Strike-slip faults in Bathys Planum, Mars

Andrew Gerrit Siwabessy[1], John Nicholas Adrian[2], Nathan Onderdonk[2], James Matthew Dohm[3], and Robert C. Anderson[4]

[1]University of Western Ontario
[2]California State University, Long Beach
[3]Exploration Institute
[4]Jet Propulsion Lab (NASA)

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Abstract

Structures in Bathys Planum, southwest of the Tharsis Rise, Mars, compare to strike-slip faults in California, western United States. Local topographic highs and lows at step-overs between fault segments are likened to pop-up structures and pull-apart basins formed due to left-lateral strike-slip displacement along the faults. The faults are interpreted to have reactivated structures that preceded the propagation of Tharsis-incipient (Stage 1 Claritas tectonic center) graben through this region.

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[1]Geosciences Group, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, United States 91109, [2]Department of Geography, California State University-Long Beach, Long Beach, California, United States 90840,[3]STEM Teacher-Researcher Program (STAR), California Polytechnic State University, San Luis Obispo, California, United States 93407, [4]Department of Geological Sciences, California State University-Long Beach, Long Beach, California, United States 90840, [5]Exploration Institute, 710 N Post Oak Rd Ste 400, Houston, Texas, United States 77024-3812

Keywords: Tectonics; Mars, surface; Terrestrial planets

Highlights :

Strike-slip faults formed in the Noachian period in Bathys Planum, Mars.

The strike-slip faults reactivate of pre- or early Tharsis tectonic features.

A pre/early Tharsis intrusion may have formed the antecedent faults.

Abstract

Structures in Bathys Planum, southwest of the Tharsis Rise, Mars, compare to strike-slip faults in California, western United States. Local topographic highs and lows at step-overs between fault segments are likened to pop-up structures and pull-apart basins formed due to left-lateral strike-slip displacement along the faults. The faults are interpreted to have reactivated structures that preceded the propagation of Tharsis-incipient (Stage 1 Claritas tectonic center) graben through this region.

1. Introduction

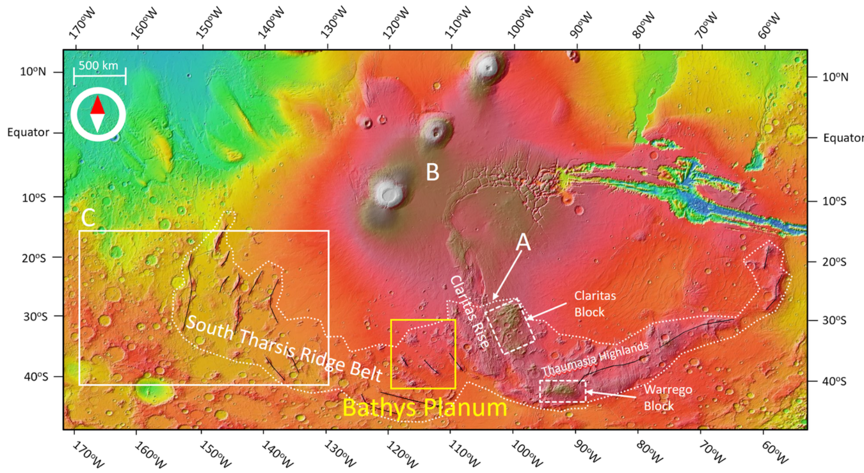

Figure 1 . MOLA hillshade regional map of the southern Tharsis Rise and the South Tharsis Ridge Belt (white dotted outline). Also shown are ridges initially mapped by Schultz and Tanaka [1994] (black lines), centers of Tharsis-driven tectonism [Anderson et al., 2001], including Claritas (A—Stage 1) and Pavonis (B—Stage 3), the Memnonia-Sirenum map [Anderson et al., 2019b] (white box) labeled [C], and the Bathys Planum map region (yellow box).

Bathys Planum is a provisionally named region of Mars located on the southwest periphery of the Tharsis Rise (Figure 1). This region may have been associated with the earliest stages of development of Tharsis [Anderson et al., 2001, 2019a; Dohm et al., 2001, 2007, 2009a]. Graben associated with both the Noachian (Stage 1) Claritas and early Hesperian (Stage 3) Pavonis tectonic centers, as identified by Anderson et al. [2001], transect this map region. Graben associated with both trends distinctly exhibit an unusual stair-stepping pattern in the Bathys Planum region (Figure 2).

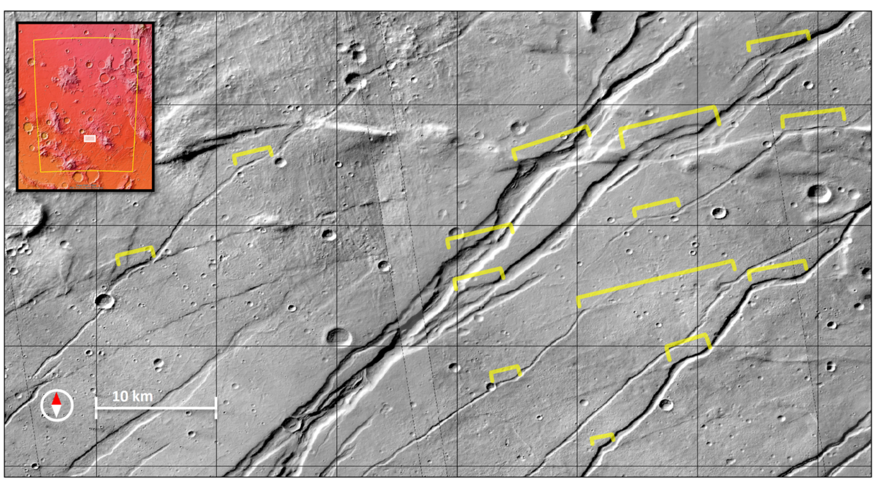

Figure 2. A CTX mosaic of a section of the Bathys Planum region, where graben associated with the Stage 1 Claritas and Stage 3 Pavonis tectonic centers [Anderson et al., 2001] assume a stair-stepped or zigzagged morphology as they intersect the E-W curvilinear basement fabric. The inset map's white box shows the location of this region in the mapping extent. Traces of the E-W basement structures can be identified indirectly due to downtrend alignments of stairsteps in the graben troughs. However, these traces sometimes manifest explicit surficial tectonic geomorphologies (see Figure 3). Instances of stairstepping and downtrend

alignment are illustrated with yellow brackets. Image is centered near 115°W, 37°S.

This stair-stepping pattern is present where the graben intersect east-west trending lineaments (Figure 2). The graben are offset or deflected where the graben intersect, suggesting that the east-west trending structures influenced the development of the graben.

Additionally, downtrend of the graben-lineament intersections, depressions and hills have been identified adjacent to the lineament traces. These hills and depressions are consistent with pop-ups and pull-apart basins observed along strike-slip faults on Earth, suggesting that the lineaments are left-lateral strike-slip faults. In this study, the morphology and relative timing of these structures were examined and compared to other structures identified in this region.

2. Methodology

Faults were mapped at a 1:24,000 scale within the Bathys Planum map region using Esri's ArcGIS Pro. Distinctive structures were identified and interpreted to be strike-slip faults in the southern half of the mapping area, centered near 115°W, 38°S. Although Mars Global Surveyor (MGS) Thermal Emission Imaging System (THEMIS with average resolution of 100 m/px; Christensen et al., [2004]) daytime-infrared global basemap v. 13.6 was used as the project's overall basemap, the structures could only be resolved using Mars Reconnaissance Orbiter (MRO) Context Camera (CTX with 6 m/px average resolution; Malin et al., [2007]) images co-registered to the THEMIS basemap.

