Deformation band clusters on Mars and implications for subsurface fluid flow

Chris H. Okubo†
Lunar and Planetary Laboratory, The University of Arizona, 1541 East University Boulevard, Tucson, Arizona 85721, USA

Richard A. Schultz
Geomechanics–Rock Fracture Group, Department of Geological Sciences/172, Mackay School of Earth Sciences and Engineering, University of Nevada, Reno, Nevada 89557, USA

Marjorie A. Chan
Department of Geology & Geophysics, University of Utah, 135 S. 1460 E, Salt Lake City, Utah 84112, USA

Goro Komatsu
International Research School of Planetary Sciences, Università d’Annunzio, Viale Pindaro 42, 65127 Pescara, Italy

High-Resolution Imaging Science Experiment (HiRISE) Team
Lunar and Planetary Laboratory, The University of Arizona, 1541 East University Boulevard, Tucson, Arizona 85721, USA

ABSTRACT

High-resolution imagery reveals unprecedented lines of evidence for the presence of deformation band clusters in layered sedimentary deposits in the equatorial region of Mars. Deformation bands are a class of geologic structural discontinuity that is a precursor to faults in clastic rocks and soils. Clusters of deformation bands, consisting of many hundreds of individual subparallel bands, can act as important structural controls on subsurface fluid flow in terrestrial reservoirs, and evidence of diagenetic processes is often preserved along them. Deformation band clusters are identified on Mars based on characteristic meter-scale architectures and geologic context as observed in data from the High-Resolution Imaging Science Experiment (HiRISE) camera. The identification of deformation band clusters on Mars is a key to investigating the migration of fluids between surface and subsurface reservoirs in the planet’s vast sedimentary deposits. Similar to terrestrial examples, evidence of diagenesis in the form of light- and dark-toned discoloration and wall-rock induration is recorded along many of the deformation band clusters on Mars. Therefore, these structures are important sites for future exploration and investigations into the geologic history of water and water-related processes on Mars.

Keywords: deformation band, fault, fluid flow, diagenesis, Mars.

INTRODUCTION

Faults and other structural discontinuities can act as important controls on fluid flow in terrestrial reservoirs. The mechanics of deformation band formation have been discussed at length in many previous works (e.g., Wong et al., 1997; Schultz and Siddharthan, 2005; Aydin et al., 2006; Fossen et al., 2007), and thus only a brief overview is provided here. Deformation bands are tabular structural discontinuities that form through localized inelastic strain in porous and granular materials. The process of deformation band formation is commonly quantified in terms of the mean and differential driving stresses using a capped strength envelope (e.g., Schultz and Siddharthan, 2005; Aydin et al., 2006). Deformation bands form through inelastic shear and involve varying amounts of either dilation or compaction of the host rock, depending on the magnitudes of the causative driving stresses. Localized inelastic dilation occurs under mean driving stresses that are either tensile or slightly compressive. Larger magnitudes of mean stress lead to inelastic compaction. Strain along deformation bands is accommodated through localized changes in porosity, grain rolling, and grain crushing within the tabular thickness of the band (Aydin, 1978; Wong et al., 1997; Schultz and Siddharthan, 2005; Aydin et al., 2006). Deformation bands do not form through frictional slip but instead create the necessary discontinuities along which frictional slip can occur (Aydin and Johnson, 1978; Schultz and Balasko, 2003; Schultz and Siddharthan, 2005; Aydin et al., 2006).

Individual deformation bands typically have widths on the order of one to several millimeters and have meter-scale lengths (Fig. 1A; Aydin, 1978; Eichhubl et al., 2004; Fossen et al., 2007). Deformation bands often occur in clusters consisting of many hundreds of individual subparallel bands, and these clusters can attain widths on the order of several meters and lengths of several hundred meters to kilometers (Figs. 1B and 1C; Aydin and Johnson, 1978; Antonelli and Aydin 1995; Fossen et al., 2005; Shipton et al., 2005; Okubo and Schultz, 2005).

