipitation. The inlet valley, outlet valley, and fan morphologies in the paleolakes are used to qualitatively discern the hydrologic history of the paleolakes; based on topography constraints, the three basins combined once held 56 km^3 of water. Depositional features within the basins that change with drainage area and nearby valleys that start near drainage divides indicate that the paleolakes may have been fed by precipitation driven runoff. This suggests the presence of an atmosphere, at least locally, that was capable of supporting a hydrological cycle.

1. Introduction

The characteristics of geologic features formed by the action of surface water on early Mars are important to help understand the martian climate near the Noachian–Hesperian boundary. Fundamental questions, such as whether the early martian climate was cold or warm, wet or dry, remain unresolved (see for discussion: Craddock and Howard, 2002; Gaidos and Marion, 2003; Moore et al., 2003; Burr et al., 2009; Hynek et al., 2010). An assortment of evidence for past widespread fluvial activity on Mars has been found. Studies conducted on the sedimentary rock record of Mars suggest lacustrine activity and subaqueous sediment transport (Malin and Edgett, 2000; Grotzinger et al., 2005). The morphology of martian valley networks suggests that they were formed by fluvial activity (Carr, 1995; Malin and Carr, 1999; Hynek and Phillips, 2003). It has also been posited that hundreds of craters and other depressions were ancient lakes during the period when the valley networks were formed (Cabrol and Grin, 1999; Fassett and Head, 2008a, 2008b). Additionally, hydrated minerals found in valley network-related sedimentary deposits support the hypothesis of fluvial sediment transport and surface water (Ehlmann et al., 2008).

Paleolakes are a particularly important marker of water on Mars. Strong evidence for paleolakes first arose in the analysis of Viking data (e.g. Goldspiel and Squyres, 1991) and, more recently, catalogues of hundreds of potential paleolakes on Mars have been compiled by Cabrol and Grin (1999) and Fassett and Head (2008b). In this paper, we describe in detail a newly identified chain of paleolokes in Erythraea Fossa (31.5 W, 27.3 S). We also delineate evidence for precipitation and multiple phases of fluvial activity at this location.

Candidate paleolake sites are commonly found in depressions that have *inlet valleys* which postdate the depression, particularly in craters (Howard et al., 2005; Irwin et al., 2005b). In some instances *outlet valleys* are also apparent (e.g. Fassett and Head, 2008b). An inlet valley leads into the depression from a higher elevation and an outlet valley leads from the rim of the depression to areas of lower elevation. When both an inlet and an outlet valley are observed, the features are referred to as (hydrologically) *open* (e.g. Fassett and Head, 2008b). Water traveling through the inlet valley would necessarily need to fill the entire depression before breaching the impoundment and forming the outlet valley. Depressions that have only inlet valleys are known as *closed* basins, since the absence of an outlet valley does not require the basin to have filled with water (Forsythe and Zimbelman, 1995; Forsythe and Blackwelder, 1998). Since open basins have constraints on water surface elevation (i.e. inlet *and* outlet valley elevations), these features exhibit strong evidence that they once were lakes, even though closed basin lakes and even lakes regulated solely by groundwater levels are also possible. Erythraea Fossa has several inlet valleys, as well as an outlet valley, and is therefore referred to as an Open Basin Paleolake (OBP).

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The main phase of global OBP development and associated valley network and fan deposit formation is constrained to end in the late Noachian or Early Hesperian (Irwin et al., 2005b; Fassett and Head, 2008a). OBPs are often found in chains, where the outlet valley of one OBP becomes the inlet valley of another (Cabrol and Grin, 1999; Irwin et al., 2005b; Fassett and Head, 2008b), and they sometimes integrate into extensive valley systems that debouche into large basins. OBPs sometimes, but not always, contain morphological features, such as sedimentary fans (Fassett and Head, 2005; Wilson et al., 2007; Burr et al., 2009), which have been interpreted to be deltas similar to those found in lacustrine environments on Earth (e.g. Malin and Edgett, 2003; Moore et al., 2003; Bhattacharya et al., 2005; Wood, 2006).

In this paper, we report on evidence for OBPs and associated hydrologic activity in Erythraea Fossa. First we use topographic and image data to show evidence for three OBPs, some with well-preserved intra-basin fans. We also make the case for interconnecting fluvial valleys that, in cases, are sinuous and show preserved inner channels. Measurements based on data from the Mars Orbiter Laser Altimeter (MOLA) are used to show that the Erythraea Fossa OBPs had a storage capacity for water on the order of tens of cubic kilometers. We then present evidence that the OBP system in Erythraea Fossa was fed by precipitation (rain, snow, or direct condensation) and runoff for at least part of its existence, and evidence that the OBP system probably experienced variations in hydrological conditions. Last, we discuss the implications for the climate and hydrology in the surrounding region, including the Uzboi–Ladon–Margaritifer system (Grant, 2000; Grant and Parker, 2002) and Holden crater (Pondrelli et al., 2005; Grant et al., 2008).

2. Methods

Orbital missions to Mars in the past decade have supplied us with detailed information on the topography and morphology of the martian surface. For topographic information, we make use of Mars Orbiter Laser Altimeter (MOLA) 1/128 pixel per degree gridded data (463 m/px) (on board Mars Global Surveyor, see Smith et al., 1999), and High-Resolution Stereo Camera (HRSC) digital terrain models at up to 125 m/px (on board Mars Express, see e.g. Gwinner et al., 2009). Morphologic information is primarily derived from the Context Camera (CTX) (on board Mars Reconnaissance Orbiter, see Malin et al., 2007) image data at resolution ~5 m/px. To augment CTX data, we use Thermal Emission Imaging System (THEMIS) (on board Mars Odyssey Spacecraft, see Christensen et al., 2003) VIS (~18 m/px) and IR (100 m/px) images and nadir HRSC (Neukum et al., 2004) images (up to 12.5 m/px); High Resolution Imaging Science Experiment (HiRISE) (on board Mars Reconnaissance Orbiter, see McEwen et al., 2007) images (0.25 m/px) were also used in available locations. The data was compiled and co-registered in the ArcMap GIS environment using the USGS ISIS software package.

We inspected several hundred catalogued proposed paleolakes (Cabrol and Grin, 1999; Fassett and Head, 2008b) and their nearby areas. The likelihood that Erythraea Fossa (31.5 W, 27.3 S) was a paleolake was first recognized in this survey. It was chosen for detailed investigation on the basis that it was not previously described in detail and exhibited clear and well-developed sedimentary deposits, inlet and outlet valleys, and had high-quality data available.

We used a combination of morphologic data and topographic data to identify inlet and outlet valleys and determine the direction of their local slope. Surface areas and volumes of the newly-proposed OBPs were obtained by finding the highest elevation closed contour, based on HRSC data, in the sub-basin containing the OBP. The topography within these closed contours was then extracted, enabling direct measurement of the surface area and volume of the paleolakes by using 3D Analyst Tools in ArcMap 9.3.

Fans discussed in this paper were identified following the criteria outlined by Williams and Malin (2008) and Metz et al. (2009).