Only fault strands with definitive surface expressions were digitized; no inferred traces were mapped. Strands were divided into four categories (left-lateral strike-slip; right-lateral strike-slip; compressional; uncertain). Strike-slip landforms were mapped in association with all mapped fault strands and classified based on whether they are transpressional or transtensional (criteria are explained in the subsequent section).

2.1. Identification of strike-slip faults from terrestrial analogues

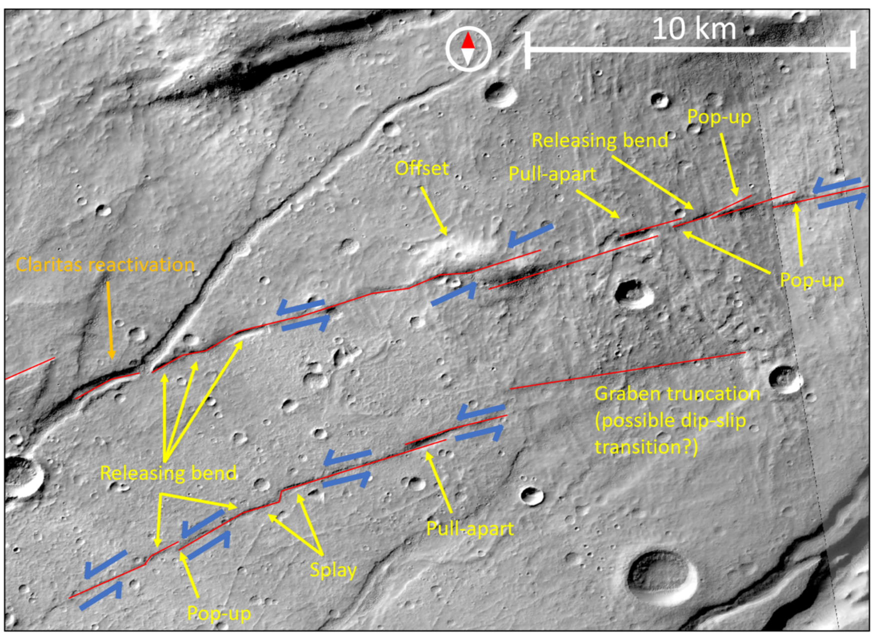

Figure 3. CTX mosaic (enlarged part of Figure 2) showing examples of E-W trending strike-slip fault morphologies within mNp, including releasing and restraining stepovers and bends. Small restraining stepover features may constitute either the positive flower structures or the push-up ridges summarized in Cunningham and Mann [2007]. The larger mound in the central part of the figure demonstrates a possible sinistral

offset of approximately 1.6 km. North at top.

On Earth, the identification of topographic features at bends or steps along the structures suggest a component of lateral slip. In Bathys Planum, topographic depressions can be identified at left bends or steps in the faults, and positive topographic features (small hills) present at right bends and steps (typical dimensions 100-200 m width, 100 m-2 km length). This morphology mimics topographic features along terrestrial strike-slip faults [e.g., Sylvester, 1988; Christie-Blick and Biddle, 1985; Cunningham and Mann, 2007] and suggests that these structures exhibit a component of left-lateral strike slip. This sense of slip is also supported by the apparent left-lateral offset of the larger hill in the central part of the area (Figure 3). Towards the peripheries of the region of interest, the structures occasionally manifest as compressional faults with vertical offsets reaching 130 m (Golombek et al., [2001]; Watters, [1998]).

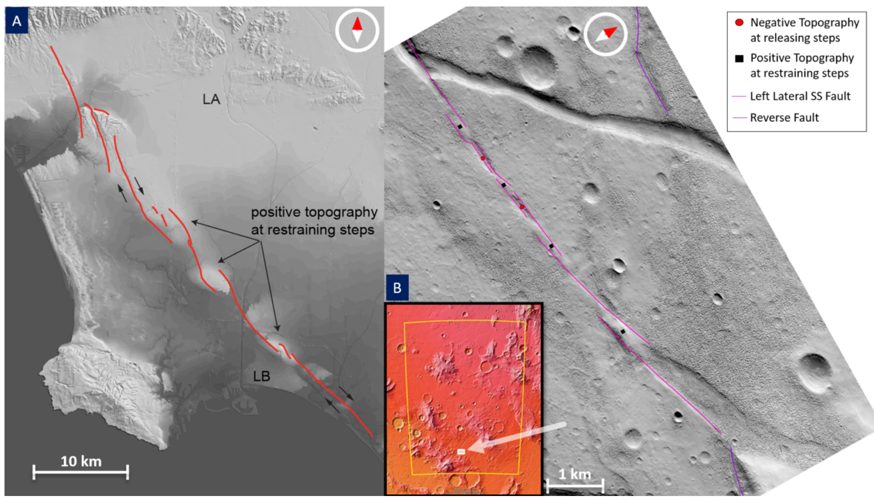

Figure 4. Subfigure A shows the right-lateral strike-slip Newport-Inglewood Fault Zone (NIFZ) in metropolitan Los Angeles, California, United States (34°N, 118°W). This is compared to strike-slip faults of Bathys Planum on account of: (1) morphological similarities between transpressional landforms; and (2) the intermittent occurrence of overstepping scarps in a regionally curvilinear trend on a plains-forming fill material. Transpressional features in stepovers and restraining bends along the fault are labeled. Digital elevation model (DEM) modified from publicly available files published by the United States Geological Survey (USGS_1_n34w199), and fault locations are modified from the USGS Q-faults database. Subfigure B shows a left-lateral strike-slip fault in Bathys Planum with similar stepover morphology.

When terrestrial strike-slip faults bend or step against their own sense (e.g., a left-lateral strike-slip fault either bends or steps to the right), a localized compressional stress is imposed within the bend or between the *en echelon* strands of that fault, creating a pop-up in the affected area. If a fault bends into its own sense (e.g., a left-lateral strike-slip fault either bends or steps to the left), a localized extensional stress is imposed in the fault's bend or between its strands, creating a pull-apart basin [Aydin and Nur, 1985; Cunningham and Mann, 2007]. A fault may bend or step over in alternating directions, creating a "porpoising" effect where pull-apart basins and pop-ups may repeatedly alternate along the fault zone (Figure 4A; Sylvester, [1988]). Assuming these morphologies observed on Earth apply to faults in Bathys Planum, then the sense of observed faults can be inferred on the basis of the presence and distribution of these landforms. For instance, the faults mapped in Figure 3, show pop-ups at right steps, and small depressions at left steps, suggesting a left-lateral sense of slip along the faults. Note that the mound in the center-right of Figure 3 appears to be offset in a left-lateral sense by more than a kilometer, consistent with the inferred left-lateral slip along the faults from the morphology of steps and bends along the same fault zone. A terrestrial example of these morphologies is comparatively presented in Figure 4.

The "stair-stepping" deflection of the Claritas-radial graben in Figure 3 appears to be right-lateral rather than left-lateral in sense. This is interpreted not to be associated with the offset of later Claritas-radial graben. Rather, a pre-existing east-west fault system is inferred to have influenced the development of the Claritas-radial graben as the latter developed, creating an apparent right-lateral deflection in the graben as they propagated through Bathys Planum. The apparent right-lateral deflection of graben and cracks is also present where they intersect east-west faults that do not display strike-slip surface morphologies. The deflections are, however, generally consistent in strike with nearby east-west faults that do exhibit strike-slip landforms. The apparent deflections of graben in these locations could be the result of other strike-slip faults associated with this ancient east-west fault system, even if those east-west faults cannot be directly confirmed or mapped with available data.