Deformation bands are commonly classified according to the sense of volumetric strain (dilation or compaction) that is accommodated within the tabular thickness of the band. The relative magnitude of shear strain along the band can be used as an additional classification metric (Fossen et al., 2007). For the purposes of this paper, simple kinematic classifications based on the sense of volumetric strain alone, e.g., “dilational shear band” and “compactional shear band,” are sufficient.
Clusters of deformation bands can act as either conduits or baffles to fluid flow depending on the sense of strain accommodated along the bands and permeability contrast with the host rock (e.g., Antonellini and Aydin 1994, 1995; Taylor and Pollard, 2000; Ogilvie and Glover, 2001; Shipton et al., 2005; Fossen et al., 2007), although not all deformation bands show a strong control on fluid flow (e.g., Fossen and Bale, 2007). The permeability of individual compactional shear bands can be one to three orders of magnitude less than the nondeformed host rock, while dense clusters of these bands can exhibit up to five orders of magnitude reduction in permeability (Fossen and Bale, 2007). Cementation can also reduce permeability within the bands by up to five orders of magnitude (e.g., Ogilvie and Glover, 2001) and can create baffles to fluid flow regardless of band type (e.g., Hesthammer et al., 2002). Pervasive cementation can also inhibit the formation of deformation bands by reducing the porosity of the host rock (Johansen et al., 2005). Evidence of paleo-subsurface fluid flow is abundant in the layered sedimentary deposits within the equatorial regions of Mars (Ormö et al., 2004; McLennan et al., 2005; Grotzinger et al., 2005; Arvidson et al., 2006; Okubo and McEwen, 2007). The present-day extent of these deposits exceeds 3 × 10^6 km^2 within ±20º latitude of the equator alone (e.g., Schultz and Lutz, 1988; Hynek et al., 2003), and thicknesses range from ~600 m in Meridiani Terra to ~9 km in Valles Marineris (Hynek et al., 2003). Since these deposits appear to have undergone extensive erosion (e.g., Malin and Edgett, 2000, 2001; Hynek et al., 2003), their original extent was likely much greater. Thus, these deposits represent a potentially vast region of reservoir rock for subsurface fluids.

Formation of the equatorial layered deposits has been attributed to a variety of clastic sedimentary processes. Various deposits are interpreted as accumulations of eolian sediment (Scott and Tanaka, 1986; Greeley and Guest, 1987; Tanaka, 2000), pyroclastic material (Scott and Tanaka, 1982; Witbeck et al., 1991; Lucchitta et al., 1992; Murchie et al., 2000; Hynek et al., 2003), hyaloclastic debris (Chapman and Tanaka, 2001, 2002), lacustrine sediment (Witbeck et al., 1991; Lucchitta et al., 1992), and fluvial sediment (Malin and Edgett, 2003; Irwin et al., 2004; Quantin et al., 2005; Dromart et al., 2007).

Layered deposits examined by the Mars Exploration Rover (MER) Opportunity in Meridiani Planum (Fig. 2A) are sandstones of eolian to shallow fluvial origin (Grotzinger et al., 2005; McLennan and Grotzinger, 2008). These rocks consist of medium to coarse (0.2–1.0 mm) grains of roughly equal amounts of...
Figure 2. (A) Shaded relief map of the Arabia Terra region, Mars, showing the location of the deformation band focus area, which is located inside Capen crater centered at 6.67°N, 14.27°E (planetographic, IAU2000). This region contains numerous anastomosing ridges, which are the surface expressions of thrust fault–related folds. The location of Mars exploration Rover (MER) Opportunity is also shown. Illumination is from the upper right. Topography based on 128 pixel/degree Mars Orbiter Laser Altimeter (MOLA) gridded data. (B) Context Imager view of Capen crater. Figures 5 and 6 lie along the trace of a thrust fault–related fold that anastomoses through the upper right corner of the High-Resolution Imaging Science Experiment (HiRISE) scene. Folding of the layered deposits along the trace of the thrust fault is evident in stereo HiRISE imagery (PSP_002574_1865/PSP_003418_1865).

Figure 3. Evidence of soft-sediment deformation is widely observed within the study area. Subhorizontal banding is due to accumulations of dust along outcropping sedimentary layers. Stereo High-Resolution Imaging Science Experiment (HiRISE) views of the study area (PSP_002574_1865/PSP_003418_1865) indicate that this surface is essentially flat, and therefore layer undulations such as these are not due to topography. Also present are incising discontinuities that show varying amounts of shear displacement of cross-cut bedding. These discontinuities exhibit both positive and negative relief. Red channel image is from PSP_002574_1865. Illumination is from the left.

data offer one to two orders of magnitude increase in resolution over the data available in previous studies (Artita and Schultz, 2005). HiRISE images typically have 30 cm pixel widths and greater than 100:1 signal-to-noise ratios. Such high-resolution observations now enable the identification of deformation band clusters based on their characteristic meter-scale architectures, and they also allow diagenetic effects (e.g., cementation) to be accounted for when making this identification. These characteristic architectures, and evidence of diagenesis reported here, were unresolved in earlier Mars data. This paper presents archetypical examples of deformation band clusters from Arabia Terra, Mars, and summarizes the types of diagenetic features that are used to distinguish deformation bands from morphologically similar features such as joints and faults.