3. Description of Erythraea Fossa

3.1. The case for paleolakes

Erythraea Fossa is a trough that extends radially east ~4000 km from Tharsis. Similar graben extend a comparable distance westward from Tharsis (Wilson and Head, 2002), and Erythraea Fossa may have been formed by cracking of the crust due to the propagation of a radial dike fed by magmatism from Tharsis. Alternatively, many large impact craters are characterized by anomalously large secondary crater chains that are generally radial to the crater and that taper in width distally (e.g. Mars: Moreux crater; the Moon: Schrodinger crater). The position of Erythraea Fossa on the rim of Holden, its generally radial nature, and its tapering and decreasing depth distally, suggest that this feature may be a secondary crater chain formed during the Holden crater-forming event. The Erythraea Fossa structure is superposed by ejecta from Holden crater (Fig. 1), and thus if it is a radial crater chain, it formed during the early phase of ejecta emplacement during the cratering event. There are three sub-basins in Erythraea Fossa (East, Middle, and West) that are divided from each other by topographic highs such that each has a closed contour delineating it as a distinct sub-basin (Figs. 2, 3, and 4A).

The sub-basins in Erythraea Fossa each have at least two large incisions into their margins: at the point where (i) a valley enters from higher elevation into the sub-basin and (ii) the bounding contour is breached by a valley leading to lower elevation than the incision (Figs. 4 and 5). There are also several small incised valleys that cross the graben rim (Fig. 6B and C). The observed valleys trend down-gradient on the basis of the present topography, many of them are sinuous, and one exhibits what appears to be well preserved inner channels (Fig. 5). Therefore, we interpret the valleys entering from higher elevations as inlet valleys—the large ones being the principal inlet valleys and the small ones being minor inlet valleys. We interpret the valleys leading to lower elevations as outlet valleys. This implies that, while the basins were fed primarily through the principal inlet valleys, flow into the basin was also augmented via flow through the minor inlet valleys.

Additionally, many of the valleys in Erythraea Fossa terminate in fan-like features, such as at the terminus of the outlet valley from West sub-basin (Fig. 5) and the lobate feature at the terminus of an inlet valley (Fig. 6B). There are also small valleys entering the graben from the south that terminate in flat, bright-tipped, lobate features (Fig. 6). The lobate features have a range of slopes from 1.3° to 4.6°, with an average slope of 2.6°. These are likely to be alluvial fans or deltas (e.g. Howard et al., 2005; Metz et al., 2009). On the south-facing slope of the graben, there are low-albedo lobate features that appear to have slumped or been transported by some other mass wasting process; these have a steeper average slope of 6.4° (Fig. 6D and E). Additionally, the features on the south side have a longer lateral extent than the features on the north side, which is also consistent with wetter processes on the south side (e.g. Williams and Malin, 2008). Mass wasting or destabilization of these slopes may or may not have been related to the period of lacustrine modification of Erythraea Fossa.

The termini of the inlet valleys to East sub-basin are at an elevation of ~−410 m and the valley connecting East sub-basin and Middle sub-basin breaches the basins at an elevation of −400 m (Figs. 2 and 3). The incision into the rim of Middle sub-basin from the inlet valley to West sub-basin is at ~−315 m. The elevation of the fan at

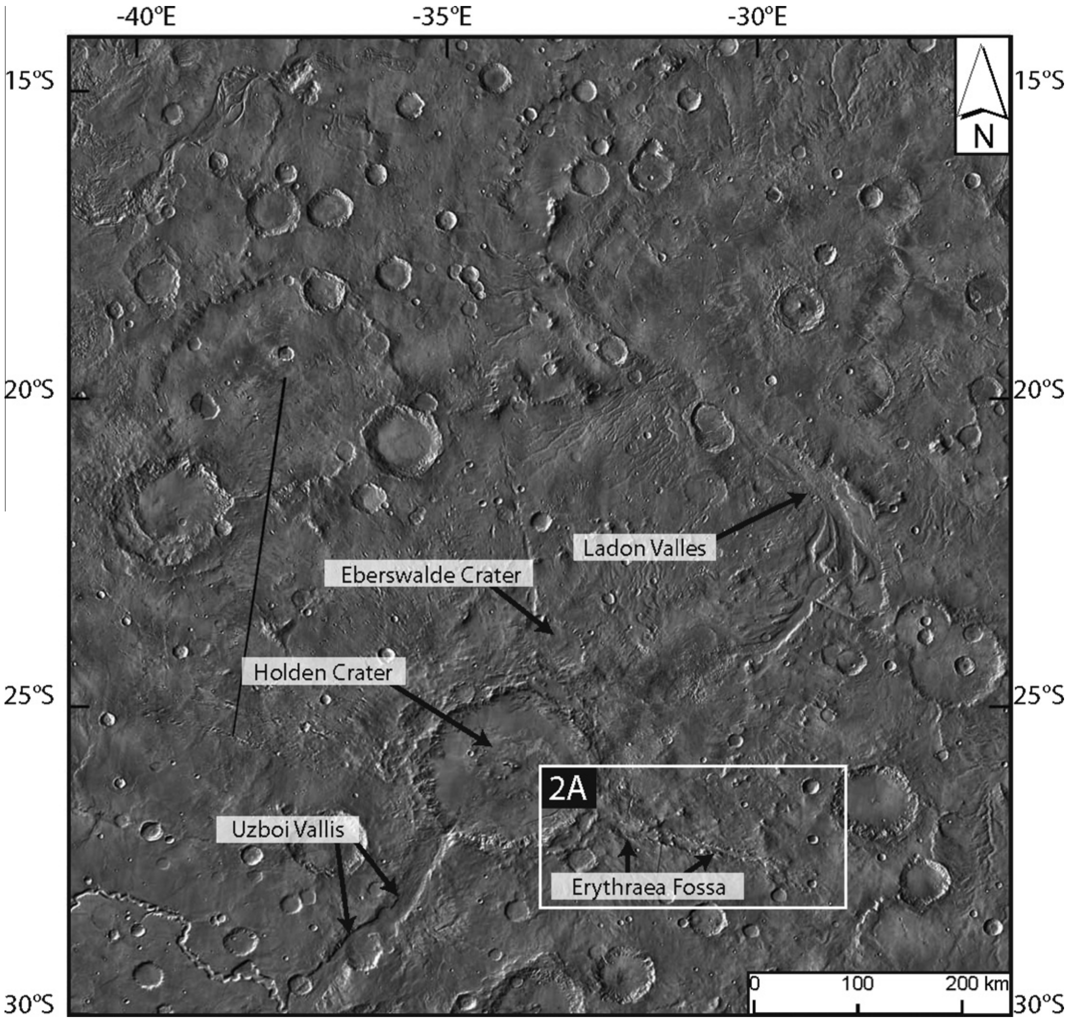


Fig. 1. Context of Erythraea Fossa (31.5 W, 27.3 S) and Fig. 2A with Holden crater, Uzboi Vallis, Ladon Valles, and Eberswalde crater. Due to the proximity of Erythraea Fossa to Holden crater, both probably experienced similar environmental conditions after the formation of Holden in the Noachian. The black region is a data gap. Image is a composite of CTX images P20_008852_1550, P19_008641_1528, P19_008272_1545, B01_010197_1545, B01_010131_1534, B01_09986_1534, P13_005978_1534, HRSC nadir image h0478_0000, and a THEMIS IR image mosaic.

the terminus of the inlet valley to West sub-basin and the incision formed by the outlet valley from West sub-basin are both at ∼−570 m (Figs. 2B and 3). The outlet valleys are the features that intersect the maximum closed contours measured for the individual sub-basins, opening the basin (Fig. 2). This is consistent with the interpretation that these valleys formed as a result of a basin-breaching event. Also, the fact that (i) the elevation of the fan at the terminus of the inlet valley to West sub-basin correlates well with the elevation of the incision formed by the outlet valley from West sub-basin (Figs. 3B and 4A) and (ii) the termini of the inlet valleys to East sub-basin line up well with the closed contour line in East sub-basin (Fig. 4B) support the hypothesis that these valleys were carved by water flow debouching into a standing body of water.