3. Results

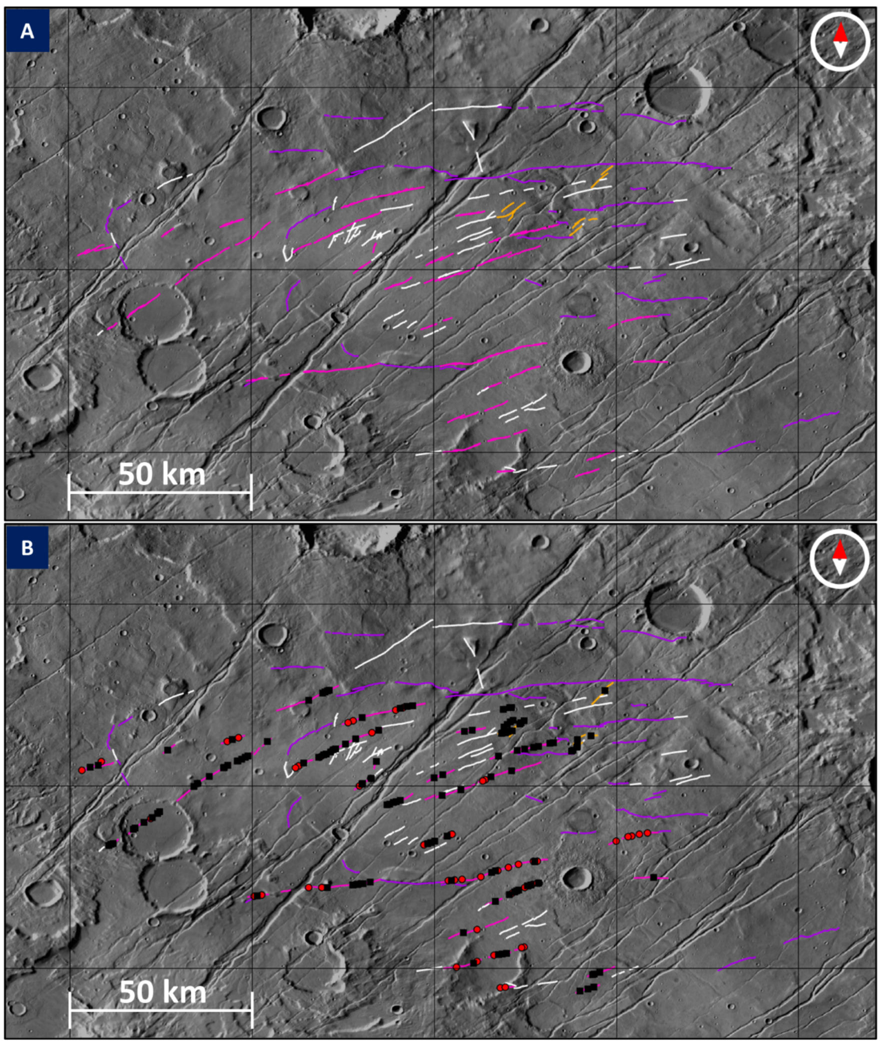

Figure 5 . A) Semi-curvilinear faults mapped on a CTX mosaic near 115°W, 38°S, in the southern-central sector of the Bathys Planum mapping area. Pink features represent sinistral strike-slip faults, yellow features represent dextral strike-slip faults, purple features represent compressional faults, and white features are possibly structural lineaments of an uncertain sense. Features are identified as left- or right- lateral based on the presence and relative orientations of strike-slip landforms to different fault segments; they are not

assigned a fault type if no such landforms are observed, or if the sense of slip is indeterminate. Note that while the “stair-stepping” of graben in this area is indicative of structural control associated with the same trends as the mapped faults, these deflections are not mapped in (A) if they do not correspond to explicit transcurrent / strike-slip geomorphologies. Note that while all other features on the geologic map of Bathys Planum [Adrian et al., 2021] were mapped at a 1:250,000 scale, mapping of the structures in this figure was performed at a 1:24,000 scale on CTX.**B)** The semi-curvilinear faults with sense of slip for strike-slip landforms overlaid. 127 transpressional landforms (restraining bends, pop-up ridges, possible positive flower structures) are digitized as black squares and 48 transtensional landforms (releasing bends, pull-apart basins, possible negative flower structures) are digitized as red circles.

A total of 19 left-lateral strike-slip fault strands were mapped between two highland ridge-forming units (Noachian highlands Nh2 and Nh3) and an inter-ridge fill unit (middle-Noachian plains mNp), per Adrian et al., [2021], in the central part of the Bathys Planum map region near 115°W, 38°S (Figure 5). The faults generally strike east/northeast-west/southwest, although 6 right-lateral strike-slip fault strands were mapped in the northern-central section of the frame of Figure 5 and may represent conjugate features to the more dominant left-lateral trend. In general, the strike-slip faults are considerably more linear than the compressional faults in this section of Bathys Planum, which are observed to dip towards a central point (using the Golombek et al., [2001] model). In some locations, the strike-slip faults appear to be overridden by the east-west compressional faults, before continuing along the same east/northeast - west/southwest parallel trend farther down the compressional fault's scarp. This suggests that the more curvilinear compressional faults preceded the emplacement of the strike-slip faults.

The Bathys strike-slip faults are relatively discontinuous with minimal lateral displacement. A distinct offset of approximately 1.6 km (Figure 3) occurs on one of the strands. Furthermore, they are associated with relatively small and shallow pull-apart basins not expected to exceed the depth of their bounding strike-slip faults [Aydin and Nur, 1985]. This suggests that the observed strike-slip faults are shallow features which do not directly represent tectonism in the deeper crust [Aydin and Nur, 1985; Christie-Blick and Biddle, 1985].

The possible strike-slip faults identified in this work notably differ from those proposed by Andrews-Hanna et al., [2008] in Terra Sirenum and Amazonis Planitia because the strike-slip morphology of the faults in Bathys Planum appear to be foremost characterized by the existence of transcurrent landforms (as opposed to linear ridges with asymmetrically tapering throws on each side of the fault). They also differ from models invoking accommodation of oblique slip in Tharsis-radial graben sets [e.g., Masson, 1980; Fernández and Ramírez-Caballero, 2019; Montgomery et al. 2009], and from regionally extensive invocations of strike-slip faulting which largely depend on offset as a kinematic indicator [Schultz, 1989; Yin, 2012]. Note that transcurrent/strike-slip landforms have also been reported on Europa [e.g., Sarid et al., 2002] and Venus [Koenig and Aydin, 1998].

4. Discussion

The curvilinear faults are interpreted to exhibit a strike-slip sense as a consequence of the imposition of Claritas- and Pavonis-linked stresses in the Bathys Planum region. A model presented in Figure 6A illustrates how the most distinctive characteristics of the faults can be kinematically explained by the Claritas- and Pavonis-associated stress fields in this region. It is plausible that extensional stresses acting obliquely on the pre-existing east-west curvilinear fault set would drive left-lateral strike-slip motion along this older fault set; the lateral component of slip at these intersections laterally mobilized the structures elsewhere on these faults, producing the stepover landforms observed across the area. Because the Claritas and Pavonis fault sets intersect these east-west faults from a similar relative direction, left-lateral slip would be expected in association with stresses tied to either tectonic center (Figure 6A). It is possible that the curvilinear, oppositely dipping reverse faults bounding the faulted area might represent the emplacement of an igneous intrusion at depth: a previously unreported, but more localized, updoming event in the style of the tectonic centers identified by Anderson et al. [2001] (Figure 6B). However, the region within the curvilinear fault sets is not associated with a topographic high as is observed for other proposed centers of tectonic activity proposed by Plescia and Saunders [1982], Anderson et al., [2001], and Ivanov and Head [2006]. If the putative dome later subsided, this might explain the lack of a clear topographic expression. However, because the putative dome in Bathys was likely too small to have been geometrically influenced by the planet's curvature [Banerdt et al., 1992], its concentric ring faults would likely have had to have formed in a reverse sense during the putative dome's uplift before being reactivated as normal faults during the dome's subsidence [Cole et al., 2005; Acocella et al., 2004], instead of the other way around [Anderson et al., 2001; Dohm et al., 2009b; Ivanov and Head, 2006].