The findings reported here provide insight into timing for the deposition of the layered deposits and extant groundwater in the Arabia Terra region of Mars (Fig. 2A). Observed soft-sediment deformation structures in the layered deposits in Capen crater (Fig. 3) indicate reworked evaporites and basaltic siliciclastic material, accompanied by varying amounts of cement (Herkenhoff et al., 2004; Grotzinger et al., 2005; McLennan et al., 2005; McLennan and Grotzinger, 2008).

Deformation bands are a prerequisite to faulting in porous and granular rocks (Wong et al., 1997; Schultz and Siddharthan, 2005; Aydin et al., 2006). Since much of the layered deposits are known or interpreted to consist of clastic sedimentary rocks, and since the layered deposits are faulted (e.g., Malin and Edgett, 2000; Okubo et al., 2007a), deformation bands can be expected to occur on Mars. Indeed, the presence of deformation band clusters on Mars has been previously proposed based on interpretations of low-resolution Viking, Mars Orbiter Laser Altimeter (MOLA), and Thermal Emission Imaging System (THEMIS) data (Artita and Schultz, 2005).

In this paper, we discuss the identification of deformation bands in recently available data collected by the High-Resolution Imaging Science Experiment (HiRISE) camera. HiRISE
that groundwater was present there early on, perhaps during sediment deposition in an eolian dune and playa environment, as previously proposed for the Burns Formation (Grotzinger et al., 2005; Arvidson et al., 2006) in Meridiani Planum (Fig. 2A). Additionally, evidence of wall-rock induration indicates the presence of groundwater after some deformation band clusters had formed. The deformation band clusters are interpreted to be contemporaneous with the growth of several wrinkle ridges (thrust fault–related folds). Assuming that the deformation band clusters formed in the late Noachian to early Hesperian (4.0–3.5 Ga), during global wrinkle ridge formation (e.g., Tanaka et al., 1991; Watters, 1993; Dohm et al., 2001; Grott et al., 2007), accumulation of these layered deposits must have occurred prior to ca. 3.5 Ga, and it was contemporaneous with extant groundwater. These findings are consistent with interpretations of a pre-Hesperian age for these layered deposits, as well as a mid-Hesperian age for groundwater recession (Arvidson et al., 2006; Bibring et al., 2006; Andrews-Hanna et al., 2007).

**DEFORMATION BANDS ON MARS**

Deformation bands are especially well exposed on a mound of layered deposits within Capen crater, in south-central Arabia Terra (Fig. 2). Mounds of layered deposits such as this are common in impact craters in this region and may represent deeply eroded remnants of an extensive sheet of sediments that once blanketed the area (Malin and Edgett, 2000, 2001). Alternatively, these mounds may have grown in situ in the impact craters by extrusion of gas/water-sediment mixtures from the subsurface (e.g., Ori et al., 2000).

Erosional exposures offer clear views of distinct syn- and postdepositional structures that indicate the sedimentary nature of these layered deposits. Cross-bedding (100 m scale) is present (Fig. 4) and points to either eolian or subaqueous deposition. Soft-sediment deformation in the form of harmonic crenulations (Chan et al., 2007) is also present (Fig. 3), indicating that these sediments were water-saturated and subjected to synsedimentary deformation prior to lithification. Such observations are consistent with the interpretation that these layered deposits are composed of clastic sedimentary material.

These layered deposits are deformed by a series of north–south–trending thrust faults (wrinkle ridges; Fig. 2). The thrust faults deform the basement rock that forms the underlying impact crater, as well as the overlying mound of layered deposits. Exposed along the trace of the faults, there are numerous anastomosing discontinuities that crosscut bedding (Figs. 3–6; Figs. DR1 and DR2). Individual discontinuities are thin (less than ~3 m wide), and they are tens of meters to roughly 3 k long. These structural discontinuities exhibit both positive and negative relief. Up to ~30 m of apparent horizontal offset of crosscut bedding is observed across the discontinuities. The clastic sedimentary nature of the host rock implies that this localized shear strain would have been accommodated through the formation of deformation bands. Localized shear strain may have also been accommodated along faults that subsequently nucleated within the deformation band clusters.