The highest closed contour is interpreted as the local maximum surface water level; a −315 m maximum elevation for the combined East and Middle sub-basins and a −570 m maximum elevation for West sub-basin (Figs. 2 and 3). Using these constraints we calculate that, if the system were filled with water to these maximum closed contours, then East and Middle sub-basin would have supported lakes with a combined surface area of 180 km^2 and a combined volume of 23 km^3, and the West would have supported a lake with a surface area of 270 km^2 and a volume of 33 km^3. The total capacity for the entire lake chain was 56 km^3.

Detailed mineralogical data is not available for Erythraea Fossa, but it will be fruitful to refine this hypothesis when this data becomes available.

3.2. Reconstruction of fluvial history

The valleys and fans in Erythraea Fossa are well preserved and there are no secondary craters from Holden superposed on Erythraea Fossa, so it is likely that the fluvial activity in and around Erythraea Fossa postdates the Holden impact (Noachian; Moore et al., 2003). If this were not the case, the ejecta deposit from Holden would be expected to superpose the fossa and observed valleys, as they are within ∼1 crater diameter of the Holden rim (e.g. Melosh, 1989, p. 90). This is consistent with the proposed timing of Late Noachian to Early Hesperian lacustrine activity in nearby Eberswalde crater (e.g. Malin and Edgett, 2003; Moore et al., 2003) and fluvial activity in Erythraea Fossa and Eberswalde (Fig. 1) may have occurred contemporaneously or in close temporal relationship.

Given the morphological and topographical evidence described in Section 3.1, we propose the following simple, long-term scenario of hydrological activity in this system, though more complicated fluctuations within this framework are possible:

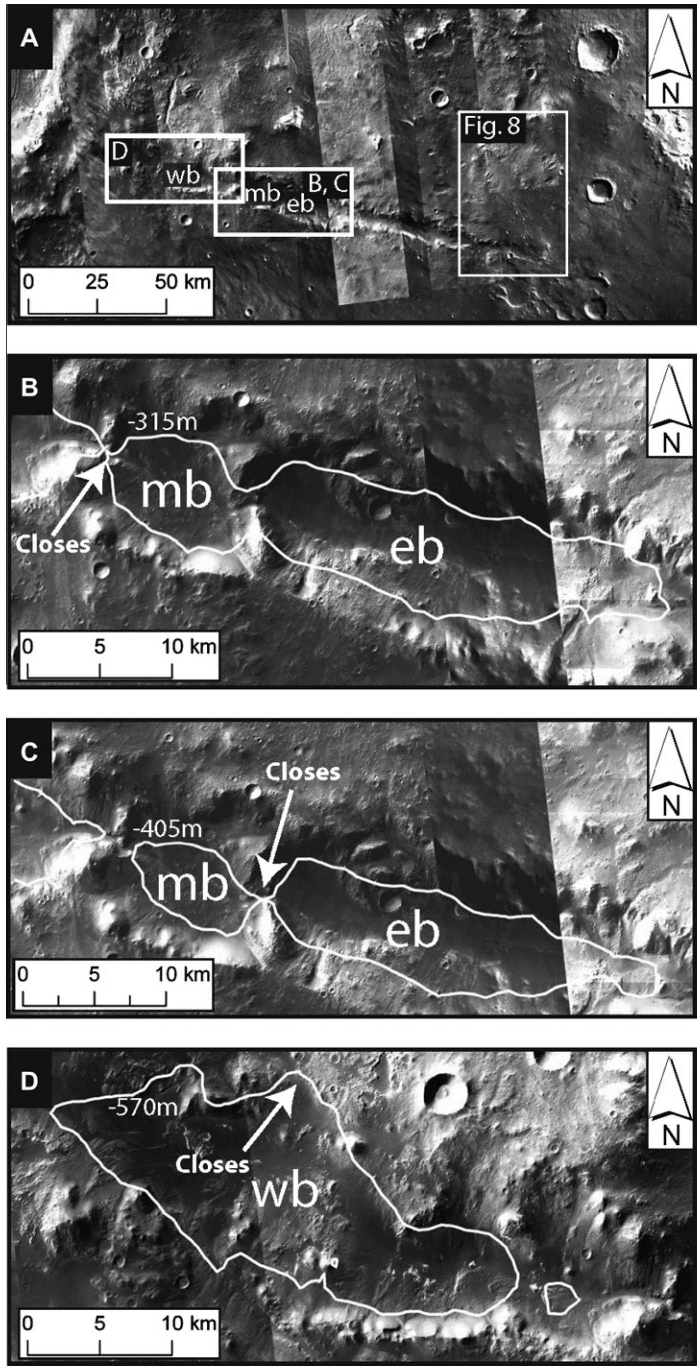


Fig. 2. (A) Erythraea Fossa is a graben located on the eastern side of Holden crater (Fig. 1). There are three sub-basins in Erythraea Fossa, here called East (eb), Middle (mb), and West (wb) sub-basins. These sub-basins are separated from each other by what the authors interpret to be slumps or underlying bedrock topography. The contours in (B), (C), and (D) show the highest elevation closed contour inside each of the sub-basins to within 5 m, relative to global mean elevation. Context for Fig. 8 is also given. (B) The highest closed contour in Middle sub-basin is −315 m; (C) East sub-basin, −405 m; (D) West sub-basin, −570 m. This figure is a composite of CTX images P20_008852_1550, P19_008641_1528, P19_008496_1532, P19_008272_1545, B01_010197_1545, B01_010131_1534, B01_09986_1534, P13_005978_1534, HRSC nadir image h0478_0000, a THEMIS IR image mosaic. Topographic data is from MOLA global mosaic data.

The three well-developed inlet valleys to East sub-basin (Fig. 4B), and the fact that the drainage area leading into East sub-basin from the east is the largest catchment area connecting to Erythraea Fossa (Fig. 7), imply that water flowed into the Erythraea Fossa OBP system mainly via the inlet valleys at the east end of the fossa. When water reached an elevation slightly above −405 m (Fig. 2D) East sub-basin was breached, spilling into Middle sub-basin. Once water in Middle sub-basin reached a level of slightly above −315 m (Fig. 2C) it also breached, spilling down the inlet channel to West sub-basin. West sub-basin then filled up, potentially sourced both from the Middle sub-basin and from minor valleys that directly fed it from the south (Fig. 6B). When West sub-basin was filled to an elevation of −570 m, it overtopped and formed the outlet channel to the north (Fig. 5).