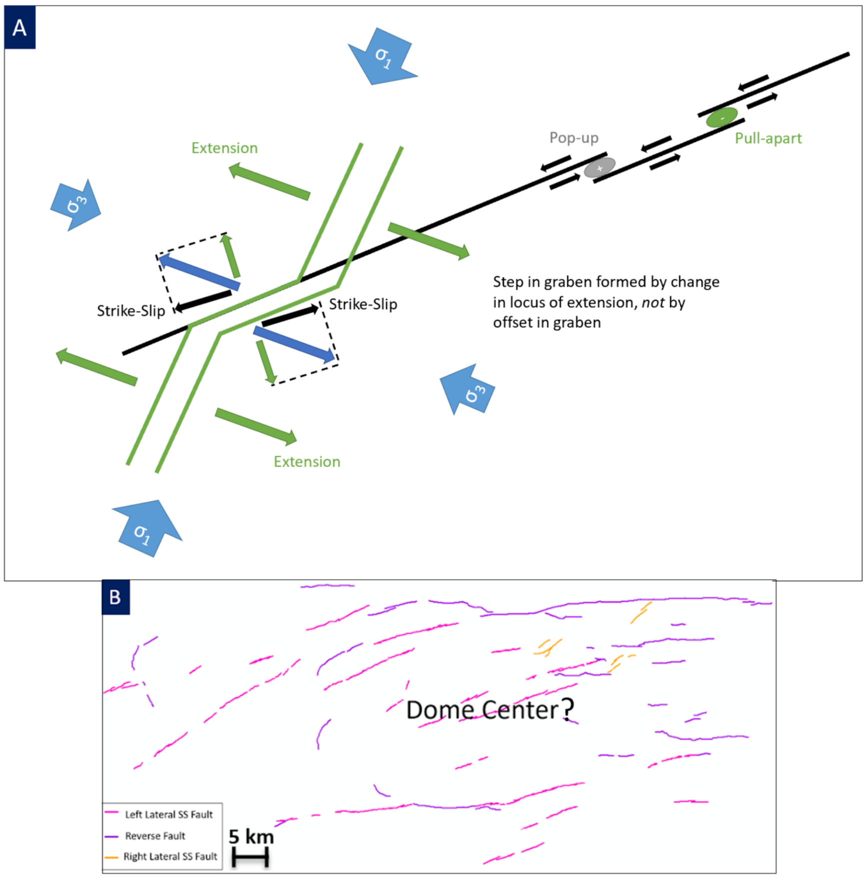

Figure 6. Subfigure A illustrates how Tharsis-driven extension in Bathys Planum might reactivate an antecedent basement fault (black) as a strike-slip fault, causing the observed stairstepping graben morphologies. Green illustrates both the graben and the direction of extension (σ_3) implied by the graben's formation. When the graben intersects with the antecedent structure, the same regional stress field drives a component of throw and heave (in green, perpendicular to the structure) and a component of left-lateral motion (in black, parallel to the structure) that causes similar lateral deformation elsewhere on the fault, driving the aforementioned stairstepping morphologies. Subfigure B shows the mapped faults (other than graben) without the basemap to highlight the curvilinear form of faults.

Conclusion

Evidence of strike-slip faults in Bathys Planum region of Mars is presented. The Bathys intrusion (a possible tectonic center) and the Stage 1 Claritas tectonic center are argued to have simultaneously influenced Bathys Planum in the Noachian Period, with flexural stresses driven by the Claritas tectonic center influencing the geometry of a possible Bathys dome. Bathys center tectonics ceased, and the dome subsided, prior to the propagation of Claritas-radial graben through Bathys Planum. The orientations of the graben were then influenced by the pre-existing Bathys center-linked fault system, driving a lateral component of slip presenting in mostly left-lateral strike-slip tectonics on the antecedent fault system.

Acknowledgements

Data is available from a repository hosted by the Open Science Framework, accessible via the following link: osf.io/se53m

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Andrew G. Siwabessy[1,2*], John N. Adrian[1,3], Nathan W. Onderdonk[4], James M. Dohm[5], Robert C. Anderson[1]

[1]Geosciences Group, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, United States 91109, [2]Department of Geography, California State University-Long Beach, Long Beach, California, United States 90840, [3]STEM Teacher-Researcher Program (STAR), California Polytechnic State University, San Luis Obispo, California, United States 93407, [4]Department of Geological Sciences, California State University-Long Beach, Long Beach, California, United States 90840, [5]Exploration Institute, 710 N Post Oak Rd Ste 400, Houston, Texas, United States 77024-3812

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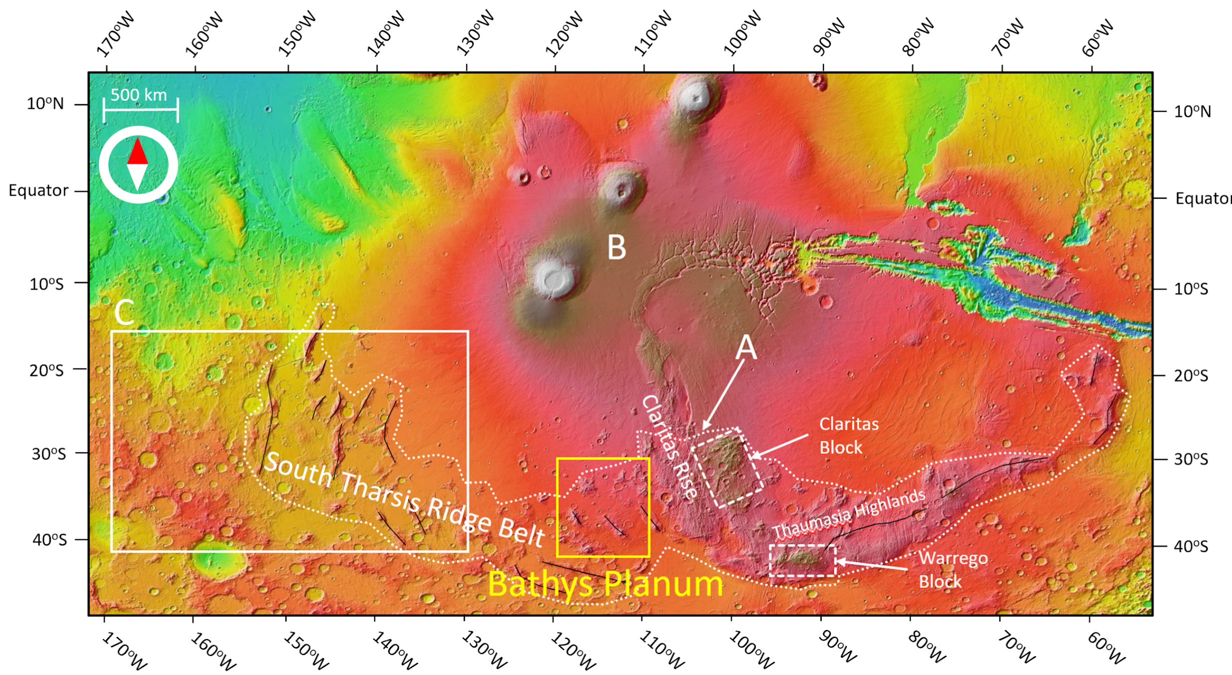

Figure 1. MOLA hillshade regional map of the southern Tharsis Rise and the South Tharsis Ridge Belt (white dotted outline). Also shown are ridges initially mapped by Schultz and Tanaka [1994] (black lines), centers of Tharsis-driven tectonism [Anderson et al., 2001], including Claritas (A—Stage 1) and Pavonis (B—Stage 3), the Memnonia-Sirenum map [Anderson et al., 2019b] (white box) labeled [C], and the Bathys Planum map region (yellow box).