The structural discontinuities in Figures 3–6 (and Figs. DR1 and DR2 [see footnote 1]) exhibit map-view geometries that are consistent with clusters of deformation bands. The discontinuities show inosculating traces (compare Fig. 1B with Figs. 5, 6A, and 6B) that are a characteristic of individual deformation bands (Aydin, 1978; Aydin and Johnson, 1978) and clusters of bands (Davis, 1999) that have dип-slip shear displacements. These discontinuities

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occur along and are subparallel to the trace of thrust faults, consistent with a common driving stress field for both (e.g., Okubo and Schultz, 2005). Therefore, thrust displacements along these discontinuities are likely. Accordingly, the observed shear displacements of bedding (Figs. 3 and 6) are attributed to oblique exposures of thrust slip along these discontinuities.

Discontinuities that exhibit meter-scale crenulations and negligible shear, and which also crosscut bedding (Fig. 6C), are also present. This distinct geometry is consistent with the morphology of “compaction bands” (Mollema and Antonellini, 1996; Sternlof et al., 2005), a type of deformation band that forms with negligible shear strain.

Taken together, these lines of contextual and structural observations drive the interpretation that these discontinuities are clusters of deformation bands. This deformation is interpreted to have occurred at depth, after which the features were exhumed through erosion. The meter-scale widths of these discontinuities are consistent with the widths of deformation band clusters on Earth. Typical examples have millimeter-scale widths of individual deformation bands that would not be resolved in HiRISE images. The recognition of deformation band clusters is perhaps of greater significance than the identification of individual deformation bands because clusters of bands have a greater impact on fluid flow than individual bands do (e.g., Fossen and Bale, 2007).

The sense of volumetric strain along these deformation bands can be inferred from their erosional morphology as observed in terrestrial examples. Deformation bands commonly exhibit distinct erosional morphologies that reflect the sense of volumetric strain that they accommodate (Fig. 1). Dilational shear bands accommodate increases in intergranular pore space through breaking of grain-to-grain cements within the tabular thickness of the band. Thus, the rock within these bands is mechanically weaker than the surrounding host rock, and dilational shear bands can be expected, and are typically observed, to erode in negative relief (e.g., Okubo and Schultz, 2005). Compactional shear bands, on the other hand, form through loss of pore space due to increased grain-packing density and potentially cataclasis and pressure solution along grain contacts. Thus, compactional shear bands are more resistant to erosion than the host rock and typically erode in positive relief (e.g., Aydin, 1978; Mollema and Antonellini, 1996; Fossen et al., 2007). This general erosional morphology holds for the larger deformation band clusters as well, assuming negligible diagenesis.

Accordingly, the proposed deformation band clusters that have negative relief are interpreted to consist predominantly of dilational shear bands, whereas the positive-relief clusters are interpreted to primarily reflect localized compaction. An important caveat to this line of reasoning is that diagenetic cementation (e.g., Ogilvie and Glover, 2001) can cause discontinuities to erode in positive relief. Criteria to evaluate cementation along fractures (joints and faults) and deformation bands are discussed in the next section.

The identification of deformation bands on Mars is significant since these structures can influence the movement of subsurface fluids. The ability to distinguish deformation bands from fractures (i.e., sharp discontinuities such as faults and joints in crystalline rock) is key when utilizing models of deformation band growth around faults (e.g., Shipton et al., 2005; Okubo and Schultz, 2005; Fossen et al., 2007; Fossen and Bale, 2007) to investigate the impact of faulting on local patterns of fluid flow. Dilational shear bands can act as conduits to fluid flow since they form through localized increases in porosity and permeability. Compactional shear bands on the other hand can act as baffles to fluid flow since they form as a result of significant decreases in pore space and permeability. Therefore, at Capen crater, subsurface flow would be enhanced along the plane of the dilational shear bands, and flow would be impeded across the compactional shear bands (Figs. 3–7). Thus, these deformation bands would have acted to enhance local fluid flow in