As the OBP system dried out, and less water was available, we hypothesize the following scenario. First, the water level in the combined East and Middle sub-basins dropped, separating West sub-basin from East and Middle sub-basins. It seems probable that

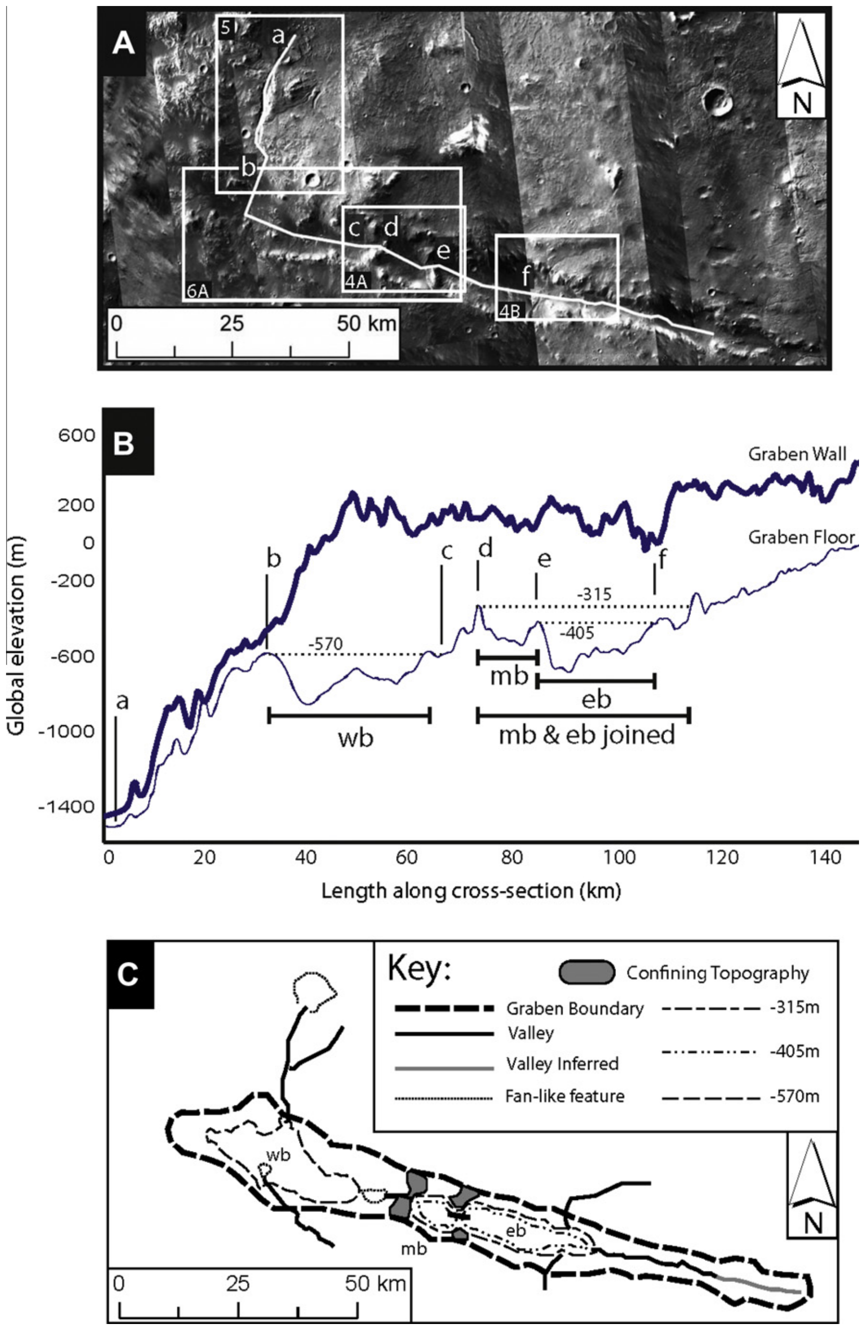


Fig. 3. (A) Erythraea Fossa showing the line from which the topographic profile is obtained. The letters correspond to (a) a region of deposition at the terminus of the outlet from West sub-basin, (b) the head of the valley leading out of West sub-basin, (c) a fan at the terminus of the valley leading from Middle to West sub-basin, (d) the valley connecting Middle and West sub-basins, (e) the valley connecting East and Middle sub-basins, (f) valleys leading into East sub-basin. Close-ups of these six locations are given in Figs. 4 and 5. Context for Figs. 4A, B, 5, and 6 are also given. (B) The unbolded line is the profile along the bottom of the graben (white line in A); the bold line in profile is the height taken along the side walls of Erythraea Fossa. The dotted horizontal lines correspond to the maximum closed contour in each of the sub-basins (see Fig. 2). (C) A schematic map of Erythraea Fossa, based on (A), showing the outline of the graben, maximum contours inside the sub-basins, and major inlet/outlet valleys with their associated fan-like features. (A) Composite of CTX images P20_008852_1550, P19_008641_1528, P19_008496_1532, P19_0087272_1545, B01_010197_1545, B01_010131_1534, B01_09986_1534, P13_005978_1534, and a THEMIS IR image mosaic. Topographic data for profile is from MOLA gridded data.

the late-stage input to the West sub-basin was primarily from the short valleys leading into it directly from the south (Fig. 6B and C), supporting deposition of the observed sedimentary fans, although the basin ultimately dried out. The water level would also drop in East and Middle sub-basins. As the water level dropped below −405 m, the Middle sub-basin may have dried out quickly because it would have been cut off from an overland source to East sub-basin (Fig. 2D) and had no other obvious major sources of water (unless groundwater was a large contributor to the local hydrology). The water level in East sub-basin would also drop until it, too, eventually completely dried out. We infer that when East sub-basin completely dried out its surface level dropped rapidly because the inlet valleys to East sub-basin are not incised more than 5 m below the closed contour elevation (Fig. 4B).

Ultimately these timescales depend on the relative rates of precipitation, evaporation, infiltration, surface water flow, and groundwater flow, which are not well known. Calculations of these rates have been pursued using various methods for other locations on Mars (e.g. Carr, 1983; Clow et al., 1988; Goldspiel and Squyres, 1991, 2000; Gulick et al., 1997; Forget et al., 2006; Lewis and