Bathys Planum is a provisionally named region of Mars located on the southwest periphery of the Tharsis Rise (Figure 1). This region may have been associated with the earliest stages of development of Tharsis [Anderson et al., 2001, 2019a; Dohm et al., 2001, 2007, 2009a]. Graben associated with both the Noachian (Stage 1) Claritas and early Hesperian (Stage 3) Pavonis tectonic centers, as identified by Anderson et al. [2001], transect this map region. Graben associated with both trends distinctly exhibit an unusual stair-stepping pattern in the Bathys Planum region (Figure 2).

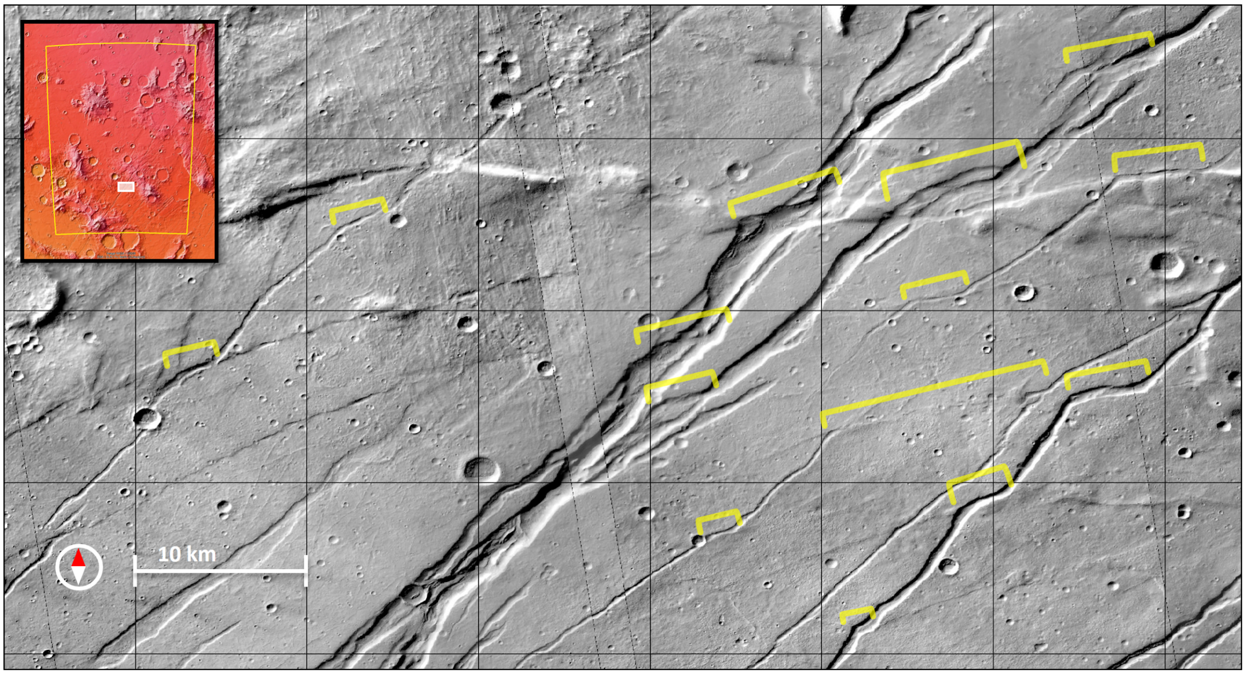

Figure 2. A CTX mosaic of a section of the Bathys Planum region, where graben associated with the Stage 1 Claritas and Stage 3 Pavonis tectonic centers [Anderson et al., 2001] assume a stair-stepped or zigzagged morphology as they intersect the E-W curvilinear basement fabric. The inset map's white box shows the location of this region in the mapping extent. Traces of the E-W basement structures can be identified indirectly due to downtrend alignments of stairsteps in the graben troughs. However, these traces sometimes manifest explicit surficial tectonic geomorphologies (see Figure 3). Instances of stairstepping and downtrend alignment are illustrated with yellow brackets. Image is centered near 115°W, 37°S.

This stair-stepping pattern is present where the graben intersect east-west trending lineaments (Figure 2). The graben are offset or deflected where the graben intersect, suggesting that the east-west trending structures influenced the development of the graben.

Additionally, downtrend of the graben-lineament intersections, depressions and hills have been identified adjacent to the lineament traces. These hills and depressions are consistent with pop-ups and pull-apart basins observed along strike-slip faults on Earth, suggesting that the lineaments are left-lateral strike-slip faults. In this study, the morphology and relative timing of these structures were examined and compared to other structures identified in this region.

2. Methodology

Faults were mapped at a 1:24,000 scale within the Bathys Planum map region using Esri's ArcGIS Pro. Distinctive structures were identified and interpreted to be strike-slip faults in the southern half of the mapping area, centered near 115°W, 38°S. Although Mars Global Surveyor (MGS) Thermal Emission Imaging System (THEMIS with average resolution of 100 m/px; Christensen et al., [2004]) daytime-infrared global basemap v. 13.6 was used as the project's overall basemap, the structures could only be resolved using Mars Reconnaissance Orbiter (MRO) Context Camera (CTX with 6 m/px average resolution; Malin et al., [2007]) images co-registered to the THEMIS basemap.

Only fault strands with definitive surface expressions were digitized; no inferred traces were mapped. Strands were divided into four categories (left-lateral strike-slip; right-lateral strike-slip; compressional; uncertain). Strike-slip landforms were mapped in association with all mapped fault strands and classified based on whether they are transpressional or transtensional (criteria are explained in the subsequent section).