Figure 6. The discontinuities exhibit inosculating geometries in (A) positive relief and (B) negative relief. Discontinuities with crenulated geometries (C) are also present. Inosculating bands commonly exhibit shear offsets of crosscut bedding, while shear offsets are not apparent across discontinuities with crenulated geometries. Light-toned areas along the discontinuities are the result of accumulating dust rather than the result of diagenesis. High-Resolution Imaging Science Experiment (HiRISE) color image is from PSP_002574_1865. Locations of (A) and (C) are given in Figure 5. Location of (B) is given in Figure 2. Illumination is from the left.
Figure 7. Examples of diagenesis along discontinuities in layered deposits in the Meridiani Planum area. Examples of each feature type are highlighted with a red (light-toned discoloration and wall-rock induration) or yellow (dark-toned discoloration) dashed line. (A) Apparent lightening in tone of the rock surrounding fractures. (B) Dark-toned discoloration along fractures. (C) Induration of the walls on either side of the fractures. The cleft formed by the fracture imparts a double-ridged morphology. (D) Dark-toned discoloration along light-toned ridges, which is attributed to overprinting of the diagenetic processes shown in (A)–(C). The light- and dark-toned patches of bedrock can be distinguished from topographic shading in stereo High-Resolution Imaging Science Experiment (HiRISE) images (Fig. DR3 [see text footnote 1]). Illumination is from the left in all images. Features such as these were proposed by Hynek et al. (2002) to be cemented fractures based on interpretations of Mars Orbiter Camera imagery.
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a generally north-south direction and vertically through the layered sediments. Signs of diagenesis provide evidence of fluid flow along some of these deformation band clusters.

Deformation bands are differentiated from the fractures that form in crystalline rock based on the degree of strain localization (e.g., Aydin et al., 2006). Strain along deformation bands is distributed within the tabular thickness of the band and, to a lesser degree, within the surrounding host rock. Conversely, strain along faults and joints is accommodated at the sharp structural discontinuity that is the fracture wall. The style in which strain localizes in porous and granular (e.g., clastic sedimentary) rocks is influenced by the pervasiveness of cementation at the time of deformation. The trademarks of deformation band formation—changes in porosity, grain rolling, and grain crushing—are hindered by intergranular cements (e.g., Wong et al., 1997). Thus, in pervasively cemented sandstone (e.g., the Whatanga contact in the Burns Formation; McLennan et al., 2005; Grotzinger et al., 2005), structural discontinuities behave mechanistically as fractures do in crystalline rock rather than as deformation bands (e.g., Johansen et al., 2005). Therefore, characterization of the degree of cementation at the time of deformation is important when inferring the presence of deformation bands.

DIAGENETIC FINGERPRINTS

Prior to the arrival of HiRISE at Mars, orbiter-based evidence of structurally controlled fluid flow (flow along fractures and other geologic discontinuities) was limited to interpretations of imagery at greater than ~3–5 m resolution (e.g., Burr et al., 2002; Hynes et al., 2002; Ormö et al., 2004; Treiman, 2008) and was bolstered by strong mineralogic evidence of diagenesis and subsurface fluid flow (Christensen et al., 2000, 2001; Gendrin et al., 2005; Birbring et al., 2006). Data collected by MER Opportunity subsequently offered some of the strongest lines of evidence for subsurface fluid flow through the layered deposits in Meridiani Planum (McLennan et al., 2005; Squire et al., 2006; Arvidson et al., 2006).

Light-toned halos along structural discontinuities (e.g., fractures and deformation bands) are commonly observed in HiRISE images of equatorial layered deposits (Fig. 7A). Such halos were initially observed in Candor Chasma (Okubo and McEwen, 2007). These halos are interpreted to reflect dissolution of dark-toned minerals, precipitation of light-toned minerals, or both, due to fluid flow along fractures. Precipitation of light-toned minerals may mask any dark-toned minerals within the host rock. Precipitated minerals may also help to preserve the appearance of a light-toned halo by indurating the host rock and thereby hindering the development of rough erosional surfaces that can act to trap dark-toned sand.

Conspicuous dark-toned patches were observed along structural discontinuities in many HiRISE images of equatorial layered deposits (e.g., Fig. 7B). Such features were not observed in the outcrops studied by Okubo and McEwen (2007). This discoloration is interpreted to be the result of grain coatings and cements of dark-toned minerals that have precipitated from fluids circulating along the discontinuity. Morphologically similar features have been interpreted as evidence of fluid flow on Earth (e.g., Eichhubl et al., 2004; Chan et al., 2000, 2005). These dark-toned discolorations are commonly localized at discrete points along discontinuities, suggesting that fluids were concentrated at structural stepovers where focused fluid flow can be expected.