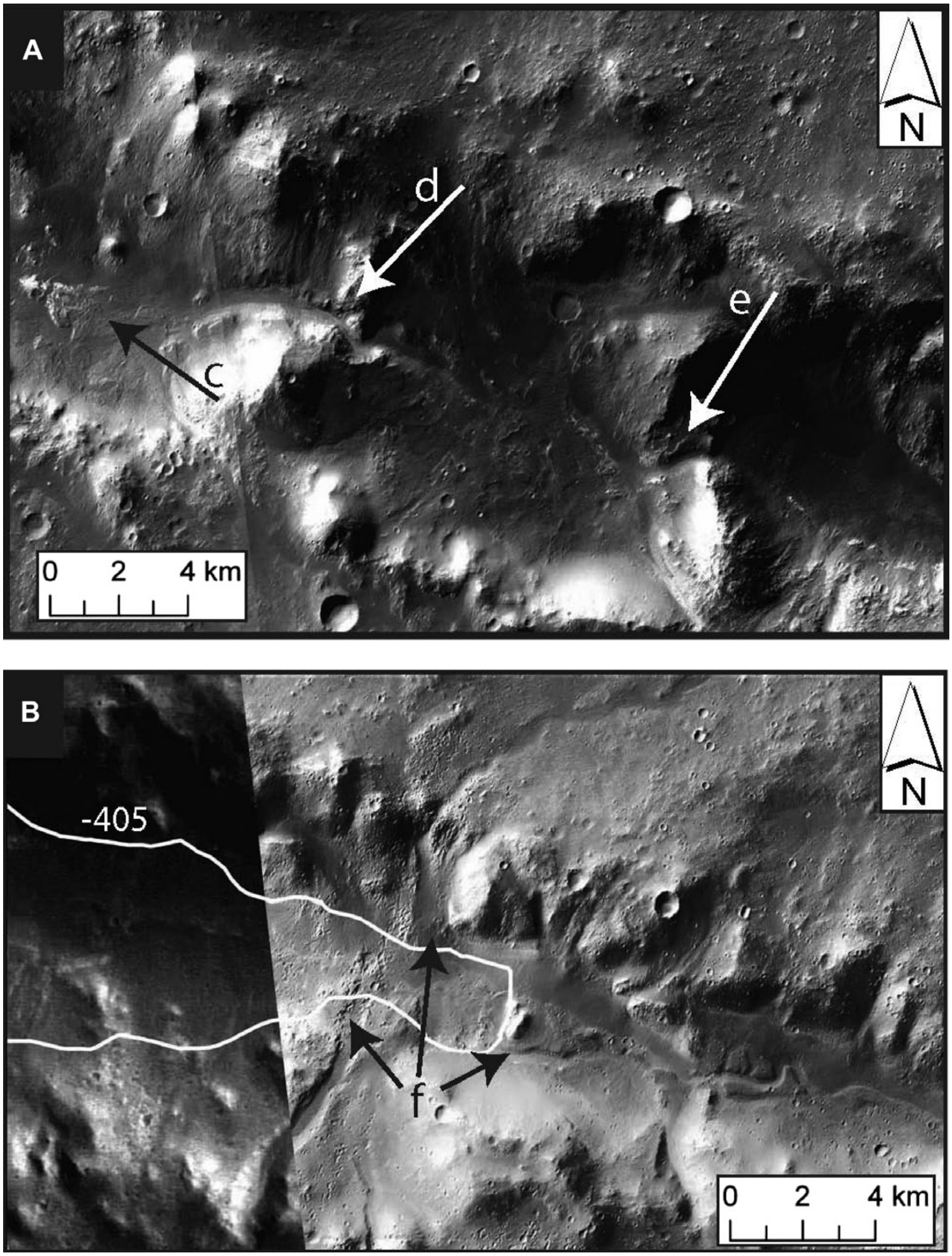


Fig. 4. (A) This detail shows higher resolution views of locations c, d, and, e from Fig. 3: (c) a fan at the terminus of the valley between Middle and West sub-basins, (d) the valley between Middle and West sub-basins, sloping into West sub-basin, (e) the valley between East and Middle sub-basins, sloping into Middle sub-basin. The mounds separating the sub-basins can also be seen in more detail. (B) A close-up of location (f) from Fig. 3, three inlet valleys to East sub-basin. (A) Composite of CTX images P20_008852_1550 and B01_010131_1534. (B) Composite of CTX image P19_008641_1528 and HRSC nadir image h0478_0000.

Aharonson, 2006), but calculations of this type fall outside of the scope of this paper.

4. Signs of precipitation and varying hydrological conditions

4.1. Evidence for precipitation

Two lines of evidence suggest that precipitation was an important source of water to the Erythraea Fossa OBP system. First, there are many small, high-elevation valleys to the northeast, many of which start at or near local elevation maxima (Fig. 8). The highest elevation points of most of the valleys (Fig. 8C) are located at elevations ranging from 600 m to over 800 m. Given this high elevation, and the isolated relief of these ridges, these are unlikely to have been primarily fed by groundwater (at least not groundwater that is not being actively recharged by local precipitation) (Grant, 2000; Gilmore and Phillips, 2002; Costard et al., 2002; Craddock and Howard, 2002; Lamb et al., 2006; Andrews-Hanna et al., 2007; Dickson et al., 2007; Di Achille et al., 2007). Their morphology also suggests that they were formed by surface fluid flow: they

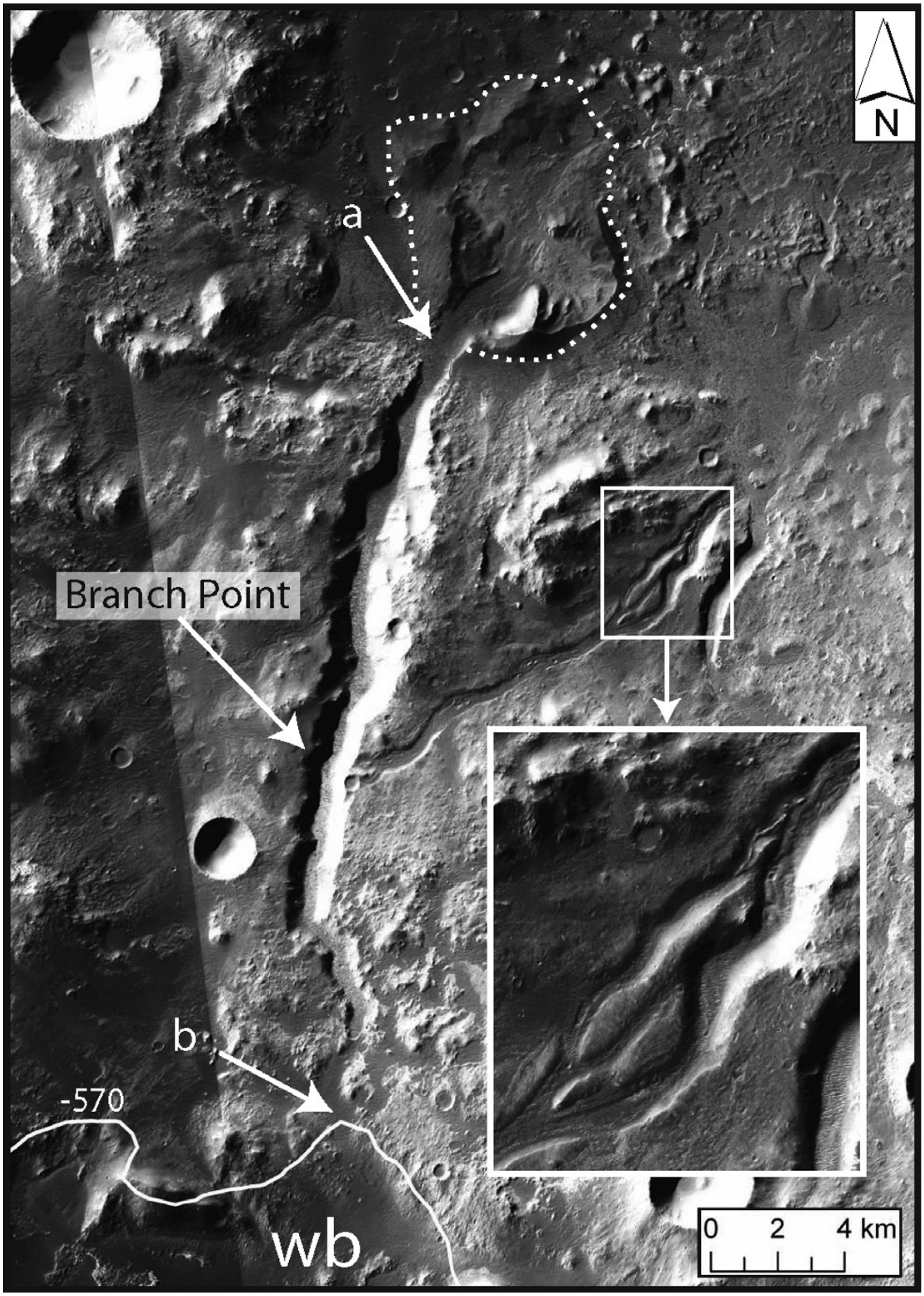


Fig. 5. A close-up of locations (a) and (b) from Fig. 3: (a) partially deflated fan at the terminus of the valley leading out of West sub-basin, (b) the head of the valley leading out of West sub-basin. The zoomed inset shows braided inner channels and point bars in an outlet valley. At the branch point the small valley is hanging; it appears to have been abandoned. Image is a composite of CTX images P20_008852_1550 and B01_009986_1534.

trend down-gradient on the present topography, they have v-shaped cross-sections (e.g. Williams and Phillips, 2001), and are generally sinuous (e.g. Mangold et al., 2004).