2.1. Identification of strike-slip faults from terrestrial analogues

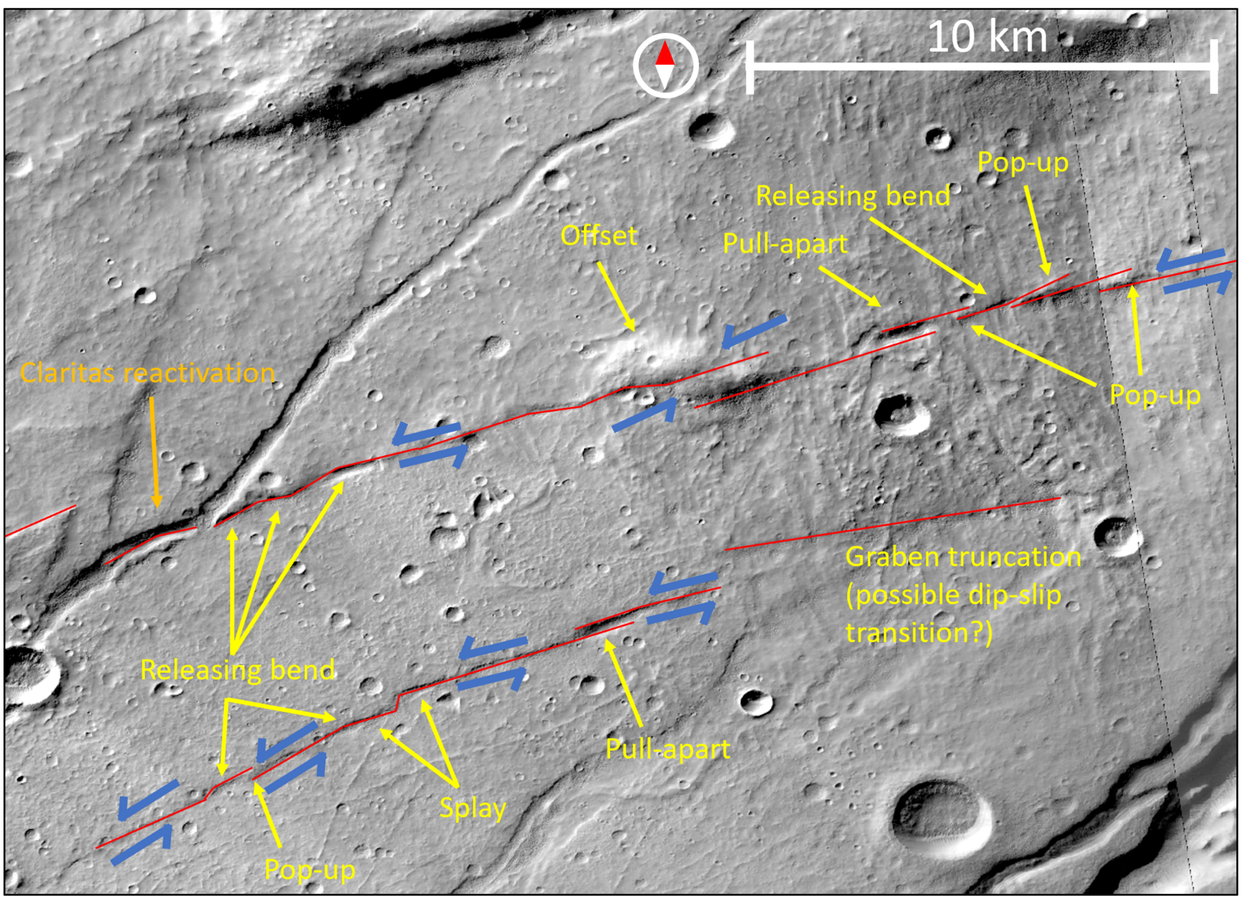

Figure 3. CTX mosaic (enlarged part of Figure 2) showing examples of E-W trending strike-slip fault morphologies within mNp, including releasing and restraining stepovers and bends. Small restraining stepover features may constitute either the positive flower structures or the push-up ridges summarized in Cunningham and Mann [2007]. The larger mound in the central part of the figure demonstrates a possible sinistral offset of approximately 1.6 km. North at top.

On Earth, the identification of topographic features at bends or steps along the structures suggest a component of lateral slip. In Bathys Planum, topographic depressions can be identified at left bends or steps in the faults, and positive topographic features (small hills) present at right bends and steps (typical dimensions 100-200 m width, 100 m-2 km length). This morphology mimics topographic features along terrestrial strike-slip faults [e.g., Sylvester, 1988; Christie-Blick and Biddle, 1985; Cunningham and Mann, 2007] and suggests that these structures exhibit a component of left-lateral strike slip. This sense of slip is also supported by the apparent left-lateral offset of the larger hill in the central part of the area (Figure 3). Towards the peripheries of the region of interest, the structures occasionally manifest as compressional faults with vertical offsets reaching 130 m (Golombek et al., [2001]; Watters, [1998]).

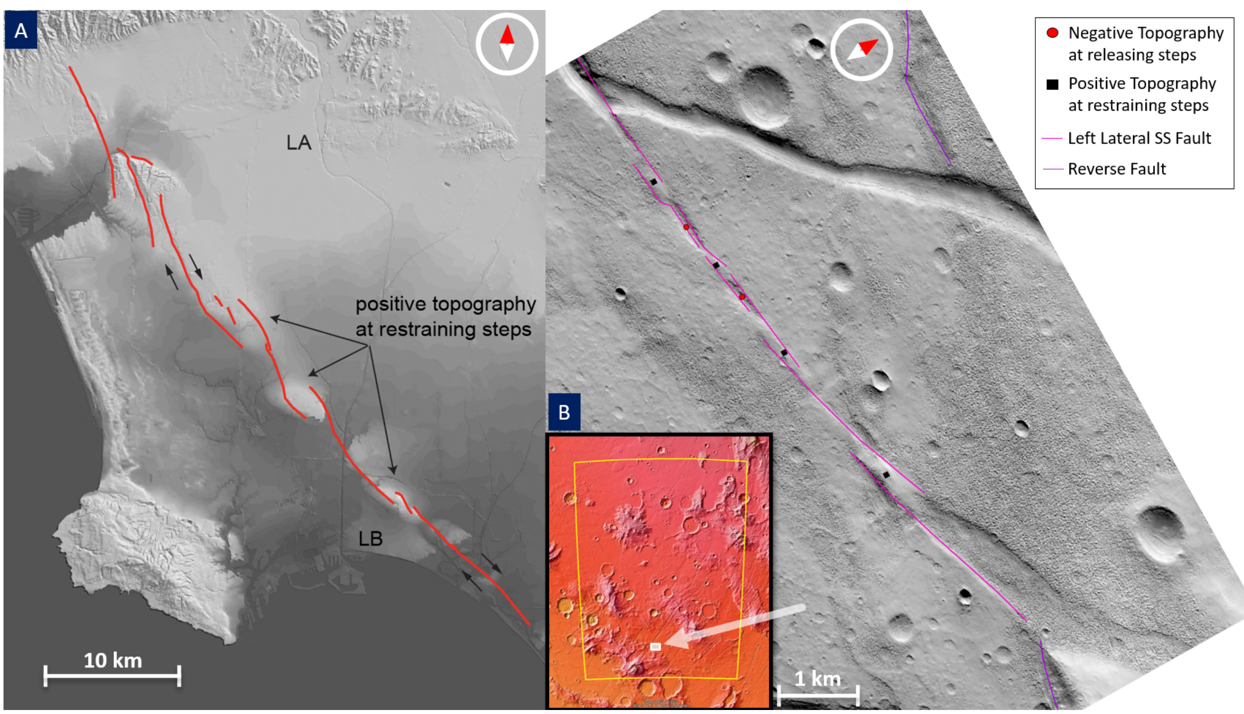

Figure 4. Subfigure A shows the right-lateral strike-slip Newport-Inglewood Fault Zone (NIFZ) in metropolitan Los Angeles, California, United States (34°N, 118°W). This is compared to strike-slip faults of Bathys Planum on account

of: (1) morphological similarities between transpressional landforms; and (2) the intermittent occurrence of overstepping scarps in a regionally curvilinear trend on a plains-forming fill material. Transpressional features in stepovers and restraining bends along the fault are labeled. Digital elevation model (DEM) modified from publicly available files published by the United States Geological Survey (USGS_1_n34w199), and fault locations are modified from the USGS Q-faults database. Subfigure B shows a left-lateral strike-slip fault in Bathys Planum with similar stepover morphology.

When terrestrial strike-slip faults bend or step against their own sense (e.g., a left-lateral strike-slip fault either bends or steps to the right), a localized compressional stress is imposed within the bend or between the *en echelon* strands of that fault, creating a pop-up in the affected area. If a fault bends into its own sense (e.g., a left-lateral strike-slip fault either bends or steps to the left), a localized extensional stress is imposed in the fault's bend or between its strands, creating a pull-apart basin [Aydin and Nur, 1985; Cunningham and Mann, 2007]. A fault may bend or step over in alternating directions, creating a "porpoising" effect where pull-apart basins and pop-ups may repeatedly alternate along the fault zone (Figure 4A; Sylvester, [1988]). Assuming these morphologies observed on Earth apply to faults in Bathys Planum, then the sense of observed faults can be inferred on the basis of the presence and distribution of these landforms. For instance, the faults mapped in Figure 3, show pop-ups at right steps, and small depressions at left steps, suggesting a left-lateral sense of slip along the faults. Note that the mound in the center-right of Figure 3 appears to be offset in a left-lateral sense by more than a kilometer, consistent with the inferred left-lateral slip along the faults from the morphology of steps and bends along the same fault zone. A terrestrial example of these morphologies is comparatively presented in Figure 4.