HiRISE imagery also reveals that dark-toned discoloration of the host rock commonly occurs along discontinuities that are surrounded by light-toned halos (Figs. 7B and 7D; Fig. DR3 [see footnote 1]). This new observation indicates successive diagenetic events and demonstrates how temporal changes in groundwater chemistry can be recorded along structural discontinuities such as deformation band clusters (e.g., Parry et al., 2004). Thus, fluid flow along deformation bands and other discontinuities may be an important mechanism for concentrating hematite and other iron-bearing minerals within the layered deposits on Mars.

The processes of iron cycling (e.g., Parry et al., 2004; Chan et al., 2005, 2006; McLennan and Grotzinger, 2008; Tosca et al., 2008) and diagenetic recrystallization (McLennan et al., 2005; McLennan and Grotzinger, 2008) likely contribute to the changes in host-rock color along the fractures observed by Okubo and McEwen (2007) and in this paper. Iron cycling is likely given the abundances of iron minerals that are often detected (Geissler et al., 1993; Christensen et al., 2000, 2001; Arvidson et al., 2006; Farrand et al., 2007) in association with layered deposits. Recrystallization of evaporite minerals has been observed by MER Opportunity (e.g., McLennan et al., 2005; McLennan and Grotzinger, 2008) and can be expected in layered deposits that have a similar origin and geologic history.

Additionally, while Okubo and McEwen (2007) were unable to infer topographic evidence for wall-rock induration along the features they studied, discontinuities with a double-ridged morphology may be commonly observed in stereo HiRISE images (Figs. 7C and 8; see also anaglyph in Fig. DR2 [see footnote 1]). These discontinuities do not exhibit the clearly defined, meter-scale inosculations that are characteristic of deformation band clusters (Fig. 6). Instead, formation of these structures is attributed to induration of the wall rock on either side of the discontinuity. Accordingly, this double-ridged morphology is interpreted to be an indicator of preferential cementation (and fluid flow) along that discontinuity. The discontinuity may be a joint or a deformation band, depending on the degree of host-rock induration, and therefore strain localization, at the time of deformation. Pervasive cementation along the discontinuity is expected to mask any of the characteristic deformation band geometries. Therefore, classification of the discontinuity in remotely sensed data will be difficult if the degree of pre-tectonic diagenesis is unknown.

The alternative interpretations of the discontinuities shown in Figures 5 and 6 as either volcanic dikes or veins can be ruled out based...
on their observed widths and lengths (i.e., displacement-length scaling: Schultz et al., 2006, and references therein). An opening mode fracture (joint, dike, or vein) in layered deposits on Mars would have a width-to-length ratio of $\sim 5 \times 10^{-3}$ (Okubo et al., 2007b). For a discontinuity length of 3 km, 15 m of opening (width) would be expected if the discontinuity were a magmatic dike or vein. Instead, discontinuities of this length have a maximum observed width of $\sim 3$ m. Thus, the dimensions of the discontinuities are inconsistent with the critical strain required for a magmatic dike or vein. Additionally, dike material is not observed within these discontinuities as it is in other HiRISE images (e.g., PSP_004159_1660). Further, discontinuity length of 3 km, 15 m of opening (width) would be expected if the discontinuity were a double-ridged morphology points to wall-rock induration along some, but not all, clusters (Fig. 8; Fig. DR2 [see footnote 1]). The clusters that contain evidence of induration are scattered amongst others that show no such evidence of cementation or discoloration. These variations in wall-rock induration suggest spatial differences in groundwater chemistry. Structural discontinuities that cut diagenetic hematite and manganese oxides and fault-related fluid flow in Jurassic sandstones: Examples from the Thermal Emission Spectrometer: Evidence for near-surface water: Journal of Geophysical Research, v. 105, no. E4, p. 9623–9642, doi: 10.1029/2000JE001415.

The apparent lack of discoloration may be the result of a lack of reactive fluids, a lack of primary dark-toned (e.g., iron) minerals in the bedrock, or these features may be obscured by the thin covering of light-toned dust that is pervasive throughout much of Arabia Terra.

Clusters of deformation bands and evidence of fluid flow along them (and other fractures) are now recognized in many HiRISE images of equatorial layered deposits. This work shows the importance of structural discontinuities in concentrating past diagenetic processes. Structural discontinuities are therefore recognized as key sites for furthering our understanding of past groundwater migration and chemistry throughout the equatorial layered deposits on Mars.

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