Although these valleys are not contained within the drainage basin containing Erythraea Fossa, they are within 2 km of the boundary demarcating the drainage into Erythraea Fossa (Fig. 7); as such, it is likely that the processes leading to high-elevation valleys were also at work within the drainage boundaries of East basin. Additionally, other small, sinuous, but poorly preserved valleys of similar size are present inside the drainage boundaries leading into East basin.

Differences in the morphology exhibited on the north and south sides of West sub-basin also support precipitation as a source for fluvial activity. The most prominent minor inlet valleys are on

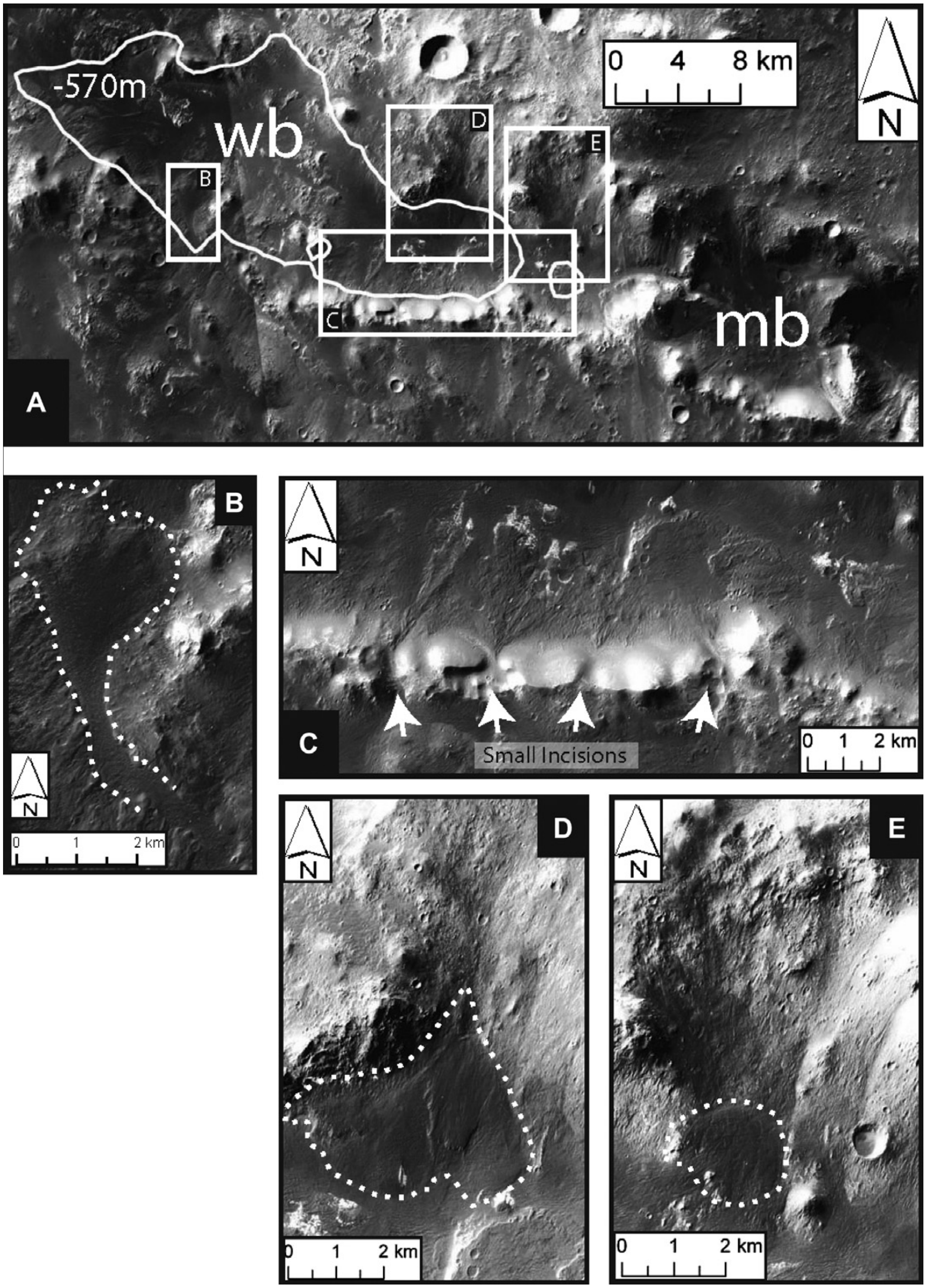
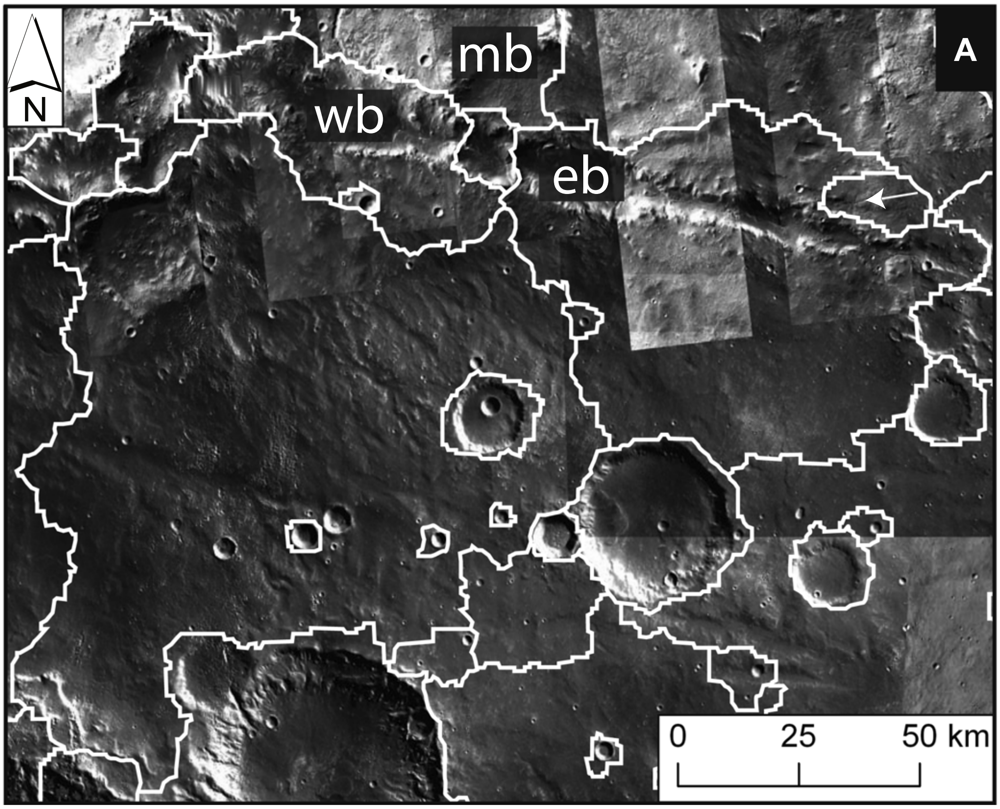