The "stair-stepping" deflection of the Claritas-radial graben in Figure 3 appears to be right-lateral rather than left-lateral in sense. This is interpreted not to be associated with the offset of later Claritas-radial graben. Rather, a pre-existing east-west fault system is inferred to have influenced the development of the Claritas-radial graben as the latter developed, creating an apparent right-lateral deflection in the graben as they propagated through Bathys Planum. The apparent right-lateral deflection of graben and cracks is also present where they intersect east-west faults that do not display strike-slip surface morphologies. The deflections are, however, generally consistent in strike with nearby east-west faults that do exhibit strike-slip landforms. The apparent deflections of graben in these locations could be the result of other strike-slip faults associated with this ancient east-west fault system, even if those east-west faults cannot be directly confirmed or mapped with available data.

3. Results

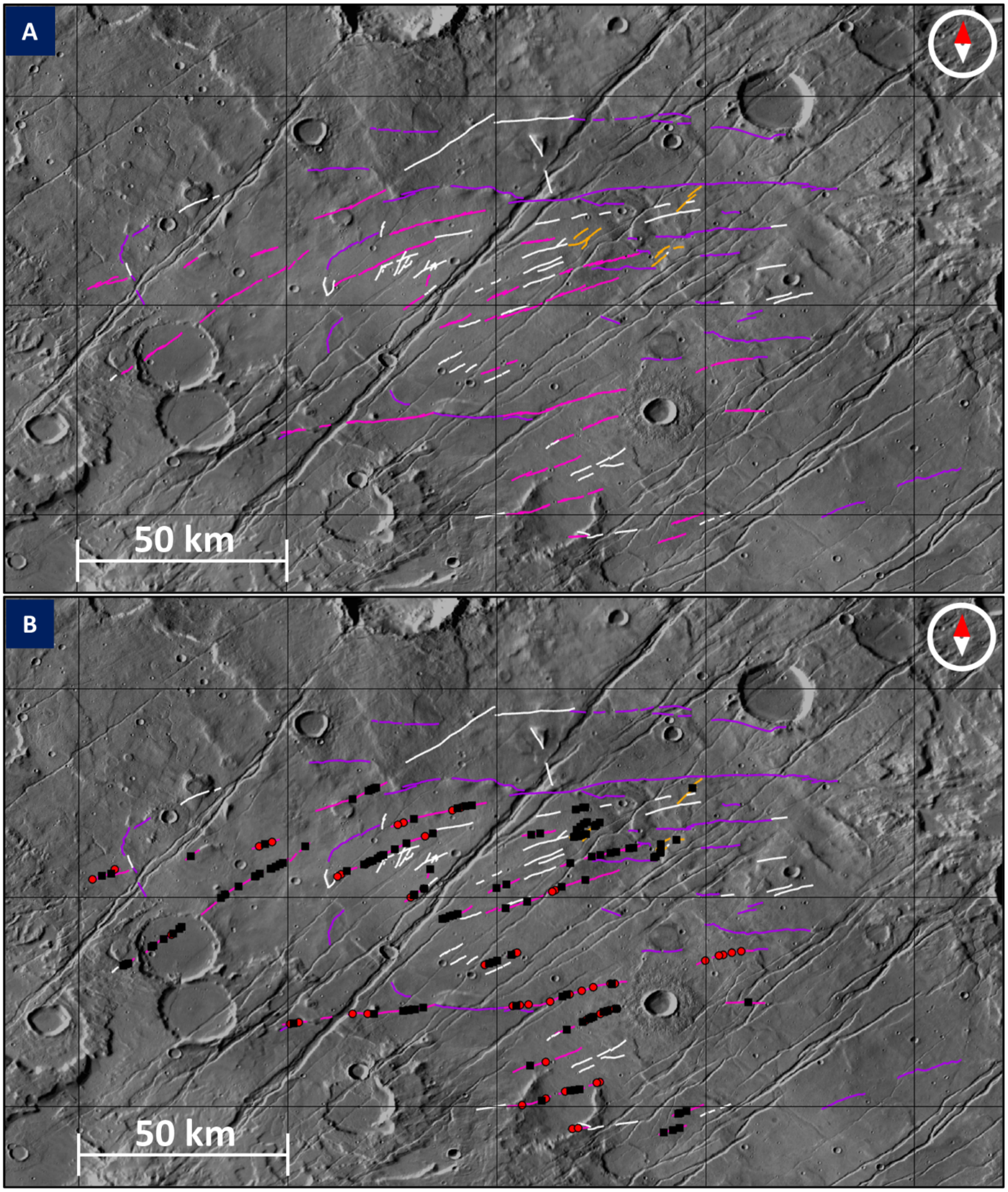
A
50 km
B
50 km

Figure 5 . A) Semi-curvilinear faults mapped on a CTX mosaic near 115°W, 38°S, in the southern-central sector of the Bathys Planum mapping area. Pink features represent sinistral strike-slip faults, yellow features represent dextral strike-slip faults, purple features represent compressional faults, and white features are possibly structural lineaments of an uncertain sense. Features are identified as left- or right- lateral based on the presence and relative orientations of strike-slip landforms to different fault segments; they are not assigned a fault type if no such landforms are observed, or if the sense of slip is indeterminate. Note that while the "stair-stepping" of graben in this area is indicative of structural control associated with the same trends as the mapped faults, these deflections are not mapped in (A) if they do not correspond to explicit transcurrent / strike-slip geomorphologies. Note that while all other features on the geologic map of Bathys Planum [Adrian et al., 2021] were mapped at a 1:250,000 scale, mapping of the structures in this figure was performed at a 1:24,000 scale on CTX. **B)** The semi-curvilinear faults with sense of slip for strike-slip landforms overlaid. 127 transpressional landforms (restraining bends, pop-up ridges, possible positive flower structures) are digitized as black squares and 48 transtensional landforms (releasing bends, pull-apart basins, possible negative flower structures) are digitized as red circles.

A total of 19 left-lateral strike-slip fault strands were mapped between two highland ridge-forming units (Noachian highlands Nh2 and Nh3) and an inter-ridge fill unit (middle-Noachian plains mNp), per Adrian et al., [2021], in the central part of the Bathys Planum map region near 115°W, 38°S (Figure 5). The faults generally strike east/northeast-west/southwest, although 6 right-lateral strike-slip fault strands were mapped in the northern-central section of the frame of Figure 5 and may represent conjugate features to the more dominant left-lateral trend. In general, the strike-slip faults are considerably more linear than the compressional faults in this section of Bathys Planum, which are observed to dip towards a central point (using the Golombek et al., [2001] model). In some locations, the strike-slip faults appear to be overridden by the east-west compressional faults, before continuing along the same east/northeast - west/southwest parallel trend farther down the compressional fault's scarp. This suggests that the more curvilinear compressional faults preceded the emplacement of the strike-slip faults.

The Bathys strike-slip faults are relatively discontinuous with minimal lateral displacement. A distinct offset of approximately 1.6 km (Figure 3) occurs on one of the strands. Furthermore, they are associated with relatively small and shallow pull-apart basins not expected to exceed the depth of their bounding strike-slip faults [Aydin and Nur, 1985]. This suggests that the observed strike-slip faults are shallow features which do not directly represent tectonism in the deeper crust [Aydin and Nur, 1985; Christie-Blick and Biddle, 1985].