Fig. 6. (A) West sub-basin and Middle sub-basin for context of flat, bright-tipped, shallower (average slope angle is 2.6°), and laterally extensive fan features on the south side and lower-albedo, steeper (average slope angle is 6.4°), multi-lobed, and laterally contained possible slumps on the north side of Erythraea Fossa. Based on these morphologies, we interpret the southern features as having formed under wetter conditions than the northern features. (B) The westernmost fan-like feature is the most lobate. (C) Light-tipped, laterally extensive fan-like features at the terminus of short valleys sloping into West sub-basin. The light-tipped ends of the southern fans may be either the exposed ends of fans that are entirely light-toned or an exposure of a light-toned layer beneath the fans. (D) A low-albedo feature with several lobes evident coming from the northern side of Erythraea Fossa. This feature appears to have collapsed locally. (E) Another dark-toned lobate feature on the north side of the graben that appears to have moved as one mass. Figure is a composite of CTX images P20_008852_1550, B01_010197_1545, and B01_09986_1534.

the south side of the fossa, where the catchment areas are larger than to the north (Fig. 7). For example, in West sub-basin, on the north side the drainage divide is less than a kilometer away from the hypothesized lake surface, whereas on the south side the drainage divide ranges up to 20 km away from it, providing more drainage area for runoff. Also visible on the south side of the fossa are laterally extensive, light-tipped, lobate features (Fig. 6B and C), whereas on the north side of the sub-basin there are darker



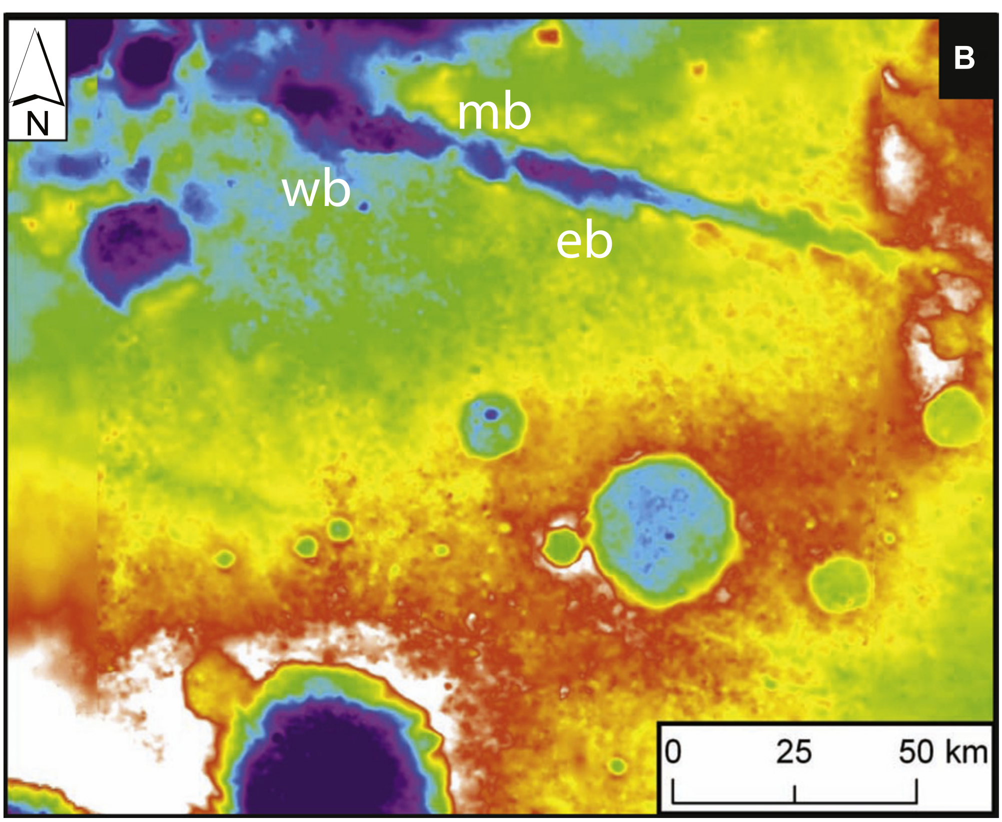


Fig. 7. (A) Bounded drainage areas near Erythraea Fossa; West (wb), Middle (mb), and East (eb) sub-basins are labeled. The drainage area to the south of Erythraea Fossa is larger than the area to the north, which is consistent with the morphological features we see on the north and south sides of the graben (see Fig. 6). The white arrow points to small, high-elevation valleys that are within a few kilometers of the drainage divide leading to East basin. The topographic data used to generate the drainage areas is MOLA 1/128 pixel per degree gridded data (463 m/px). (B) A DEM of the study area; elevation ranges from −800 m (purple) to +800 m (white) global elevation. (A) Composite of CTX images B01_010131_1534, P19_008641_1528, P19_008496_1532, a THEMIS IR image mosaic, and HRSC nadir images h0478_0000 and h0489_0000. (B) Composite image of HRSC nadir images h0478_0000 and h0489_0000 with MOLA data along the left edge.