The possible strike-slip faults identified in this work notably differ from those proposed by Andrews-Hanna et al., [2008] in Terra Sirenum and Amazonis Planitia because the strike-slip morphology of the faults in Bathys Planum appear to be foremost characterized by the existence of transcurrent landforms (as opposed to linear ridges with asymmetrically tapering throws on each side of the fault). They also differ from models invoking accommodation of oblique slip in Tharsis-radial graben sets [e.g., Masson, 1980; Fernández and Ramírez-Caballero, 2019; Montgomery et al. 2009], and from regionally extensive invocations of strike-slip faulting which largely depend on offset as a kinematic indicator [Schultz, 1989; Yin, 2012]. Note that transcurrent/strike-slip landforms have also been reported on Europa [e.g., Sarid et al., 2002] and Venus [Koenig and Aydin, 1998].

4. Discussion

The curvilinear faults are interpreted to exhibit a strike-slip sense as a consequence of the imposition of Claritas- and Pavonis-linked stresses in the Bathys Planum region. A model presented in Figure 6A illustrates how the most distinctive characteristics of the faults can be kinematically explained by the Claritas- and Pavonis-associated stress fields in this region. It is plausible that extensional stresses acting obliquely on the pre-existing east-west curvilinear fault set would drive left-lateral strike-slip motion along this older fault set; the lateral component of slip at these intersections laterally mobilized the structures elsewhere on these faults, producing the stepover landforms observed across the area. Because the Claritas and Pavonis fault sets intersect these east-west faults from a similar relative direction, left-lateral slip would be expected in association with stresses tied to either tectonic center (Figure 6A). It is possible that the curvilinear, oppositely dipping reverse faults bounding the faulted area might represent the emplacement of an igneous intrusion at depth: a previously unreported, but more localized, updoming event in the style of the tectonic centers identified by Anderson et al. [2001] (Figure 6B). However, the region within the curvilinear fault sets is not associated with a topographic high as is observed for other proposed centers of tectonic activity proposed by Plescia and Saunders [1982], Anderson et al., [2001], and Ivanov and Head [2006]. If the putative dome later subsided, this might explain the lack of a clear topographic expression. However, because the putative dome in Bathys was likely too small to have been geometrically influenced by the planet's curvature [Banerdt et al., 1992], its concentric ring faults would likely have had to have formed in a reverse sense during the putative dome's uplift before being reactivated as normal faults during the dome's subsidence [Cole et al., 2005; Acocella et al., 2004], instead of the other way around [Anderson et al., 2001; Dohm et al., 2009b; Ivanov and Head, 2006].

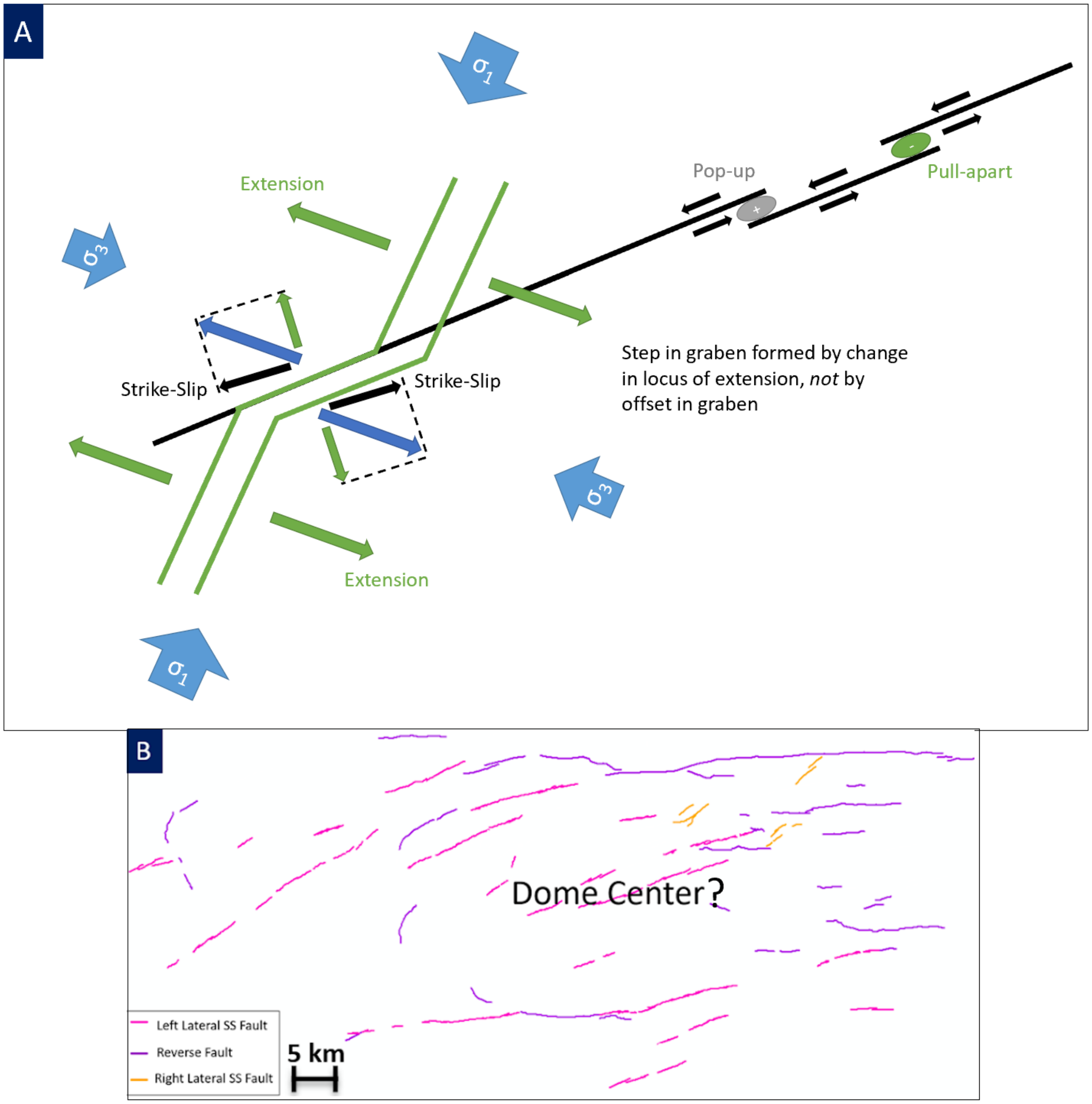

Figure 6. Subfigure A illustrates how Tharsis-driven extension in Bathys Planum might reactivate an antecedent basement fault (black) as a strike-slip fault, causing the observed stairstepping graben morphologies. Green illustrates both the graben and the direction of extension ($_3$) implied by the graben's formation. When the graben intersects with the antecedent structure, the same

regional stress field drives a component of throw and heave (in green, perpendicular to the structure) and a component of left-lateral motion (in black, parallel to the structure) that causes similar lateral deformation elsewhere on the fault, driving the aforementioned stairstepping morphologies. Subfigure B shows the mapped faults (other than graben) without the basemap to highlight the curvilinear form of faults.

Conclusion

Evidence of strike-slip faults in Bathys Planum region of Mars is presented. The Bathys intrusion (a possible tectonic center) and the Stage 1 Claritas tectonic center are argued to have simultaneously influenced Bathys Planum in the Noachian Period, with flexural stresses driven by the Claritas tectonic center influencing the geometry of a possible Bathys dome. Bathys center tectonics ceased, and the dome subsided, prior to the propagation of Claritas-radial graben through Bathys Planum. The orientations of the graben were then influenced by the pre-existing Bathys center-linked fault system, driving a lateral component of slip presenting in mostly left-lateral strike-slip tectonics on the antecedent fault system.

Acknowledgements

Data is available from a repository hosted by the Open Science Framework, accessible via the following link: osf.io/se53m

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