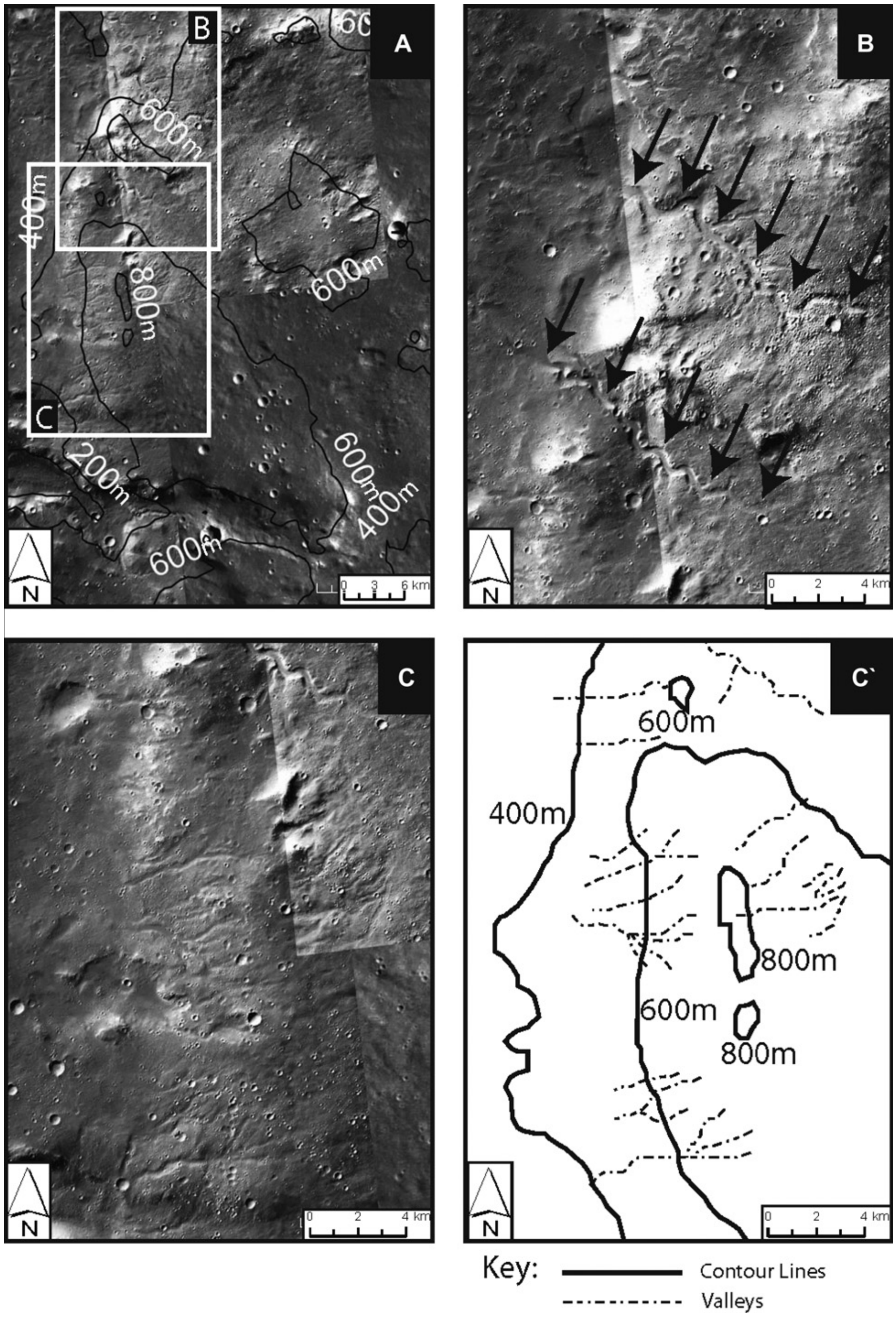


Fig. 8. Small valleys at high elevation slightly to the northeast of Erythraea Fossa (context is given in Fig. 2A). We interpret these features as evidence of precipitation, since they have characteristics of fluvially carved valleys (sinuosity, v-shaped cross-sections, following the steepest downhill gradient) and they start at or near a local maximum elevation/drainage divide. (A) Gives context for (B) and (C) and also displays contour lines to demonstrate that the valleys start at high elevation. (B) Two prominent and sinuous valleys; the northern valley has a maximum elevation at ~450 m, and the southern valley has a maximum elevation at ~600 m global elevation. (C) Numerous high-elevation valleys, (C′) a sketch of the high-elevation valleys with topographic contours. Figure is a mosaic of CTX images P19_008641_1528 and P19_008496_1532.

features that appear to have collapsed locally (Fig. 6D and E). The morphology on the north side is consistent with drier mass movement and the morphology on the south side is consistent with sediment movement under wetter conditions (e.g. Metz et al., 2009). The correlation between catchment size and the likely fluvial conditions for sediment mobility on the north and south sides of the fossa are consistent with (though not diagnostic of) precipitation.

4.2. Evidence for change in hydrological conditions

There is strong evidence that the hydrologic conditions of Erythraea Fossa were variable over time. The outlet valley from West sub-basin (~1 km to ~2.5 km wide) ends in a large, partially deflated, fan and there is another, smaller valley (~400 m to ~550 m wide) that appears to have been the main outlet valley prior to the current, deeper and larger outlet valley (Fig. 5). The smaller valley shows strong signs of fluvial origin, including inner channels with widths of ~30 m to ~80 m (e.g. Irwin et al., 2005a) and intervening islands (Fig. 5 inset). From the extent of the inner channelization and overall incision, it is likely that this valley actively supported fluvial activity for an extended period of time (e.g. Mangold et al., 2004; Wood, 2006). The two outlet valleys have different morphologies (the large valley is straight and without preserved inner channels, whereas the smaller valley is more sinuous and has preserved inner channels); they also have different widths, which is consistent with different water discharges (e.g. Leopold and Maddock, 1953). Based on this, we postulate that the hydrological conditions of Erythraea Fossa were likely different when each of the outlet valleys were operating. However, we cannot rule out the possibility that at one time both valleys were active simultaneously, and the smaller valley was abandoned by a more gradual process due to higher incision rates and progressive capture of flow by the larger valley.

5. Implications

An active hydrological cycle in Erythraea Fossa would have ramifications for the paleoclimate in the nearby area, including Holden and Eberswalde craters, which are currently candidate landing sites for the Mars Science Laboratory (e.g. Griffes et al., 2009). The evidence for fluvial activity in Erythraea Fossa extends the evidence for paleolakes in Holden and Eberswalde craters to a broader region, as well as providing context for the climatologic factors to which they were subject.

The evidence that precipitation was an important source of water for the Erythraea Fossa system likely implies that precipitation was also a source of water for Holden and the surrounding area. While the OBPs in Erythraea Fossa could also have been supported in part by groundwater, based on observations elsewhere on Mars, precipitation is probably required to close the hydrological cycle and recharge aquifers (e.g. discussions in Grant, 2000; Craddock and Howard, 2002; Irwin et al., 2005b; Lamb et al., 2006; Di Achille et al., 2007; Williams and Malin, 2008).

It is also possible that there was a localized active hydrological cycle prior to the Holden impact, if dike formation associated with the formation of Erythraea Fossa interacted with the cryosphere or hydrosphere. This could potentially allow release of groundwater and/or cryospheric melt to the local environment, as may have happened in Cerberus Fossa (Head et al., 2003). However, the Holden impact likely would have obliterated any signs of that activity due to its size and proximity, and the features we see appear to be unrelated to the formation of the fossa.

The evidence of pervasive hydrological activity in Erythraea Fossa also has implications for the global martian paleoclimate. For example, the findings in this location imply that this region of Mars once had an atmosphere in a pressure and temperature range that permitted precipitation and liquid surface water (see Carr, 1996; Hynek et al., 2010). However, there is insufficient evidence to show whether the precipitation was rain, atmospheric condensation, or whether surface hydrology was dominated by snow, as it is today in the Antarctic dry valleys (Hecht, 2002; Costard et al., 2002; Christensen et al., 2003; Balme et al., 2006; Dickson et al., 2007; Marchant and Head, 2007; Dickson and Head, 2009). Also, sweeping generalizations about the entire hydrological cycle of Mars cannot be inferred solely from this investigation; just as local terrestrial environments vary widely, those on Mars probably also varied (e.g. discussion in Di Achille et al. (2007)).

6. Conclusion

Erythraea Fossa is a graben in close proximity to Holden crater that exhibits signs of extensive fluvial modification. We find three sub-basins connected to each other via a series of valleys that are likely of fluvial origin, forming a chain of three Open Basin Paleolakes (OBPs). The OBP chain has the capacity to hold 56 km^3 of water. Light-toned sedimentary deposits that are likely of deltaic or alluvial origin are observed on the graben floor.

Valleys at high elevation that were likely to have been carved by fluvial activity, along with fans and mass-wasting features in conjunction with catchment areas suggest that precipitation (or precipitation recharged aquifers) is at least one of the sources for water in the Erythraea Fossa OBP chain. Additionally, an abandoned distributary channel at the outlet of the West sub-basin of Erythraea Fossa with well preserved inner channels suggests that an avulsion took place that might have been caused by changes in hydrologic conditions either abruptly (e.g. a flood) or more gradually.

The findings at Erythraea Fossa have important consequences both for the local and the global paleoclimate. Their formation appears to require a climate that was at the correct pressure and temperature range to support surface water and precipitation and give clues about the nature of the Holden and Eberswalde hydrological cycles.

Future work examining the mineralogy of Erythraea Fossa, particularly in the high albedo tips of the fans, would further our understanding of the processes that took place in Erythraea Fossa. Additional high resolution images of the area, especially of the inner channels in the avulsed outlet from West sub-basin and of the fans, will also facilitate additional investigation into channel forming processes and allow us to look for layering in the fans.

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